Energy and Buildings 130 (2016) 219–227

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Hygrothermal behaviour and thermal comfort of the vernacular housings in the Jerte Valley (Central System, Spain)

Beatriz Montalbán Pozas[a,*], Francisco Javier Neila González[b]

[a] University of Extremadura, Department of Construction, School of Technology, Avenida de la Universidad s/n, 10004, Cáceres, Spain
[b] Technical University of Madrid, Department of Construction and Architectural Technology, School of Architecture, Avenida de Juan de Herrera 4, 28040, Madrid, Spain

ARTICLE INFO

Article history:
Received 16 March 2016
Received in revised form 5 July 2016
Accepted 12 August 2016
Available online 13 August 2016

Keywords:
Energy efficiency
Thermal comfort
Vernacular architecture
Bioclimatic strategies climate-responsive building design

ABSTRACT

Vernacular architecture is closely and traditionally linked to energy efficiency due to its adaptation to climate and location. The main purpose of this paper is to diagnose the hygrothermal behaviour inside the vernacular housings of the Jerte Valley (*Valle del Jerte*), located in the Spanish Central System mountain range (*Sistema Central*). This region is widely characterised by a Mediterranean continental mountain climate with medium-sized mountains and presents two distinguished six-month periods: one is warm and dry, whereas the other is cold and rainy. The objective of the aforementioned diagnosis is to promote the preservation of buildings and its energy refurbishment. As a starting point, a study that associates the region's monthly climate data with the thermal comfort has been developed. Afterwards, a regional building type has been defined for further use by an energy simulation program in order to measure the hygrothermal behaviour of the envelope. Finally, these results have been related both to thermal comfort and bioclimatic strategies. The results suggest that, during the warm period, indoor conditions are comfortable without the need for an additional energy supply. Nevertheless, in the cold period, indoor conditions are warmer than outdoor conditions, but an additional external energy supply will be required to achieve the comfort zone. Accordingly, it is determined that the refurbishment solutions used for those constructions must maintain intact the bioclimatic strategies that benefit summer conditions. However, strategies that give rise to winter conditions without changing its summer behaviour must be improved.

1. Introduction

Vernacular architecture, unlike many modern buildings, presents high-efficiency bioclimatic strategies due to its design, which was adapted to climate and location [1–3]. Consequently, a different kind of house is built for each territory [4–6], there are no universal models, and each zone generates its own building typology. This fact implies the existence of a situation close to thermal comfort inside the buildings [7–9]. In this regard, heat or cold is preserved and distributed wisely with the available resources within its reach [10–12].

Unfortunately, this building stock is deteriorating gradually: a large number of houses are empty and abandoned; others are usually refurbished with unsuccessful interventions that worsen its thermal comfort and/or damage its patrimonial value, while others, in the latter case, are replaced by less sustainable or less energy-efficient constructions [13].

Against this background, there is a pressing need to act in order to ensure the future of these traditional housings and historic centres, through the recovery of bioclimatic strategies and the indoor comfort inherent in its construction [14–17].

This study is specifically focused on half-timbered housings belonging to eleven settlements in the Jerte Valley (the Valley from now on). These dwellings are an inhabited sample from the vernacular heritage in the Spanish Central System mountain range, since these housings undergo a progressive deterioration, while the economy in the region is active, and its population of eleven thousand inhabitants has neither grown nor decreased in the last century (Fig. 1).

In brief, the Valley is described as a well-defined and homogeneous geographical unit, from both the territorial and the socioeconomic perspectives. This region is enclosed by two mountain ranges, and is linearly arranged with NE-SW inclination along the Jerte's river course (Fig. 2). Due to its narrowness, its depth, and its southern opening, the region presents its own climatic fea-

* Corresponding author.
E-mail addresses: bmpozas@unex.es (B. Montalbán Pozas), fjavier.neila@upm.es (F.J. Neila González).

http://dx.doi.org/10.1016/j.enbuild.2016.08.045

Fig. 1. Vernacular inhabited housings in El Valle.

Fig. 2. Map of the territory of the Spanish Central System and the Valley mountain range.

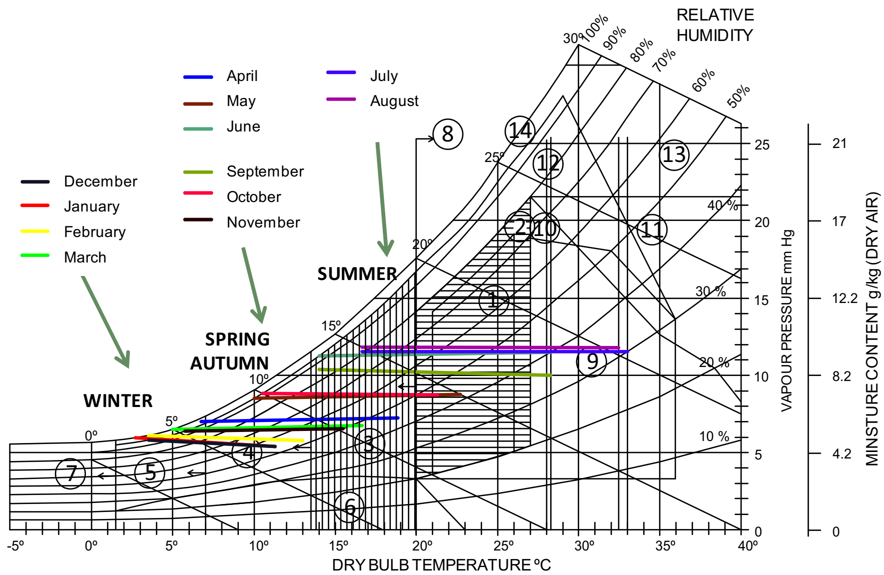
tures. It is characterised by a continental Mediterranean climate in its mountain variable, with two very pronounced periods: the warm period, with high temperatures and low rain in autumn, and the cold period, with sub-zero temperatures and plentiful rain in autumn. Both of them present the usual oscillation between night and day temperatures in mid-latitudes.

2. Material and methods

The first step of this research was to determine, in a global way and as a first approach, the relationship between climate in the region [18,19] and thermal comfort situation, which is defined when the human body requires the minimum energy consumption, i.e., taking in all cases an individual wearing light clothing, with low muscular activity and in the shade. The results lead on to the identification of the required thermal conditions and the possible passive heating and cooling improvement strategies [7,14]. Givoni's psychrometric chart was used for that purpose. Thermal comfort situations, which are based on inhabitants' experience, are reflected in this chart by means of the introduction of regional climate values (monthly average dry bulb temperature and relative humidity) [2,20].

In second place, a computational model was developed, defining the following aspects: on the one hand, the representative building type [21–23] according to a study of the vernacular dwelling stock [24], in order to examine the construction system and the design patterns of the dwelling, and on the other hand, the use, the activities and the characteristic covering of the dwellings. Thereby, DesignBuilder of EnergyPlus (version 2.4.2.026), an energy simulation software to study the energy exchanges [25] and the indoor hygrothermal behaviour of this model [26] on daily, weekly, monthly and semesterly basis, has been used. In addition, a study of the hourly climate values specific to the region, considering the different internal gains, has been included.

Finally, the energy balances and hygrothermal results obtained in the housing, as well as the reduction in energy consumption, have been analysed regarding thermal comfort according to Givoni [27], evaluating the improvements achieved in relation to the outdoor climate constraints. Furthermore, the improvement strategies are selected [21–23], in order to propose the adequate refurbishment strategies for each vernacular building in future actions [24–26,28].



COMFORT ZONE (striped in the drawing)		
Zone 1, thermal comfort	Zone 2, admissible thermal comfort	Zone 3, heating by internal gains
Individual with light clothing, low muscular activity and in the shade	Perimeter added to zone 1 by the use of clothing adapted to winter or summer	Room temperature increase when inhabiting a building
ADDED COMFORT ZONES (by the use of bioclimatic strategies)		
Zone 4, passive solar heating	Zone 8 (from20ºC), shade line	Zone 9, high-mass cooling
Solar radiation strategy	Solar protection strategy	High thermal inertia strategy

Fig. 3. Givoni's psycrhometric chart adapted to monthly climate in the Valley according to the data of the meteorological station in Barrado.

3. Case study results

3.1. Approach to the thermal comfort situation and to the bioclimatic strategies in the Valley using Givoniís psychrometric chart

The monthly climate data, which were collected from the weather station placed in the municipality of Barrado (first order station, n° 3–439, with historical records dating from more than 30 years ago [32]), were introduced in Givoni's psycrhometric chart. Due to its altitude, latitude, land topography, weather, pluviometry, and solar radiation, the station was considered a representative location of the eleven settlements in the Valley [33].

Each monthly value has been represented by a coloured line, which is positioned in different chart areas of the diagram according to the thermal comfort during the corresponding period.

Therefore, according to Givoni's psycrhometric chart, the Valley is located in the thermal comfort zone almost entirely during the summer months, the end of the spring, and the beginning of the autumn (terming this time frame warm period, when cooling strategies are needed, and since approximately April 16th to October 15th). In the summer months, the hottest midday hours must be exempted, in which the chart proposes thermal inertia as a strategy to diminish the exterior heat flow. Additionally, the coolest night hours in spring and autumn must be excluded, when solar radiation is proposed in the chart. Likewise, the adequate bioclimatic strategy from 20° C would be sun protection (Fig. 3).

In the same chart it can be noted that the climate during the rest of the year is outside the thermal comfort zone (the cold semester, in which heating strategies are needed from approximately October 16th to April 15th). In this cold period, the passive strategy suggested by Givoni is solar radiation during the midday hours in spring and autumn months (Fig. 3).

3.2. The Valley building envelope behaviour through energy simulation

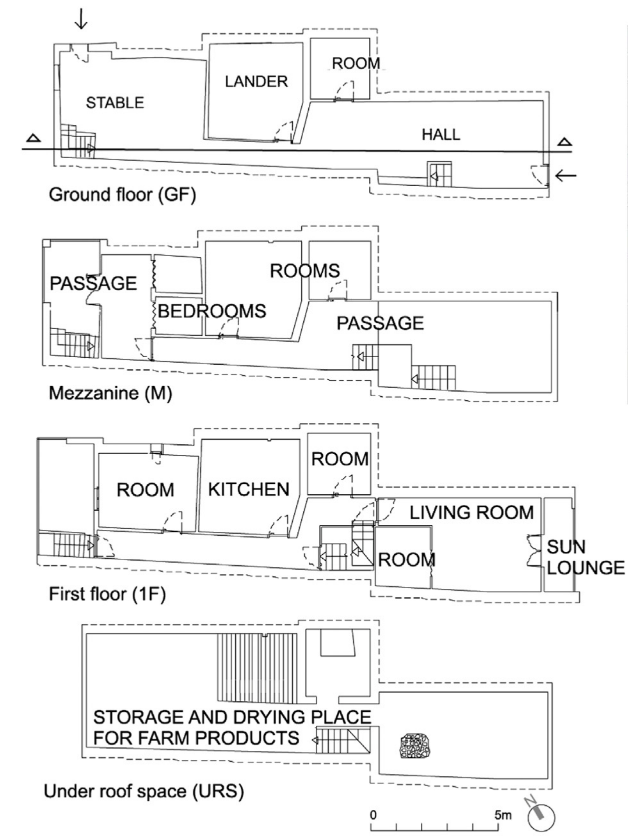
3.2.1. Energy model definition

In order to carry out the subsequent data extrapolation, the building type and, by means of this typology, the energy model that will be used in the energy simulation are defined. To that end, the following bibliographic elements will be used: firstly, the existing literature about the region, as well as the land registry, the National Institute of Statistics, and the planning regulations database to obtain the territorial and urban definition.

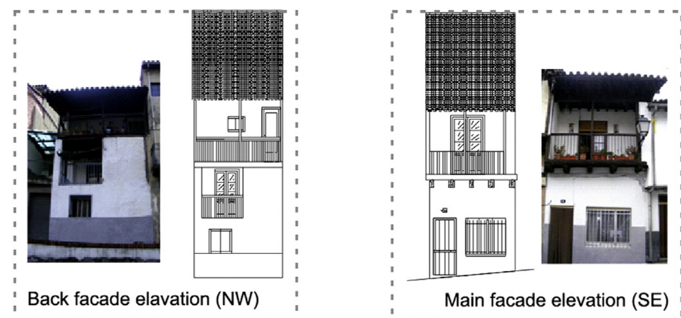
In addition, the fieldwork in each settlement, with the data collection of the most representative housings (example in Fig. 4.), as wells as material testings for the architectural and constructive definition, can be also found among the collected data.

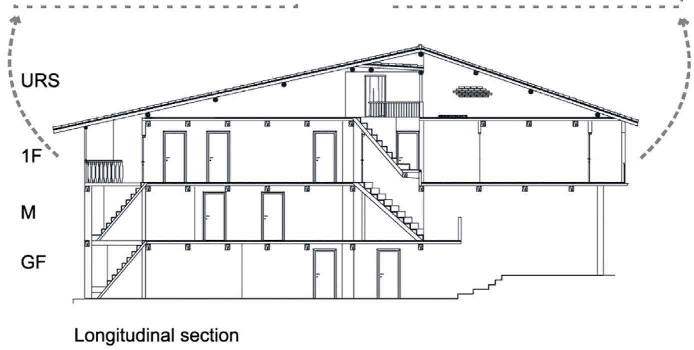
By collecting the previous data, the Valley building typology (Fig. 5) has been defined as a building situated in a lengthened rectangular plot, with a width/long ratio of 1/5, an average area of 125 m^2, and a predominant orientation SE-NW. This housing type has two floors, plus another under the roof. Likewise, the building envelope consists of two narrow exterior facades, orientated towards two facing streets, two great party walls, the plot, and a low-pitched gable roof.

In architectural terms, at the ground floor, the thick walls are built up of granite stones, with small windows on the facade, whereas the first floor presents half-timbered walls made of chestnut wood and adobe, with long balconies protected by large overhangs. Both floors have the same structure and internal par-



SITUATION			
Cabezuela del Valle			
Orientation		Nº of floors	Height till eaves
Main Facade SE (34 Hondón St)		2	6,40 m
Back Facade NW (Plasencia Avenue)		3	7,10 m
PLOT			
Area	Width	Length	Width/length ratio
100 m²	4,5/5,5 m	22 m	1/5
GEOMETRIC DEFINITION			
Double bay, one with stairs and corridor and the other one with rooms. Double access with two stairs up to under roof space.			
Roof slope	Balconies length	Eaves	Overhang
30%	1,40/2,45 m	0,60/1,40 m	1,00 m
Clearance height			
GF: 2,35 m (Hall: 3 m)	M: 2,35 m	1F: 2,65 m	URS: De 0 a 2,80 m





DISTRIBUTION	
Ground Floor	Double height hall, lander and stable with separate entrance from the river. The ground floor is under the ground level.
Mezzanine	Rooms, passage with two bedrooms.
First Floor	Living room with sun lounge and bedroom facing main facade, kitchen and room facing back facade.
Under Roof Space	Secondary usage of storage and drying place for some farm products.

Fig. 4. Half-timbered housing example in the Valley (drawings from Heras [29]).

titions. The horizontal building envelopes are light and are made of timber frame, identical to the roof, which favours ventilation. Lime mortar and mud are used as cladding.

Regarding the interior layout, the housing is divided into two bays: the first floor houses the main entrance (hall) and the rooms for cattle and crop storage (stable and wine cellar); the second floor contains the living part of the house in the strict sense (living rooms, kitchens and bedrooms); and the under-roof space, which is not habitable, has a secondary use as storage and drying place for some agricultural products. The geometric, constructive and distributive definition of the computational model is specified in Fig. 5. Air impermeability, crack template, and modelling of grids have been introduced in the model and have adapted to each situation. Infiltrations have been simulated according to the different constructive systems of the envelope: airtight walls at the ground floor, and permeable ones on the first floor and the under-roof space,

With respect to the rest of parameters introduced in the energy simulator, it is important to note the following aspects: firstly, climate data made reference to a specific schedule study about regional climate, thereby incorporating the nigh-day behaviour [30].

Secondly, the activity patterns, the clothing as well as the use have been adjusted to the traditional lifestyles and the local customs. These parameters are considered for each room, taking into account the housing usage, bearing also in mind the farming activity carried out in the building [31].

Thirdly, the highest internal gains are considered during the cold period, 15000 kWh, in comparison to the 4000 kWh in the warm period. Such a difference is due to the wood fire on the first floor (which is lit all day during this period), the occupancy and the latent gains resulting from the animals on the ground floor (where they are sheltered in the coldest months). The solar gains through windows are minimal because of the lack and the small dimensions of the openings (Fig. 6).

Finally, no additional energy supply was introduced in the energy simulator.

3.2.2. Heat exchanges in the envelope and hygrothermal behaviour model

Once the above-defined Valley housing model has been introduced in the energy simulation and its energy behaviour has been obtained, it appears that the heat exchanges balance is negative during two periods per annum. That means the internal heat is lost to the outside all the time. With regard to exchanges between the thermal envelope with the exterior, the highest heat losses are due to exfiltrations, which take place during the whole year (56% of the total: 10000 kWh). These heat losses are higher in the cold period and are mostly produced in the under-roof floor, through

SITUATION			
Zone 1		Street width: 4 m	
Orientation	Nº of facades	Nº of floors (height till eaves)	
SE and NW	2	2 (5,75 m)	
PLOT			
Area	Width	Length	Width/ length ratio
125 m²	5 m	25 m	1/5
GEOMETRIC DEFINITION			
Roof slope: 30%		Eaves: 0,6 m	
Balconies length: 1,00/1,50 m		Overhang: 1,00 m	
Double bay: corridor and rooms. Double access. Two stairs (straight directrix).			
Floors	Clearance height	External doors and windows	
Ground floor	2,80 - 3,80 m	Two access doors (1,3 x 2 m) and two small windows in larder and stable (0,5 x 0,5 m)	
First floor	2,40 m	Two balcony doors (2 x 0,9 m)	
Under cov. floor	From 0 to 2,20 m	No doors or windows	

CONSTRUCTION CHARACTERISTICS		
Construction elements	Thickness (cm)	U-value (W/m²K)
M2+R. Granite mansory wall in ground floor rendering lime mortar in the internal face (including internal walls)	70+5	1,713
M3+R. Timber framework wall in the remaining floors rendering lime mortarin the internal face (including internal walls)	20	1,924
S1. Dirt floor in the larder	30	2,178
S2. Dirt floor and lime mortar in the hall	30+10	1,954
S3. Dirt floor with straw and dung in the stable	30+30	0,956
F1. Wooden floor structure with chestnut beams	4+4	1,548
F2. Idem with grain on the floor of the under cover floor		0,763
F3. Idem with terraccota tiles and lime mortar on the kitchen floor	4+4+20	2,172
F4. Idem with wooden boarding in the kitchen ceiling	4+4	
F5. Slope roof with chestnut beams and wooden boarding	2+2,5	3,542
D. External chestnut door (10 cm)	10	1,169
W. Single glazed wooden windows (3 mm)	3	5,894

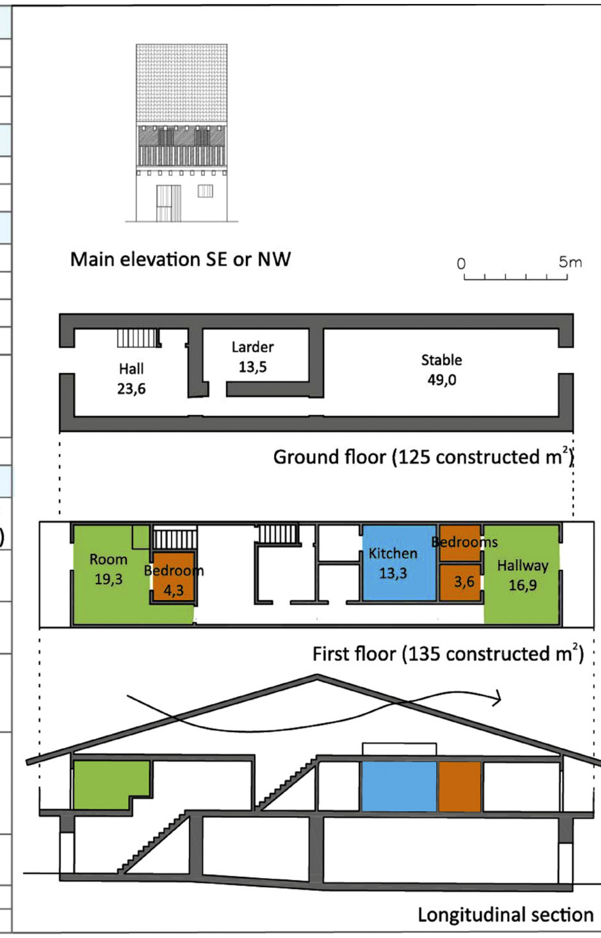
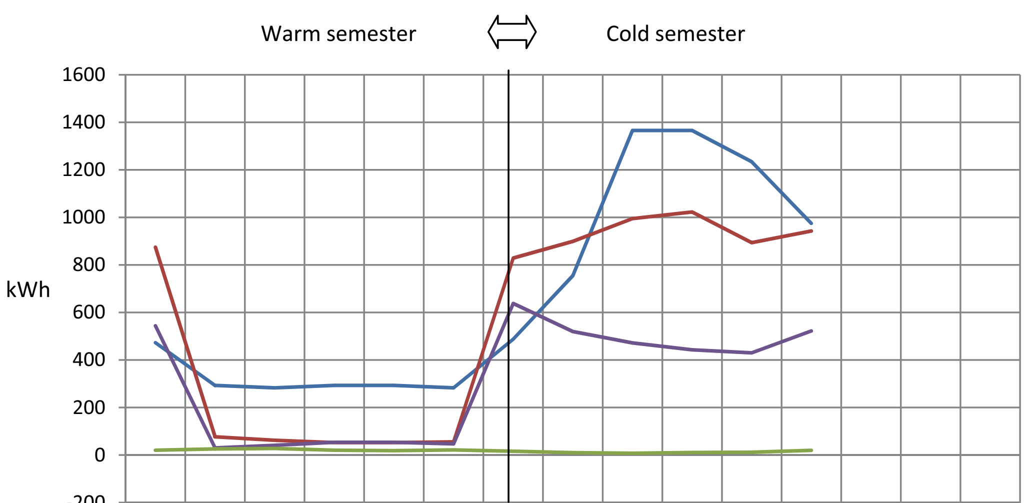
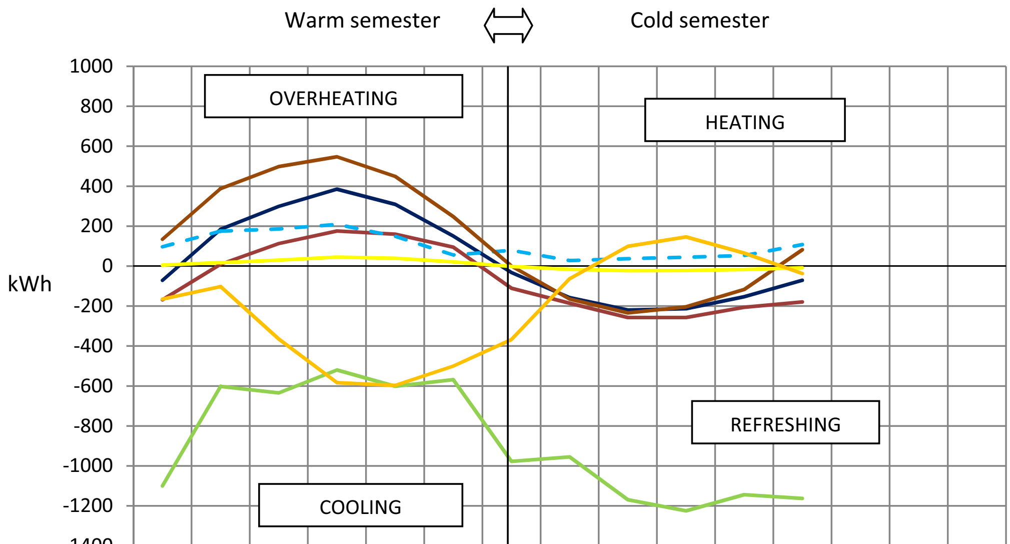


Fig. 5. Vernacular half-timbered building type in the Valley.



	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec	Jan	Feb	Mar		Warm Sem.	Cold Sem.
Cooking gains	473	293	283	293	293	283	488	755	1366	1366	1234	975		1918	6184
Occupancy	875	77	62	53	52	56	829	899	995	1023	894	943		1175	5583
Latent gains	544	30	41	54	54	47	638	520	472	443	430	522		770	3025
Solar gains	20	26	28	21	19	21	16	10	8	11	12	20		135	77
TOTAL	1908	426	414	420	418	407	1971	2184	2841	2844	2572	2462		3997	14869

Fig. 6. Internal heat gains entered in the energy model.



	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec	Jan	Feb	Mar		Warm Sem.	Cold Sem.
External walls	-72	184	299	385	309	151	-32	-158	-220	-213	-153	-71		1255	-847
Stone	-169	9	113	176	160	95	-111	-186	-257	-257	-206	-179		383	-1196
Adobe blocks	97	175	186	209	149	56	79	28	37	44	53	108		872	349
Roof	134	388	498	547	449	248	0	-165	-234	-204	-117	82		2264	-638
External infiltration	-1100	-602	-635	-520	-601	-568	-977	-955	-1169	-1225	-1144	-1163		-4026	-6633
Glazings	5	17	30	45	39	21	-2	-16	-23	-22	-17	-8		157	-88
Ground	-166	-102	-365	-583	-597	-501	-368	-63	99	146	65	-37		-2313	-157
TOTAL	-1198	-115	-172	-126	-401	-649	-1379	-1357	-1547	-1518	-1366	-1197		-2662	-8364

Fig. 7. Heat exchanges in the envelope of the energy model.

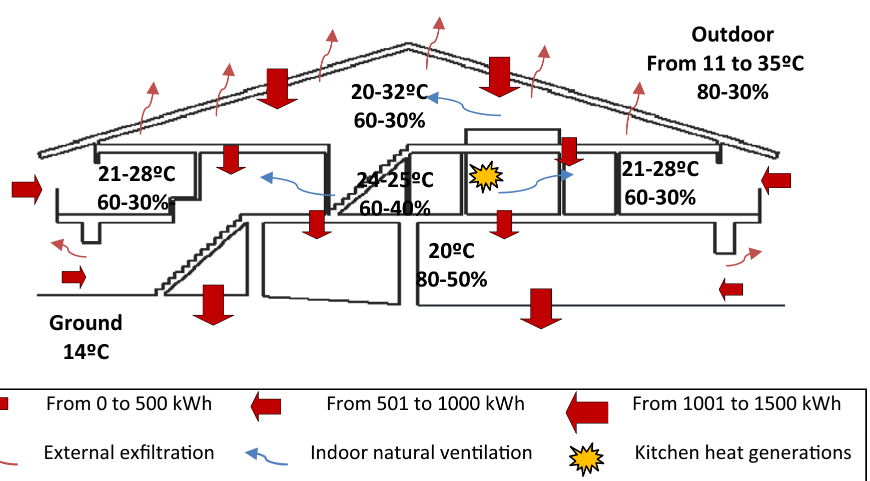


Fig. 8. Heat flow in the warm period and average temperatures during the warmest week of the year in the Valley half-timbered housing.

the roof. The soil, which is the ground floor flooring, favours the internal heat loss (with 13% of exchanges: 2800 kWh), but presents small gains in the coldest months of the winter (300 kWh). The external walls, which are made of stone on the ground floor or of adobe block on the first floor, and the roof (with 14% and 15% respectively) work in reverse: heat is lost during the cold period (1430 and 2300 kWh), gaining it during the warm period (900 and 640 kWh). The glazing does not imply remarkable energy exchanges (1%).

As a consequence, the "overheating" occurs in summer and it originates in the roof and external walls, while the "refreshing" comes from the soil as well as from the air infiltration. Nevertheless, the winter "heating" is poor and it comes from the ground and the "cooling" enters through the external walls and the roof (Fig. 7).

The results of the heat exchanges through the envelope during the two characteristic climate periods are summarised below. Likewise, the findings of the hygrothermal behaviour (operating temperature and the indoor relative humidity) corresponding to the two most extreme weeks in each period, are also taken into account:

3.2.2.1. Model envelope behaviour in the warm period (Fig. 8). In the warm period, the outdoor heat flow penetrates across the outer envelope surface into the housing: to a large extent

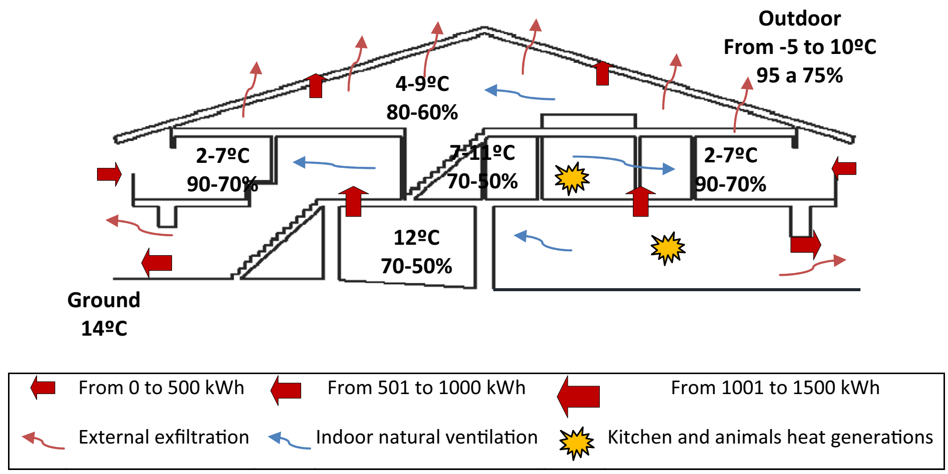
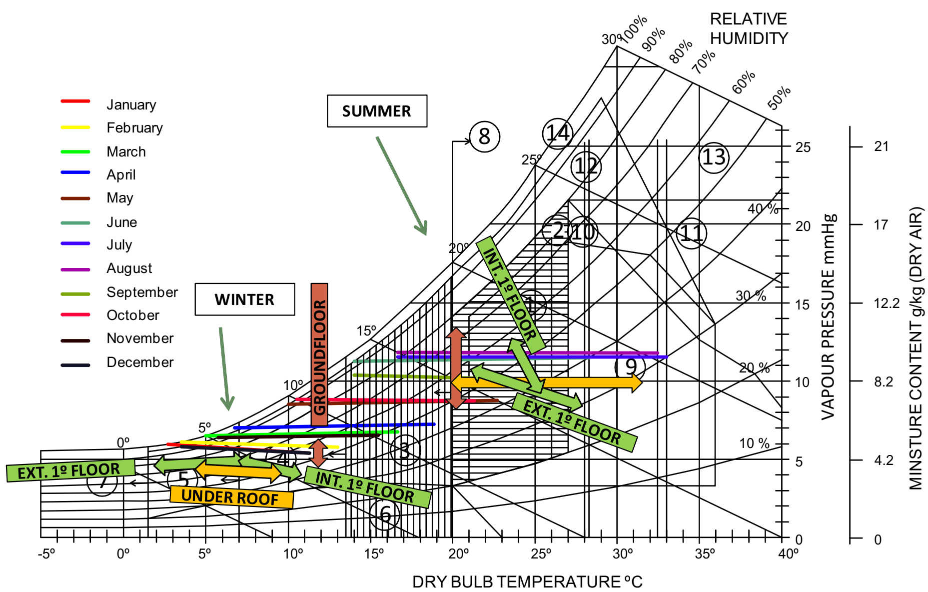


Fig. 9. Heat flow in the cold period and average temperatures during the coldest week of the year in the Valley half-timbered housing.



COMFORT ZONE (striped in the drawing)		
Zone 1, thermal comfort	Zone 2, admissible comfort	Zone 3, heating by internal gains
Individual with light clothing, low muscle activity and activity in the shade.	Perimeter added to zone 1 by the clothing use adapted to winter or summer.	Room temperature increase when the building is inhabited.
ADDED COMFORT ZONES (by bioclimatic strategies usage)		
Zone 4, passive solar heating	Zone 8 (from20ºC), shade line	Zone 9, high mass cooling
Solar radiation strategy	Solar protection strategy	high thermal inertia strategy

Fig. 10. Hygrothermal behaviour according to the energy simulation in the two most extreme summer and winter weeks per floor using Givoni's psycrhometric chart (adapted to monthly climate in the Valley).

through the roof surface (with a 2264 kWh heat gain); in second place, through the first floor exterior walls (872 kWh); and the rest, through the ground floor external walls (383 kWh). The exchange continues and descends towards the ground, crossing the house vertically (2313 kWh heat loss). The most important external exfiltrations occur through the roof (3454 kWh heat loss). The inner air movement is stronger on the upper floor, due to the heat generations coming from the kitchen (3628 kWh) (Fig. 8).

The hygrothermal behaviour per floor during the warmest week of the year (from 11th to 17th July), when the extreme outdoor conditions are between 11–35 °C and 80–30% humidity (night – day), can be summarised by the following average values:

- The under-roof floor temperature fluctuates between 20–32 °C and humidity between 60–30% (night – day values);
- The first floor temperature ranges vary between 21 and 28 °C in the exterior rooms and between 24 and 25 °C in the inner rooms. The humidity content varies from 60 overnight to 30 and 40% during the daytime;
- The ground floor is the coolest, with a constant temperature of 20 °C throughout the day, and high humidity content: 80–50%.

3.2.2.2. Model envelope behaviour in the cold period (Fig. 9). In the cold period, the heat flow goes from the ground floor and the first floor outward, throughout the envelope (847 kWh heat losses through the walls surface and 638 kWh through the roof). The most important exfiltrations occur through the roof (6633 kWh), and the inner air movement is stronger on the first floor (8551 kWh) (Fig. 9).

The hygrothermal behaviour per floor during the coldest week of the year (from 11th to 17th January), when the outdoor conditions are between −5–10 °C and 95–75% humidity (night-day), can be summarised by the following average values:

- The under-roof floor temperature ranges from 4 to 9 °C and humidity from 80 to 60% (night-day values).
- The first floor presents variable conditions: the exterior room temperature ranges fluctuates from 2 to 7 °C, whereas the difference between indoor and exterior humidity levels is minimal; the temperature ranges fluctuate between 7 and 11 °C in the inner rooms, and the humidity content between 70 and 50%.
- The ground floor presents a constant average temperature of 12 °C throughout the day, and a humidity content ranging from 70 to 50%.

3.2.3. Heat flows analysis

Taking into account the previous results, it can be pointed out that the main thermal exchanges occur vertically (up or down) in both periods. This phenomenon is due to the lightness of the horizontal envelope, as well as the opposite temperature conditions in the house: the ground (with constant temperature), and the under-roof space (with similar hygrothermal conditions to the outdoor conditions). Also, there are two other heat sources in the housing between the floors during the cold period: the stable and the kitchen.

In addition, throughout the year, the indoor conditions vary greatly overnight, and from summer to winter. The greatest thermal variations occur in the under-roof floor, which is the most exposed part of the envelope, owing to its large surface and its highly ventilated construction system. However, it acts as a barrier, preventing the outside temperatures from reaching the ground floor.

On account of this phenomenon, the hottest part of the house in the warm season is the under-roof floor; followed by the first floor; and, finally, the ground floor, which is the coolest one. The order is reversed during the cold period: the hottest zone is the ground floor; which transmits the heat flow to the first floor; and which finally goes to the under-roof floor.

4. Results and discussion

To assess the thermal comfort situation and the use of bioclimatic strategies, Givoni's psychrometric chart is used again, including this time hygrothermal results obtained in the building energy simulations from the Valley houses. For this purpose, the two least comfortable weeks of the year are represented by arrows in the chart. These arrows indicate the temperature and humidity ranges per floor, and their endpoints constitute the day-night oscillation. The distance between the endpoints represents the annual situation (Fig. 10).

In this case, other hygrothermal improvement actions are already included in the diagram. These result from the inherent use of the building, such as natural ventilation (programming of the windows opening). Other improvements were operational, as they had already been incorporated by the construction system or the architectural design, such as thermal inertia, solar protection or solar gains. These improvements had already been introduced into the model and favoured the results obtained.

Givoni's chart reveals that the Valley's buildings generally improve the outdoor climate conditions. The uncomfortable months are reduced both in summer and winter, favouring this thermal situation on the inhabited floors. Also, the possible bioclimatic strategies that cause these improvements are reflected on the chart. They can be summarised as follows (Fig. 5):

- On the ground floor, a substantial improvement of outside hygrothermal conditions can be confirmed in conjunction with an annual temperature control, which decreases the hot summer temperatures and increase the cold winter ones. Its day-night temperature is constant and its humidity level ranges slightly. The strategies applied for this improvement, according to the chart, are thermal inertia and solar protection as refreshing (coinciding the heavy inertia walls, the flooring being in direct contact with the ground and the existence of little hollows in the facade). In terms of heating, the improvement is manifested in the internal gains, which are reinforced by the floor inertia.
- On the first floor, indoor conditions are only slightly enhanced with respect to the outdoor conditions on the ground floor, which exhibits a great day-night fluctuation, despite the fact that the humidity variance is smaller. The inner rooms are more comfortable than the exterior ones, which are more exposed to the outside conditions. The warm period is almost in the comfort zone, unlike the cold semester, in which an external energy supply will be required. On this floor there are no thermal inertia elements and for this reason, the envelope, made of light and highly conductive walls, does not retain the internal gains because of the occupancy. Nevertheless, solar protection exists on the windows.
- The indoor conditions of the under-roof space are very similar to the outside ones, presenting large day-night and summer-winter fluctuations. There are solar protection strategies, but thermal inertia or internal gains are non-existent.

5. Conclusions

Taking into account the study developed in this paper, the need to elaborate specific energy audits for the vernacular architecture is evident. The purpose is to diagnose the behaviour and the potential contribution of both the constructive systems and the architectural design as thermal comfort strategies. Thereby, heritage interventions can be correctly proposed, preserving the existing beneficial strategies (which, in addition, enhance the design and the traditional techniques) and, at the same time, the necessary actions to improve its drawbacks can be undertaken. In this way, a sustainable refurbishment process will be promoted.

Furthermore, a methodology that illustrates how to carry out the energy analysis of the traditional architecture was presented, with the objective being to preserve and to intervene in historical sites.

The need to document the vernacular knowledge with a specific case study strengthens the understanding of passive design strategies, which are perfectly adapted in local climate conditions as a thermal comfort measure. On the other hand, the previous building definition for this settlements group allows a wide use of the study carried out, as well as the extensive application of the interventions.

It is nevertheless important to note that the results obtained should be transferred to a specific dwelling for further development of the proposals. Both the current usages and the updated thermal loads of the dwelling in question, along with the constructive changes from specific refurbishment studies, should be kept in mind.

In conclusion, as shown in this paper, the energy refurbishment proposals for the Valley's housings should incorporate solutions that keep unchanged in summer, when hygrothermal conditions are suitable (such as inertia of the stone walls, ground contact, ventilated roof construction or compact construction design). In contrast, winter conditions should be improved (such as solar gains, air infiltration reduction, additional insulation layers or heating).

Even if this study is strictly referred to the characteristics of the Valley, the conclusions provide relevant information about the climate adaptation of half-timbered constructions in the Central System mountain range. The results will also be a valuable input when studying the adjustment of other places with similar architectural features and Mediterranean continental climate in the mountainous area of southern Europe

The extrapolation of the findings to the current building industry in a modern context will be made by means of the implementations of climate adaptation strategies to new models. To that end, the elucidation of the strategies responsible for these bioclimatic behaviours will be needed in further studies. The goal is to implement the strategies in the refurbishment and the design of the building on the area.

Acknowledgements

This work was supported by the European Regional Development Fund (ERDF), and the regional government of Extremadura (*Junta de Extremadura*) and was carried out by the research group "DIPAMAC" thanks to the grant GR15107.

References

[1] ICOMOS. 12th General Assembly, Charter on the built vernacular heritage, México, 1999. http://www.international.icomos.org/charters/vernacular_sp.pdf (accessed 02.17.16).
[2] C. Rubio-Bellido, J. Pulido-Arcas, J. Cabeza-Lainez, Adaptation Strategies and Resilience to Climate Change of Historic Dwellings, Sustainability, 7 (2015) 3695–3713. doi: 10.3390/su7043695.
[3] M. De Luxan, Garcia De Diego, M.E. Roman Lopez, G. Gómez Muñoz, Sustainable Living. Environmental, 2014, http://oa.upm.es/37093/1/INVE_MEM_2014_197162.pdf (accessed 23.11.15).
[4] M. Jiménez, L. Goncalves, Bioclimatic analysis for a vernacular Guarani house, in: C. Mileto, F. Vegas, V. García Soriano, V. Cistini (Eds.), Vernac. Archit. Towar. a Sustain. Futur., 2015, pp. 377–380 http://www.crcnetbase.com/doi/abs/10.1201/b17393-67.
[5] L. Tang, M. Nikolopoulou, N. Zhang, Bioclimatic design of historic villages in central-western regions of China, Energy Build. 70 (2014) 271–278, http://dx.doi.org/10.1016/j.enbuild.2013.11.067.
[6] M. Baran, M. Yıldırım, A. Yılmaz, Evaluation of ecological design strategies in traditional houses in Diyarbakir, Turkey, J. Clean. Prod. 19 (2011) 609–619, http://dx.doi.org/10.1016/j.jclepro.2010.11.001.
[7] C. Saá, J.L. Míguez, J.C. Morán, J.A. Vilán, M.L. Lago, R. Comesaña, A study of the influence of solar radiation and humidity in a bioclimatic traditional Galician agricultural dry storage structure (horreo), Energy Build. 55 (2012) 109–117, http://dx.doi.org/10.1016/j.enbuild.2012.05.020.
[8] L.G.F. Cannas, G. Desogus, Bioclimatic comparative analysis in vernacular architecture: two Sardinia examples, in: Vernac. Herit. Earthen Archit. Contrib. Sustain. Dev, 2013, https://apps.webofknowledge.com/full_record.do?product=UA&search_mode=GeneralSearch&qid=4&SID=X1bJnLkOepl4JKqsWYd&page=1&doc=1 (accessed 11.01.16). p. 501.
[9] M. Soussi, M. Balghouthi, A. Guizani, Energy performance analysis of a solar-cooled building in Tunisia: passive strategies impact and improvement techniques, Energy Build. 67 (2013) 374–386, http://dx.doi.org/10.1016/j.enbuild.2013.08.033.
[10] S. Bodach, W. Lang, J. Hamhaber, Climate responsive building design strategies of vernacular architecture in Nepal, Energy Build. 81 (2014) 227–242, http://dx.doi.org/10.1016/j.enbuild.2014.06.022.
[11] M.M. Barbero-Barrera, I.J. Gil-Crespo, L. Maldonado-Ramos, Historical development and environment adaptation of the traditional cave-dwellings in Tajuña's valley, Madrid, Spain, Build. Environ. 82 (2014) 536–545, http://dx.doi.org/10.1016/j.buildenv.2014.09.023.
[12] M. Fernandez, A. Martinez, A. Alonso, V. LLopis, Primary energy and CO2 emissions in vernacular as compared to convencional architecture, in: C. Mileto, F. Vegas, V. García Soriano, V. Cristini (Eds.), Vernac. Archit. Towar. a Sustain. Futur., 2015, pp. 287–291 http://www.crcnetbase.com/doi/abs/10.1201/b17393-51.
[13] M, De Luxan, Garcia, M.E. De Diego, M.D.M. Roman Lopez, G. Barbero Barrera, Gómez Muñoz, Consecuencias constructivas y energéticas de una mala práctica. Arquitecturas desolladas, Int. Conf. Energy Effic. Hist. Build E.T.S. Arquitectura (UPM) (2014), http://oa.upm.es/37092/1/INVE_MEM_2014_197132.pdf (accessed 17.02.16).
[14] I. Cañas, S. Martıín, Recovery of Spanish vernacular construction as a model of bioclimatic architecture, Build. Environ. 39 (2004) 1477–1495, http://dx.doi.org/10.1016/j.buildenv.2004.04.007.
[15] C. Bionaz, Preservation and energy behaviour in Aosta Valleyís traditional buildings, in: V.C.C. Mileto, F. Vegas, L. García Soriano (Eds.), Vernac. Archit. Towar. a Sustain. Futur., 2015, pp. 129–134.
[16] I. Costa Carrapico, J. Neila González, Study for the rehabilitation of vernacular architecture with sustainable criteria, in: Vernac Herit. Earthen Archit. Constributions Sustain. Dev., 2013, https://apps.webofknowledge.com/full_record.do?product=UA&search_mode=GeneralSearch&qid=31&SID=N2nQZZk28CyjfB8sBkM&page=5&doc=48 (accessed 23.07.15).
[17] D. Ferreira, E. Luso, S. Fernandes, A.J.F. Vaz, C. Moreno, R. Correia, Bioclimatic solutions existing in vernacular architecture, Rehabilitation techniques (2013) 639 (accessed 240.7.15) http://bibliotecadigital.ipb.pt/handle/10198/9066.
[18] I.J. Gil Crespo, M.M. Barbero Barrera, L. Maldonado Ramos, Climatic analysis methodology of vernacular architecture, in: V.C.C. Mileto, F. Vegas, V. García Soriano (Eds.), Vernac. Archit. Towar. a Sustain. Futur., CRC Press/Balkema, 2015, 2016, pp. 327–332 (http://oa.upm.es/33711/1/ Gil Crespo, Barbero Barrera, Maldonado 2015_Climatic analysis Vern Arch_VerSus.pdf.).
[19] A.-T. Nguyen, S. Reiter, A climate analysis tool for passive heating and cooling strategies in hot humid climate based on typical meteorological year data sets, Energy Build. 68 (2014) 756–763, http://dx.doi.org/10.1016/j.enbuild.2012.08.050.
[20] B. Givoni, Comfort, climate analysis and building design guidelines, Energy Build. 18 (1992) 11–23, http://dx.doi.org/10.1016/0378-7788(92)90047-K.
[21] I. Theodoridou, A.M. Papadopoulos, M. Hegger, A typological classification of the Greek residential building stock, Energy Build. 43 (2011) 2779–2787, http://dx.doi.org/10.1016/j.enbuild.2011.06.036.
[22] E.G. Dascalaki, K.G. Droutsa, C.A. Balaras, S. Kontoyiannidis, Building typologies as a tool for assessing the energy performance of residential buildings — a case study for the Hellenic building stock, Energy Build. 43 (2011) 3400–3409, http://dx.doi.org/10.1016/j.enbuild.2011.09.002.
[23] C. Santos, T.M. Ferreira, R. Vicente, J.A.R. Mendes da Silva, Building typologies identification to support risk mitigation at the urban scale – case study of the old city centre of Seixal, Portugal, J. Cult. Herit. 14 (2013) 449–463, http://dx.doi.org/10.1016/j.culher.2012.11.001.
[24] E.G. Dascalaki, K. Droutsa, A.G. Gaglia, S. Kontoyiannidis, C.A. Balaras, Data collection and analysis of the building stock and its energy performance—an example for Hellenic buildings, Energy Build. 42 (2010) 1231–1237, http://dx.doi.org/10.1016/j.enbuild.2010.02.014.
[25] A.F. Tzikopoulos, M.C. Karatza, J.A. Paravantis, Modeling energy efficiency of bioclimatic buildings, Energy Build. 37 (2005) 529–544, http://dx.doi.org/10.1016/j.enbuild.2004.09.002.
[26] M.K. Singh, S. Mahapatra, S.K. Atreya, Thermal performance study and evaluation of comfort temperatures in vernacular buildings of north-east India, Build. Environ. 45 (2010) 320–329, http://dx.doi.org/10.1016/j.buildenv.2009.06.009.
[27] A.R. Abd Elrady, M. Hasan, Conservation of morphological characters as an approach to thermal comfort, Vernac Archit. Towar. a Sustain. Futur., (2015) 15–20.
[28] C. Tonelli, M. Grimaudo, Timber buildings and thermal inertia: open scientific problems for summer behavior in Mediterranean climate, Energy Build. 83 (2014) 89–95, http://dx.doi.org/10.1016/j.enbuild.2013.12.063.
[29] J. Blanco, B. Serrano, L. Soto, O.L, Srategies for energy retrofitting of vernacular architecture of Cabanyal-Canyamelar, in: C. Mileto, F. Vegas, L. García Soriano, V. Cristin (Eds.), Vernac. Archit. Towar. a Sustain. Futur., 2015, pp. 135–141.
[30] D. Bosia, L. Savio, Guidelines for rehabilitation of vernacular architecture, in: C. Mileto, F. Vegas, L. García Soriano, V. Cristin (Eds.), Vernac Archit. Towar. a Sustain. Futur., 2015, pp. 153–156, https://apps.webofknowledge.com/full_record.do?product=UA&search_mode=GeneralSearch&qid=31&SID=N2nQZZk28CyjfB8sBkM&page=2&doc=12 (accessed 17.02.16).
[31] E. Giancola, S. Soutullo, R. Olmedo, M.R. Heras, Evaluating rehabilitation of the social housing envelope: experimental assessment of thermal indoor improvements during actual operating conditions in dry hot climate, a case study, Energy Build. 75 (2014) 264–271, http://dx.doi.org/10.1016/j.enbuild.2014.02.010.
[32] M. de, M. Ambiente, Guía resumida del clima en España 1971–2000, Plan estadístico Nacional 2001–2004 (2005).
[33] X. Ninyerola, M. Pons, J.M. Roure, Atlas Climático Digital de la Península Ibérica. Metodología y aplicaciones en bioclimatología y geobotánica, Bellaterra: UAB, 2005.