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# Study of thermal environment inside rural houses of Navapalos (Spain): The advantages of reuse buildings of high thermal inertia

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ABSTRACT

The main purpose of a residential building is to provide a comfortable environment for human activities. Nowadays this objective is the responsible for the consumption of more than 40% of total energy demand in European Union. The construction sector in Spain has been in rapid growth in the last decades, yet there exists many abandoned buildings in rural areas. In this article we try to analyze the environmental advantages of reuse abandoned rural buildings. Due to their thick exterior walls of high thermal inertia, the indoor environment inside them can be comfortable with less energy consumption than new buildings. Here we show the monitoring results of three different houses, two traditional and one modern building, constructed of different building materials. The aim of this work is to analyze and compare the thermal behaviour of existing constructive solutions in a Spanish district, not to improve them. The field test results show better indoor conditions inside the traditional houses. In summer, thermal comfort is achieved with no energy supply inside traditional houses but not inside the modern one. In winter, the indoor environment is more stable inside the traditional houses, however none of them were able to provide thermal comfort naturally. In the case studied, the only inhabitant of a small village lives in a prefabricated wooden house, and it is demonstrated that the indoor conditions of traditional houses in the same location are of higher quality.



## 1. Introduction

The energy consumption of the construction sector is estimated at more than 40% of the total final energy demand in European Union [1]. Therefore, the reduction of energy use in the air conditioning of buildings is an issue of increasing interest in which various research works have been developed [2–5]. The first regulation about thermal insulation of housings in Spain was created in 1979 [6]. The concern about energy use in buildings has led the Spanish Government to prepare a new regulation for the reduction of building energy consumption which has been introduced as a part of the new Technical Building Code [7].

The operating energy during the life cycle of a building is much greater than the energy consumed during the construction phase (embodied energy). There is a great potential for energy savings and reduction of environmental impact through the implementation of energy efficiency in the construction sector.

Due to the fast growth of construction sector in the last decades, in Spain there are many rural areas which have been abandoned, and many of the rural buildings are vacant and without use. From the department of construction and rural roads the possibilities of the reuse of abandoned rural buildings are analyzed. We think that the reuse of abandoned buildings has other advantages besides those commonly outlined as: keep the vernacular architecture up, reactivate the social fabric and preserve rural landscapes. This process can be seen as a mechanism to save energy in the framework of the energy supply sector. Thanks to a research project funded by the Ministry of Education and Culture of Spain, a lot of work of inventory and cataloguing of rural buildings in the province of Soria (province in the interior area of Spain) has been carried out. The village of Navapalos is located in a district from Soria, whose area is 2450 km$^2$ and the population is 13,884 people with a marked agrarian character and undergoing a process of depopulation [8]. The area is characterized by a continental climate (hot summers and cold winters) with high temperature oscillations. Navapalos is placed on the banks of Duero River, with an altitude above the sea level of 800 m (see Fig. 1). The village was abandoned due to the rural exodus in the fifties. In 1984 the "Centro Navapalos" was set-up as a private institute for the research and experimentation of traditional building materials and constructive techniques, with a particular interest in the use of earth as a building material [9]. In 1996 it created the "Navapalos Foundation" for the investigation and teaching in matters related to sustainable development, architectural heritage and earthen constructions. At present only one person from the Navapalos

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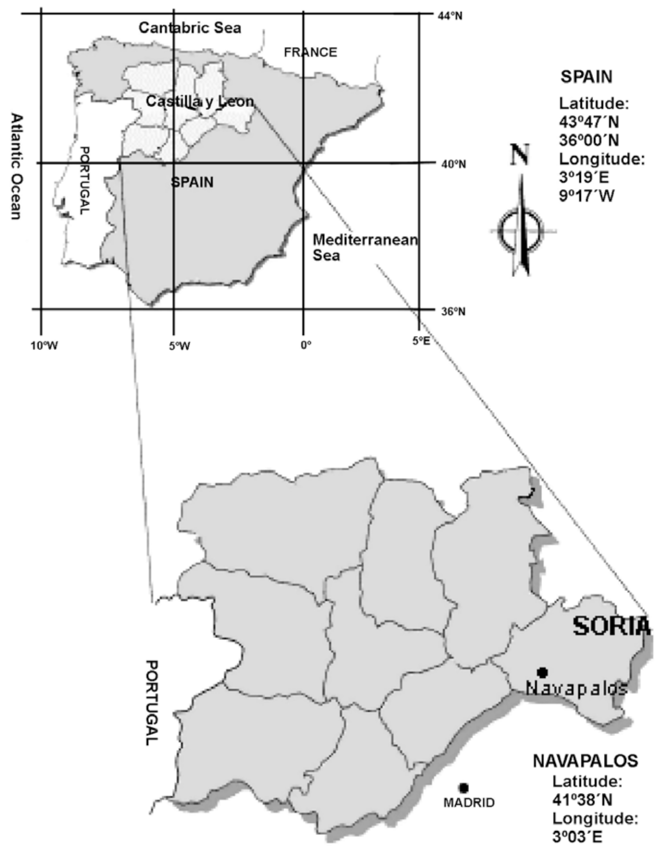


**Fig. 1.** Map of location of the studied area.

Foundation lives in the village. Despite the existence of many abandoned, but well maintained, traditional houses, the foundation decided to install a prefabricated wooden building for the only inhabitant in the village. Aiming at assessing the advantages of reusing abandoned rural buildings, three houses in the village were monitored, one of them is the prefabricated wooden house and the others are houses constructed with traditional materials and techniques. Assuming that the thermal performance of traditional and modern buildings is different [10], we try to analyze the comfort conditions inside the studied cases. In addition, it should be taken into account the influence on the indoor air caused by the habitant of the house. It is expected that the habitant makes good use of the openings and shutters to improve the indoor thermal comfort, however the presence of the habitant increases the indoor temperature and relative humidity by the body radiation and evaporation.

## 2. Description of studied houses

In the traditional houses usually found in the interior areas of Spain the structural system used was the bearing walls. The envelope was an important structural element primarily designed to support mechanical loads, therefore its thickness was quite high. The construction materials in traditional houses were those abundant in the area.

Other performance requirements such as weather resistance and energy efficiency were not taken into account, but some differences in the type of building materials and the thickness of the walls according to climatic parameters were observed [11].

Many buildings in the village were in ruins. Since 1985 some private buildings have been bought and restored as canteens, dwellings and conference centers. Every summer the Navapalos Foundation organizes international meetings, conferences and courses about traditional construction. Since the aim of this paper is to analyze the influence of the building materials and construction design on the indoor thermal performance, we chose three buildings whose envelope is made of different materials. The two traditional houses are used as dwellings for the participants in these actions. In the following we describe the three studied houses.

### 2.1. Traditional house made of stone

It is a traditional house made of local stone that was partially renovated to serve for the accommodation of volunteers coming to the village in summer to carry out restoration works. The renovation consisted of the construction of three bathrooms, and a glazing surface oriented to the south for the use of passive solar heating, and the installation of solar photovoltaic panels in the roof to obtain electrical energy. There is no heating or cooling system in the house. Figs. 2 and 3 show a picture and the floor plans of ground and first floors.

*Floors:* This house has two floors.
*Walls:* The closure walls are made of limestone with a thickness of 50 cm; the partition walls are made of brick.
*Structure:* The structure is based on bearing walls. The flooring is made of ceramic tiles.
*Roof:* The roof structure is made of wood and it is covered by clay tiles.
*Openings:* The windows are wooden framed with single glazed.
*Orientation:* Most of the openings are oriented to the south.

### 2.2. Traditional house made of adobe (called pine house)

It is a traditional house made of adobe. From a state of ruins its reconstruction began in 1990. The pine house is a recognized type

**Fig. 2.** Southern facade of stone house showing the glazing surface and the solar panels.

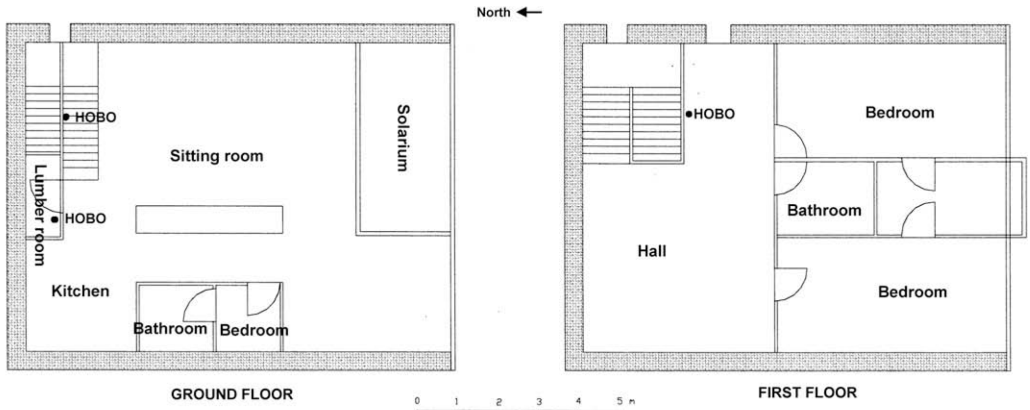


**Fig. 3.** Stone house layout.

of Spanish vernacular house located in the district and derives from the extensive pine forest found in the North of Soria province.

The building has a ground surface of 15 × 15 m, it is formed by two bodies reconstructed in different times. The two bodies are independent after the reconstruction. Only the body oriented to the south was monitored. As the stone house, this one has no heating or cooling system because it is unoccupied almost all year. Figs. 4 and 5 show a picture of the house and the floor plans of ground and first floors.

*Floors:* This house has two floors and an attic.
*Walls:* The southern facade, except one part made of stone masonry, is made of juniper wall columns filled with adobe. The closure and partition walls are made of adobe of different sizes: Closure walls: 40 × 20 × 15 cm; indoor walls: 24 × 12 × 10 cm and partition walls: 8 × 8 × 8 cm.
*Structure:* The structure is based on bearing walls. The flooring is made of ceramic tiles.
*Roof:* The structure of the roof is formed by wooden beams, covered by a layer of shingle and finally by clay tiles on the exterior side.
*Openings:* The windows are wooden framed with single glazed. There are wooden window shutters.
*Orientation:* Most of the openings are oriented to the south.

**Fig. 4.** Southern facade of the adobe house at the present moment.

### 2.3. Prefabricated wooden house

This house has only the ground floor. It is made of wooden boards of 5 cm thick, the ridge roof is covered by asphalt sheeting and the floor is also made of wood. There are openings in four orientations (N, S, E and W). The windows are wooden framed with single glazed. It is the only house in the village inhabited all the year. There is no cooling system, but there is a firewood heater in the living room and a small electric fire in the bedroom oriented to North. Figs. 6 and 7 show a picture of the house and its floor plan.

## 3. Thermal properties of walls

The exterior envelope, apart from contributing to the energy savings during the entire life span of the building by controlling the energy exchange between indoor space and environment, also promotes the development of a comfortable indoor environment.

The basic phenomenon determining the heat exchange between indoor and outdoor is the conduction heat transfer through the walls, it depends on the wall thermophysical properties. The U value and the heat capacity are very simple characteristic wall quantities describing the wall thermal performance. From the basic expressions (1), (2) and (3), and the data collected in bibliography [6,12,13] we can calculate the theoretical values for the studied buildings (see Table 1). The contribution of renderings is not taken into account in the analysis since their thickness is quite low compared to the main construction material.

$$U = [1/h_i + \Sigma(l_i/k_i) + 1/h_o]^{-1} \quad (1)$$

$$(\rho \cdot c)_{eq} = (1/L)\Sigma(\rho_i \cdot c_i \cdot l_i) \quad (2)$$

$$\alpha = k/\rho \cdot c \ (\mathrm{m^2/sg}) \quad (3)$$

where $U$ is the thermal transmittance of the wall, $l_i$ and $k_i$ are the layer thickness and the thermal conductivity respectively, $(1/h_i)$ and $(1/h_o)$ are the convective heat transfer coefficients at indoor and outdoor sides respectively, $(\rho \cdot c)_{eq}$ is the equivalent heat capacity, $\rho_i$ and $c_i$ are the densities and specific heat capacities of each layer, $\alpha$ is the thermal diffusivity and $k$ is the thermal conductivity.

## 4. On site monitoring

Indoor thermal environment field surveys in this study were conducted in the three mentioned houses in certain points during summer (06/20 to 07/01) and winter (01/29 to 03/08) times. The

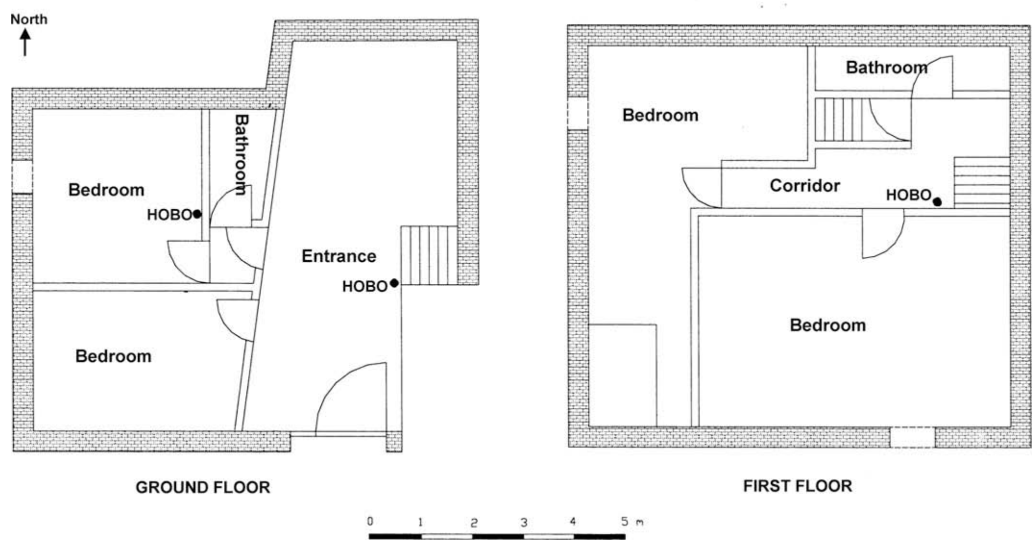


**Fig. 5.** Adobe house layout.

traditional houses (adobe and stone houses) were vacant, none of the houses has cooling equipment and only the prefabricated wooden house has two small heaters in winter.

The measurements were taken using the following instrumentation:

– Data-logger of the kind HOBO to record air temperature and humidity inside the buildings. Its resolution is 0.4 C for temperature and its accuracy for relative humidity is 5%.
– Data-logger for the measuring of external conditions. Its resolution is 0.02 C for temperature and its accuracy for relative humidity is 3%.

### *4.1. Relationship between outdoor temperature and indoor temperature*

Tables 2 and 3 show the results of indoor and outdoor temperatures measured in the three houses in summer and winter times.

These results indicate the existence of a different thermal behaviour between the two traditional houses and the prefabricated one. The traditional houses, built of adobe and stone (these building materials have great density values), have thick exterior

**Fig. 6.** Western facade of wooden house.

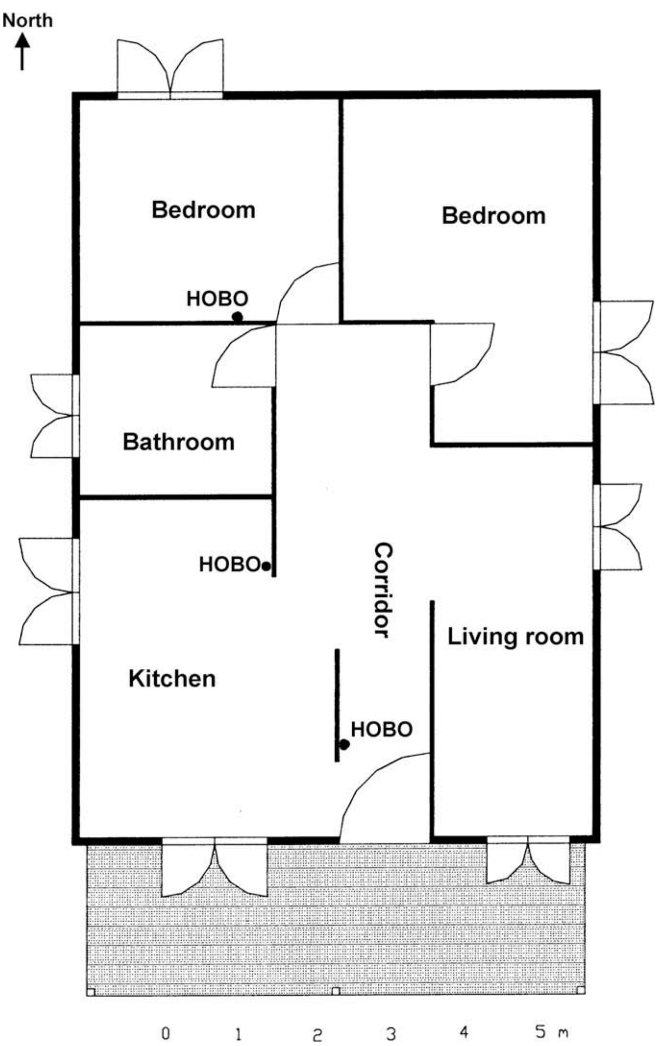


**Fig. 7.** Wooden house layout.

**Table 1**
Wall layer thickness, thermophysical properties and calculated $U$, $(\rho \cdot c)_{eq}$ and $\alpha$ values for the walls of analyzed houses.

| House | Material description | Thickness (cm) | $k$ (W/mK) | $\rho$ (kg/m$^3$) | $c$ (J/kgK) | $U$ (W/m$^2$K) | $(\rho \cdot c)_{eq}$ (J/m$^3$K) | $\alpha$ (m$^2$/sg) |
|---|---|---|---|---|---|---|---|---|
| Adobe house | Adobe[a] | 40 | 0.71 | 1772 | 969 | 1.35 | 1728.10$^3$ | $4 \times 17 \times 10^{-7}$ |
| | Plaster[b] | 1 | 1.39 | 2000 | 1085 | | | |
| Stone house | Limestone[c] | 50 | 2.33 | 2100 | 920 | 0.91 | 1937.10$^3$ | $11 \times 82 \times 10^{-7}$ |
| | Plaster[b] | 1 | 1.39 | 2000 | 1085 | | | |
| Wooden house | Wood boards[b] | 5 | 0.20 | 460 | 1400 | 2.38 | 644.10$^3$ | $31 \times 05 \times 10^{-7}$ |

[a] Meukam, 2004 [9].
[b] Tsilingiris, 2004 [10].
[c] NBE-CT-79 [6].

**Table 2**
Summary of registered temperatures (°C) in summer.

| | Maximum temperature | Minimum temperature | Average temperature | Range |
|---|---|---|---|---|
| Outdoor | 35.7 | 10.3 | 23 | 28.4 |
| *Traditional adobe house* | | | | |
| Entrance on ground floor | 27.5 | 17.5 | 22 | 10 |
| Bedroom on ground floor | 25.6 | 19 | 21.6 | 6.6 |
| Corridor on first floor | 25.2 | 20.2 | 23.6 | 5 |
| *Traditional stone house* | | | | |
| Stairway | 27.5 | 22.5 | 25.1 | 5 |
| Ground floor, North | 24.4 | 22.1 | 23.4 | 2.3 |
| Fisrt floor, east | 29.1 | 23.2 | 27.3 | 5.9 |
| *Prefabricated wooden house* | | | | |
| Kitchen | 36.6 | 16 | 26.3 | 20.6 |
| Bedroon in North orientation | 26.6 | 17.1 | 26 | 9.5 |

**Table 3**
Summary of registered temperatures (°C) in winter.

| | Maximum temperature | Minimum temperature | Average temperature | Range |
|---|---|---|---|---|
| Outdoor | 17.3 | −6.3 | 3.6 | 23.7 |
| *Traditional adobe house* | | | | |
| Entrance on ground floor | 8.6 | 2.5 | 5,7 | 6.1 |
| Bedroom on ground floor | 8.6 | 2.9 | 5,9 | 5.7 |
| Corridor on first floor | 9.0 | 1.6 | 5,5 | 7.4 |
| *Traditional stone house* | | | | |
| Stairway | 9.4 | 2.0 | 5.7 | 7.4 |
| Ground floor, North | 8.2 | 2.9 | 5.7 | 5.3 |
| Fisrt floor, east | 11.4 | 2.9 | 6.8 | 8.5 |
| *Prefabricated wooden house* | | | | |
| Kitchen | 27.1 | −2.0 | 6.7 | 29.1 |
| Bedroon in North orientation | 21.0 | −0.6 | 6.3 | 21.6 |
| Entrance | 16.8 | −0.2 | 7.4 | 17.0 |

walls due to the constructive technique (bearing walls), this provides the exterior envelopes with high thermal inertia. The high thermal inertia of external walls is shown in the results from the monitoring by the average indoor temperature (quite similar to outdoor temperature) and by the dampening of the outdoor thermal wave. The range of indoor temperature of the wooden house was higher than the temperature range in the two traditional houses. The traditional houses kept more stable indoor conditions than the wooden construction. Appendix 1 shows the results from the analysis of correlation between measured indoor and outdoor temperatures.

### 4.2. Indoor thermal stability

Fluctuation in indoor thermal temperature is mainly a reflection of the heat capacity of the structure. The ratio of internal to external diurnal temperature fluctuation ($\Delta t_i/\Delta t_o$) is an index that expresses the effects of indoor thermal stability of a building. Table 4 indicates the ratio of internal to external diurnal temperature fluctuation for the three houses in both periods.

As is shown in Table 4, the ratio of internal to external diurnal temperature fluctuation in the wooden house was higher by 3–4 times than the same ratio for the traditional houses. This proves the effect of indoor thermal stability on the traditional houses which have larger heat capacity of the walls.

### 4.3. Fluctuating properties of indoor humidity

Fig. 8 shows the fluctuation in the relative humidity of the three houses in winter and summer.

In summer, the mean relative humidity outdoors was 42%, the maximum was 93% and the minimum was 10%. The mean relative humidity in the adobe house was 43%, the maximum was 55% and the minimum was 24%. The mean relative humidity in the stone house was 39%, the maximum was 45% and the minimum was 28%. The mean relative humidity in the wooden house was 32%, the maximum was 49% and the minimum was 24%.

In winter, the mean relative humidity outdoors was 81%, the maximum was 100% and the minimum was 21%. In the adobe house, the mean relative humidity was 63%, the maximum was 82% and the minimum was 34%. In the stone house, the mean relative humidity was 64%, the maximum was 72% and the minimum was 48%. In the wooden house, the mean relative humidity was 66%, the maximum was 89% and the minimum was 27%.

The most accepted range of relative humidity for thermal comfort is from 30% to 70% [14]. Therefore, in summer 44% of registered data were out of comfort zone for the wooden house, 2% for the house made of stone and 11% for the house made of earth. In winter, 36% of the registered data were out of comfort zone for the wooden house, 18% for the house made of stone and 9% for the house made of earth. This indicates that heavy materials can provide better comfort conditions in terms of humidity than light ones.

Table 5 shows the fluctuating ratio of internal absolute humidity in the three houses. The ratio for the wooden house was 0.9 higher than that for the traditional houses in winter; in summer this ratio is also higher for the wooden house. The traditional houses with their thick external walls make the indoor humidity content to be more stable.

**Table 4**
Ratio of internal to external diurnal temperature fluctuation for the studied houses.

| Diurnal range of outdoor temperature ($\Delta t_o$) | | | Winter average 11.21 | Summer average 19.05 |
|---|---|---|---|---|
| Adobe house | Entrance | Diurnal range ($\Delta t_i$) | 1.22 | 3.17 |
| | | Ratio ($\Delta t_i/\Delta t_o$) | 0.11 | 0.17 |
| | Bedroom on ground floor | Diurnal range ($\Delta t_i$) | 1.33 | 2.57 |
| | | Ratio ($\Delta t_i/\Delta t_o$) | 0.12 | 0.13 |
| | Corridor on first floor | Diurnal range ($\Delta t_i$) | 1.57 | 2.17 |
| | | Ratio ($\Delta t_i/\Delta t_o$) | 0.14 | 0.11 |
| Stone house | Stairway | Diurnal range ($\Delta t_i$) | 1.28 | 2.04 |
| | | Ratio ($\Delta t_i/\Delta t_o$) | 0.11 | 0.11 |
| | Ground floor, North | Diurnal range ($\Delta t_i$) | 0.54 | 0.56 |
| | | Ratio ($\Delta t_i/\Delta t_o$) | 0.05 | 0.03 |
| | First floor, east | Diurnal range ($\Delta t_i$) | 1.94 | 1.28 |
| | | Ratio ($\Delta t_i/\Delta t_o$) | 0.17 | 0.07 |
| Wooden house | Corridor | Diurnal range ($\Delta t_i$) | 7.53 | 12.79 |
| | | Ratio ($\Delta t_i/\Delta t_o$) | 0.67 | 0.67 |
| | Bedroom | Diurnal range ($\Delta t_i$) | 7.27 | 11.55 |
| | | Ratio ($\Delta t_i/\Delta t_o$) | 0.65 | 0.61 |

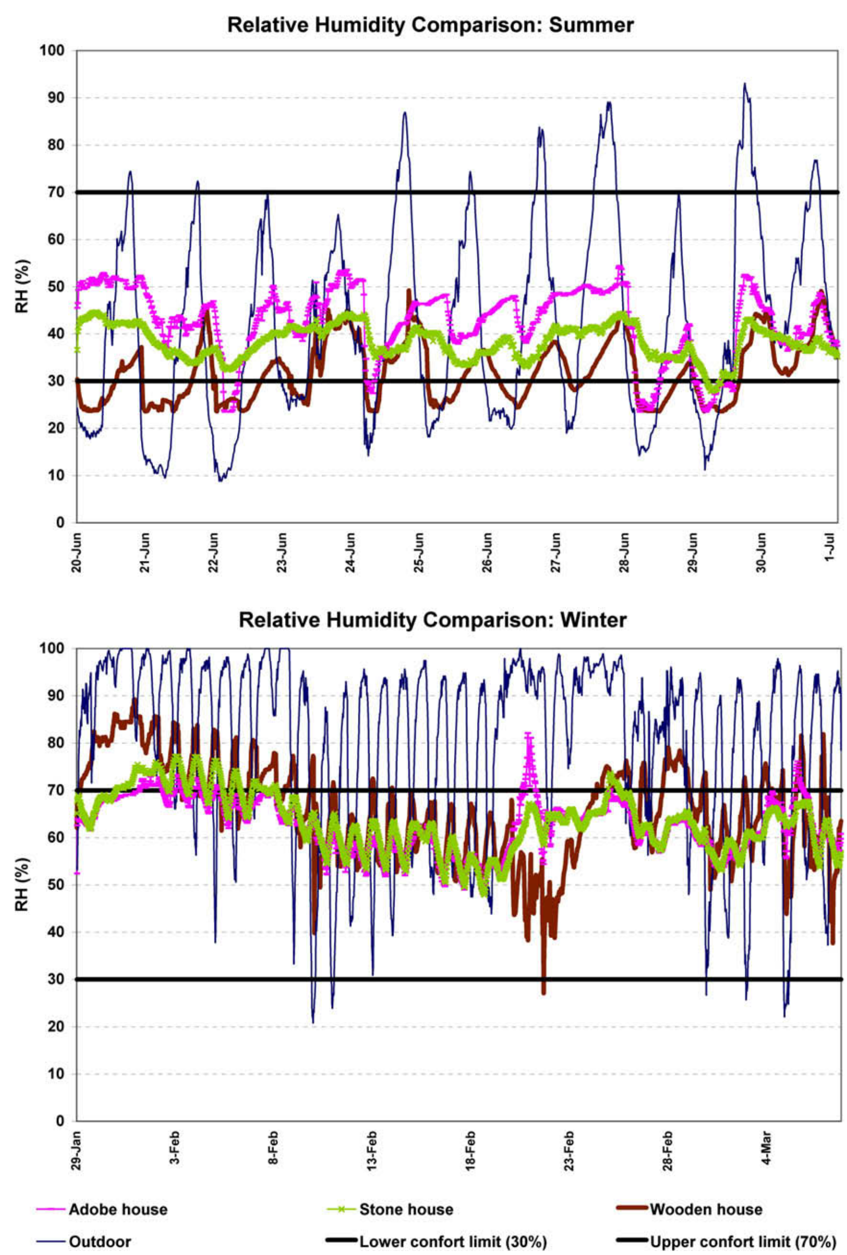


**Fig. 8.** Indoor and outdoor relative humidity for the three houses.

**Table 5**
Fluctuating ratio of internal absolute humidity.

| | Average daily fluctuation (g/m$^3$) | Ratio inside/outside |
|---|---|---|
| Outdoors | | |
| Winter | 2.28 | – |
| Summer | 4.89 | – |
| Adobe house | | |
| Winter | 0.81 | 0.36 |
| Summer | 2.70 | 0.55 |
| Stone house | | |
| Winter | 0.86 | 0.38 |
| Summer | 2.04 | 0.42 |
| Wooden house | | |
| Winter | 2.99 | 1.31 |
| Summer | 3.68 | 0.75 |

## 5. Analysis of thermal comfort

One of the main objectives of any construction allocated as a residence is to provide a comfortable and healthy indoor environment for the development of human activities.

Comfort is a very complex concept, it is affected by numerous parameters due to human nature. The thermal parameter is undoubtedly one of the most determining factor when providing a comfortable environment, but other parameters to take into account are: humidity, air movement, human activity and type of clothes as well good eyesights.

The international standard ISO 7730 [15] defines the thermal comfort as the mental condition expressing satisfaction with thermal environment. There are some indices to assess the degree of well-being. The Predicted mean vote (PMV) predicts the thermal sensation as a function of activity, clothing and four parameters: air temperature, mean radiant temperature, air velocity and humidity. The predicted percentage dissatisfied (PPD) is defined in terms of the PMV. Regrettably, all the above mentioned parameters were not recorded inside the three houses. With the aim of assessing the comfort level inside the buildings, we have made an approximation based on the statistical analysis of indoor and outdoor temperatures.

Cumulative distribution functions (CDF) were realized using Statgraphics Plus software with the series of registered temperature in the three houses during the two periods [16], see Figs. 9–11. The CDF graphs allow the understanding of the distribution of each registered temperature value inside a certain temperature range. The CDF is a function that provides cumulative probabilities as an alternative way for describing the probability distribution function for a random variable. The height of the function indicates the probability of obtaining a value less than or equal to a specified value. This function provides the probability of getting values higher, lower or equal to a specified value (in this case temperature), so

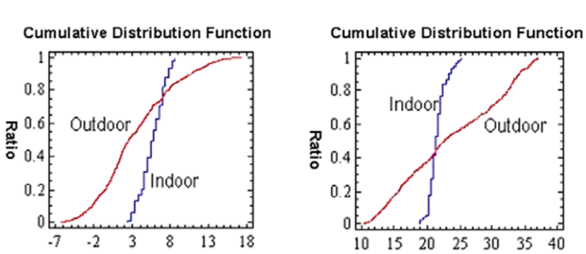


**Fig. 9.** Left: adobe house CDF temperature in winter. Right: adobe house CDF temperature in summer.

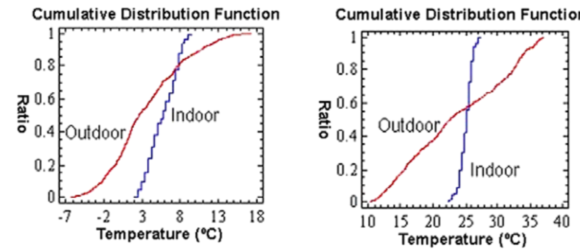


**Fig. 10.** Left: stone house CDF temperature in winter. Right: stone house CDF temperature in summer.

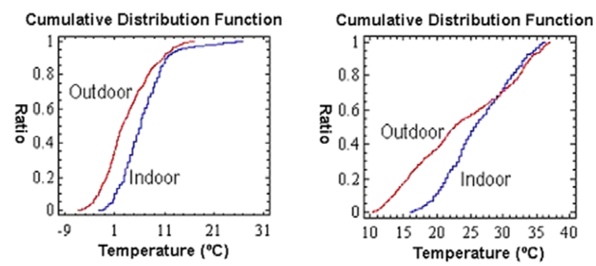


**Fig. 11.** Left: wooden house CDF temperature in winter. Right: wooden house CDF temperature in summer.

it is a way for the comparison of registered temperature in different places.

Fig. 9 shows the CDF for the indoor and outdoor temperature in the adobe house for summer and winter periods. In both periods it can be observed that the outdoor and indoor lines are crossed, this indicates that for both periods there are registered values of indoor temperature higher than outdoor temperature. In winter the cross point is at 7 °C, in summer it is at 21 °C. This means that there are more registered values above 7 °C in winter and 21 °C in summer inside than outside. The indoor CDF lines are almost vertical, it is typical of buildings with high thermal inertia which are able to soften the outside temperature CDF. Fig. 10 shows the CDFs for the stone house. The graphs are quite similar to the adobe house ones. In this case, the cross points are at 8 °C in winter and 25 °C in summer. Fig. 11 shows the CDFs for the wooden house. In winter the outdoor and indoor lines are almost parallel, the indoor CDF line is moved (1–2 °C) towards high temperatures. On the other hand, in summer both lines are crossed at 30 °C. The indoor CDF line is much more spread out that the indoor lines for the traditional houses. Again, this graph shows the low thermal inertia of the prefabricated wooden house. The CFDs also allows us to determine how many values are registered inside specific temperature limits. Next we calculate the temperature limits between which the 95% of values are placed in order to get an approach of the temperature variation. For the outdoor temperature in winter the 95% of values are between −3 °C and 12 °C, in the adobe house this happens between 3 °C and 8 °C, as in the stone house, and for the wooden house the interval is from 1 °C to 12 °C. In summer, the 95% of registered outdoor temperature are between 12 °C and 36 °C, in the adobe house this happens between 20 °C and 24 °C, in the stone house between 23 °C and 26 °C and finally in the wooden house between 18 °C and 34 °C. Again, it can be seen that the envelope in the traditional houses produces a softening of the exterior temperature wave.

The preceding analysis is a statistical analysis of the temperature registration process, it gives us quantitative information but it does not describe the temperature evolution inside the buildings.

For this purpose, the difference between indoor and outdoor temperatures against outdoor temperature is analyzed. The graphics from this analysis are shown in Figs. 12–14. In the figures showing the registered temperatures in summer and winter, the *y*-axis represents the natural effective heating or cooling and its distribution against the outdoor temperature. The thermal comfort zone is marked in each figure. For winter time the thermal comfort limits were selected around the temperature value of 18° C and ±2 °C wide, for summer time the comfort limits were selected around 24° C with the same span. These comfort limits are an approach to the complex concept of thermal comfort, which are mentioned above, and requires the measurement of numerous parameters.

In Fig. 12 the graphs of natural heating and cooling are shown for the house made of adobe. In winter time all temperature values are below the lower comfort limit, it is due to the extreme cold outdoor conditions as well as the absence of any heating equipment. The external envelope stores heat during the day and releases it when the external temperature falls because of its heat capacity, but it is not enough to provide comfort conditions. Most of the registered points (70%) are above the line of heating but the rest are below this line. In the graph for summer it is observed that all temperature values registered on first floor are inside the comfort zone. The values registered at the bedroom on ground floor are distributed inside and below the comfort zone. At the entrance on the ground floor the registered values are more spread out, being distributed below, inside and above the comfort limits.

Fig. 13 belongs to the house made of stone. The graph for winter time shows that all registered values in all locations inside the building are below the lower comfort limit, as inside the adobe house. The temperature, however, is rather higher than inside the adobe house. The 73% of registered values are above the heating line, and for the values registered on first floor this value reach 76% due to the greenhouse effect of the glazed surface. For summer the values registered on first floor are above the upper comfort limit because of the greenhouse effect, nevertheless the rest values are inside the comfort zone.

In Fig. 14 the registered values inside the wooden house are shown. The collections of points as well in summer as in winter

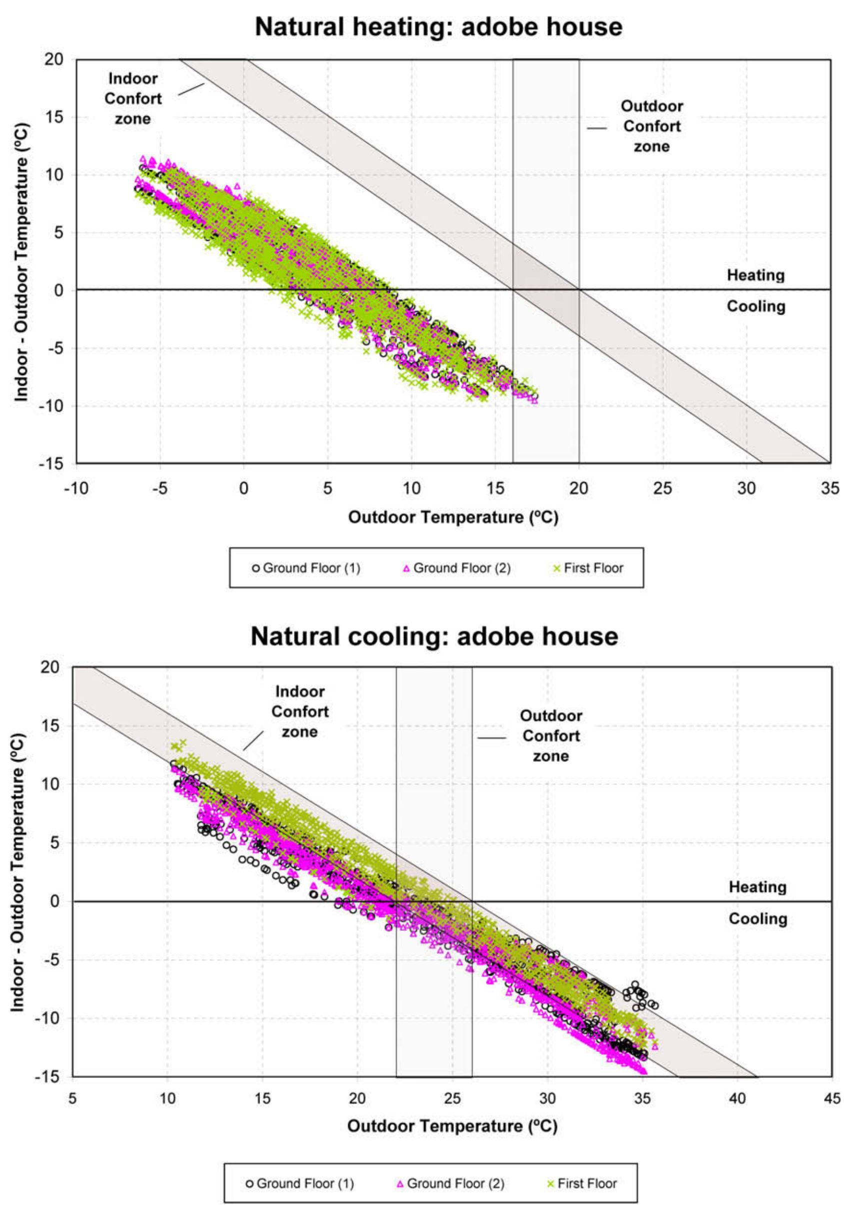


**Fig. 12.** Adobe house indoor temperature against outdoor temperature in winter (up) and summer (down). The indoor and outdoor comfort zones are shaded in grey color.

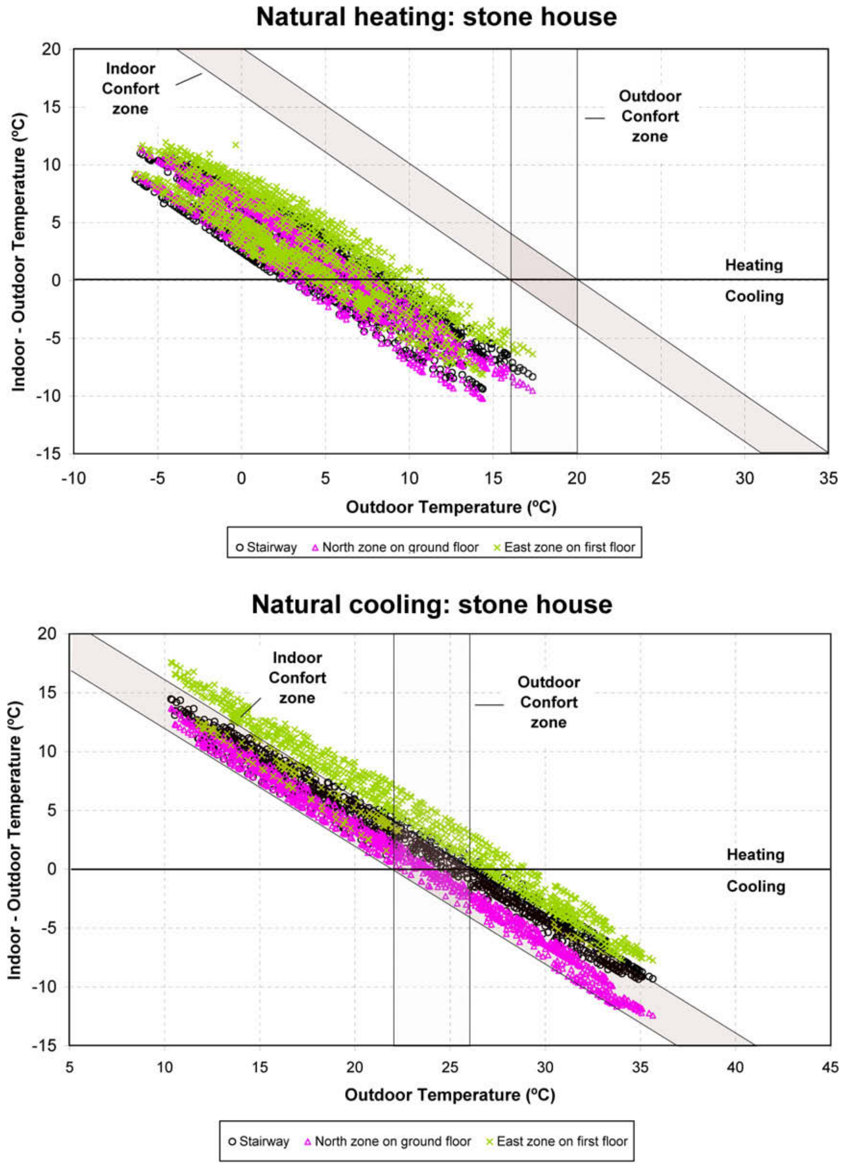


**Fig. 13.** Stone house indoor temperature against outdoor temperature in winter (up) and summer (down). The indoor and outdoor comfort zones are shaded in grey color.

are very scattered. In winter only some values registered in the kitchen are inside the comfort zone but most of the values are below the lower comfort limit and as far as 15 °C away of it. In summer 47% of registered values are above, 17% below and 36% inside the comfort zone. There are overheating problems in this building.

## 6. Conclusions

The results from the field monitoring show that there is a clear difference between the thermal behaviour of the traditional houses and the new one (prefabricated wooden house). In summer, the indoor environment in the traditional house is inside the comfort zone, but does not hold for the wooden house. In winter the indoor environment for the three houses are below the comfort limits, in spite of the existence of two small heaters inside the wooden house. Considering the dampening on the outdoor thermal wave inside the traditional houses, which keeps the temperature and relative humidity more stable inside them, if some heating system were implemented in these traditional houses, the indoor environment would reach the thermal comfort limits requiring less energy consumption than the new prefabricated wooden house.

It seems a contradiction that the only inhabitant in the village lives in a prefabricated wooden house whose indoor environment is not comfortable when the village has numerous abandoned buildings of high thermal inertia.

## Acknowledgments

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## Appendix A. Relationship between measured indoor and outdoor temperatures

The measured data where analyzed in order to assess the relationship between indoor and outdoor temperatures. We try to look

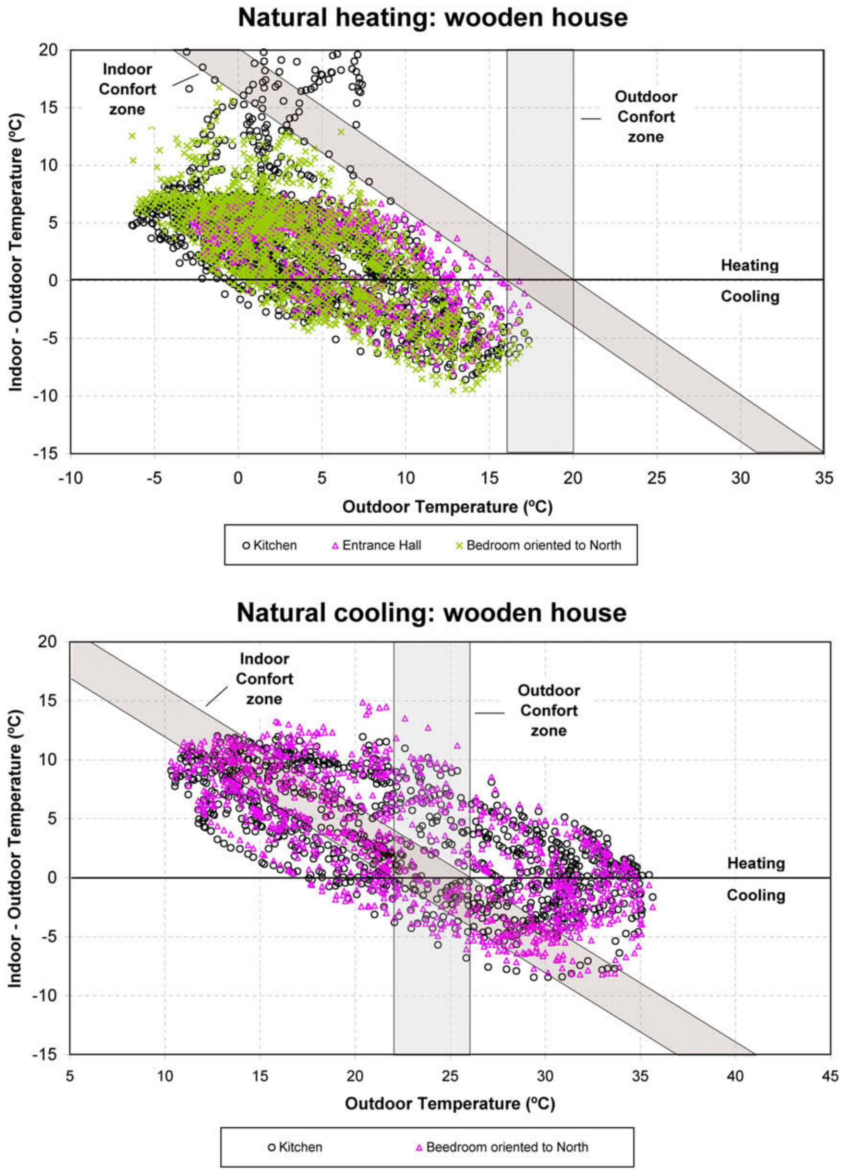


**Fig. 14.** Wooden house indoor temperature against outdoor temperature in winter (up) and summer (down). The indoor and outdoor comfort zones are shaded in grey color.

for a lineal correlation between indoor and outdoor temperatures, such as:

$$T_i = aT_o + b$$

where $T_i$ is the indoor temperature (dependent variable), $T_o$ is the outdoor temperature (independent variable), a is the inclination of the straight line which indicates how is the change of $T_i$ according to $T_o$ ($\Delta T_i/\Delta T_o$) and $b$ is the value of $T_i$ when $T_o$ is zero. The parameter $R$ is the correlation coefficient of Pearson, that shows how good is the straight line in defining the relationship between $T_i$ and $T_o$.

The results are summarized in this section.

Traditional adobe house in summer:
– entrance: $T_i = 0.12T_o + 19.29$, $R = 0.55$;
– bedroom on ground floor: $T_i = 0.08T_o + 19.75$, $R = 0.44$;
– corridor on first floor: $T_i = 0.05T_o + 22.40$, $R = 0.42$.

Traditional adobe house in winter:
– entrance: $T_i = 0.16T_o + 5.13$, $R = 0.48$;
– bedroom on ground floor: $T_i = 0.11T_o + 5.50$, $R = 0.39$;
– corridor on first floor: $T_i = 0.15T_o + 4.95$, $R = 0.40$.

Traditional stone house in summer:
– ground floor, North: $T_i = 0.003T_o + 23.36$, $R = 0.03$;
– stairway: $T_i = 0.09T_o + 22.94$, $R = 0.66$;
– first floor, east: $T_i = 0.05T_o + 26.13$, $R = 0.28$.

Traditional stone house in winter:
– ground floor, North: $T_i = 0.09T_o + 5.30$, $R = 0.32$;
– stairway: $T_i = 0.16T_o + 5.15$, $R = 0.41$;
– first floor, east: $T_i = 0.12T_o + 19.29$, $R = 0.36$.

Prefabricated wooden house in summer:
– kitchen: Ti = 0.43To + 16.13, R = 0.62;
– bedroom in North orientation: Ti = 0.54To + 13.97, R = 0.75.

Prefabricated wooden house in winter:
– entrance: Ti = 0.41To + 5.22, R = 0.42;
– bedroom in North orientation: Ti = 0.35To + 5.02, R = 0.47.

The "*a*" coefficients are lower for the traditional houses, as much in summer as in winter time. It can be observed that the indoor temperature in the wooden house is more influenced by outdoor temperature than is the indoor temperature of the traditional houses. The minimum value is that of the point placed on the ground floor of the stone house, in this spot the sensor was located distant from all the openings, so the temperature was weaken by the high thermal inertia of the stone walls and floor.

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