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Field assessment of thermal behaviour of Social Housing apartments

J. Terés-Zubiaga [(1)], K. Martín [(1)], A. Erkoreka [(1)], J. M. Sala [(1)]*

(1) ENEDI Resarch Group, Department of Thermal Engineering, Faculty of Engineering of Bilbao, University of the Basque Country UPV/EHU, Alda. Urquijo s/n, 48013 Bilbao, Spain.

Abstract

A field study of 10 social housing dwellings in the north of Spain is presented in this paper. Knowing the building stock is the first step to set up priorities in a global strategy to improve the energy efficiency of the existing building stock. Moreover, improving the energy efficiency of buildings is one of the most effective ways to tackle fuel poverty, which is increasing in Spain in the last years, being social housing one of the most vulnerable sectors of being at risk of fuel poverty.

The aim of this research is to describe a methodology for analysing the thermal performance of buildings under a holistic approach. An overview of the thermal performance of the social housing stock in a city with mild climate in Spain is presented. Social housing stock in Bilbao is classified by means of selecting 10 representative dwellings. A field study was performed during 10 months. Results of heating consumption as well as indoor conditions are presented. Results show that energy consumption in winter is not as high as expected, due to the low indoor temperatures. Amongst other factors, the influence of the occupants plays an important role in the final thermal performance of dwellings.

Keywords: *Thermal performance, holistic approach, energy renovation, social housing, fuel poverty*

* Corresponding author. Tel: +34 94 601 7322. Email address: jon.teres@ehu.es

1 Introduction

Currently the energy consumption of the construction sector is estimated to be over 40% of the total energy consumption in the European Union. Thus, the energy and environmental situation requires improving the energy performance of buildings. The National Statistics Institute (year 2001) data shows that about 67% of the Spanish dwelling stock was built before 1980, just when the first Spanish thermal regulation (NBE-CT 79) became effective. There is a similar situation in the case of the Basque Country (a region located in Northern Spain) where more than 75% of the dwelling stock was constructed before 1980 [1]. Therefore, to reduce the energy consumption, the main effort must be focused on the challenges of the existing stock.

The implications and benefits of energy renovations have consequences not only in the reduction of CO_2 emissions and energy savings, but also in financial and social aspects. One of them is the so called fuel poverty, which is mainly a consequence of a combination of three causes: poor energy efficiency of housing, high energy prices and low household incomes. [2]. Poor energy efficiency can be responsible of low winter indoor temperatures and in some countries it is an important factor contributing to cold related morbidity and mortality as well [3]. Some other studies about energy efficiency, fuel poverty and the suitability of energy renovations have been carried out, such as in [4][5][6]. This problem is increasing in the last years in Spain, as shown in [7]. Thus, improving the energy efficiency of the existing stock is one of the main strategies, not only for reducing CO_2 emissions, but also for delivering affordable warmth to the fuel poor households. Both, energy savings and improvement on the indoor comfort, have to be taken into account during energy renovations projects.

Regarding occupants influence on the energy consumption in buildings, Annex 53 states that human behaviour could have a great impact, even greater than building characteristics or other factors. Several studies have pointed out large differences in energy consumption for similar buildings [8,9] thereby suggesting to the occupant's behaviour a strong influence. In [10] relationships between behavioural patterns, user profiles and energy use are thoroughly analysed. Related to this approach, rebound effect [11] is another factor to be considered when effectiveness of energy renovations is evaluated, as shown in several studies such as in [12][13][14][15][16][17].

Because of all the above reasons, energy efficiency improvements in buildings, and especially in social housing sector, have become a priority goal for the European Union. Due to its characteristics (such as households with low incomes and construction features of the buildings), this sector is one of the most vulnerable to fuel poverty. This way, quantifying the potential energy savings in the Social housing stock must become a priority. Characterizing the social building stock is the first step to be taken, followed by the thermal behaviour analysis of this building stock. Moreover, many energy models have been developed in the last years to predict changes on energy consumption as a result of energy renovations. As affirmed in [18], the assumptions for the operating conditions are usually based on profiles considered as standard, rather than those from field measurements. Thus, having field measurements on the indoor conditions in social dwellings is necessary to obtain a more accurate analysis of the energy renovation potential in the social building sector.

A global approach is necessary to study the thermal performance of buildings, considering the building as a complex system composed by different subsystems. With this aim in mind, in this work ten occupied apartments have been studied under a holistic approach to have an overview of their thermal performance. There is no shortage of similar field studies available in the literature to assess thermal comfort and energy consumption in low energy buildings [8], office buildings [19] or vernacular or historical buildings [20][21][22]. Nevertheless, it is not so prevalent to come across with this kind of studies applied to the Social Housing Sector. One exception could be found in the large-scale surveys carried out by Warm Front Project [23].

2 Objectives

In order to define optimal strategies in building renovations, its thermal behaviour must be known. Thus, architectural and thermal behaviour of Social Housing Stock in Bilbao is assessed in a field study. Along this line, the main aims of this paper are:

(a) Provide an insight of the thermal performance of Social Housing Stock in Bilbao, Northern Spain, and identify the real energy consumption in social dwellings in a city with mild weather conditions both in winter and summer; (b) Identify the potential improvement of the social housing stock; (c) Provide energy consumption and indoor environment field measurements of these ten dwellings, which can be used in future researches and models to set up operating conditions not based on standards, but on field measurements; and (d) Provide a comparative and qualitative analysis of thermal building performance of ten selected dwellings, representatives of the social building stock.

This study is not only focusing on energy consumption itself, but also on assessing thermal comfort in the dwellings. Previously mentioned aspects related to health issues, however, are out of scope of the present study, although they must be taken into account when energy retrofitting benefits are considered.

To accomplish with these goals the building stock of social housing in Bilbao has been classified according to the criteria described in section 4. Based on this classification, 10 social housing apartments, representatives of the different construction periods of the 20th Century have been studied using a holistic approach. Results obtained from this survey provide an important database to quantify the potential benefit of retrofitting the existing social building stock in the Basque Country.

3 Approach

A holistic approach is applied in this study. In this systemic approach, buildings are treated as open systems considering interactions between them and their environment. Similar approaches are explained and used in [20] with historical buildings, in Annex 53 [24] or in [25]. The approach used in this paper is based on these references. The different considered subsystems are shown in Fig. 1.

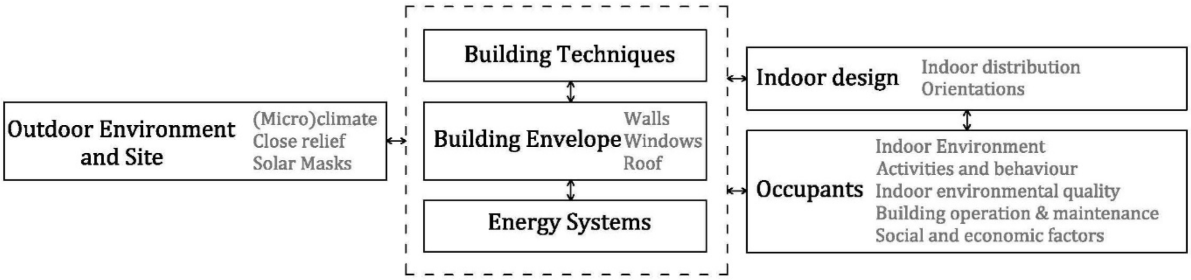

Fig. 1. Subsystems for investigation.

Building techniques, building envelope and energy systems could be considered as a boundary subsystem, which makes a separation between outdoor environment and occupants or indoor environment [26]. The combination of all these factors will give as a result the energy performance of the dwelling.

Building renovations are usually focused on the improvement of 3 subsystems: building techniques (such as thermal bridges), building envelope and energy systems. However, although the objective of any improvement in the building energy performance is usually within these subsystems, it is important to take into account the interaction amongst building techniques, building envelope and energy systems, and the other subsystems, and the consequences of these interactions on the overall energy consumption. The study presented in this paper has been carried out bearing in mind this approach.

4 Choice of buildings

This field study has been carried out in Bilbao from November 2011 to September 2012. All apartments have been occupied during the monitoring period. Different heating systems are used in the selected dwellings: out of the 10 dwellings, 4 are heated by natural gas heating systems, 3 by electric heaters, 1 by kerosene heater, 1 by butane heater and 1 has not a heating system whatsoever. All the studied dwellings have no mechanical ventilation system. The climate for the studied area (Bilbao), located in latitude 43º N, is oceanic. The proximity to the ocean makes summer and winter temperatures relatively temperate, with low intensity thermal oscillations. Average maximum temperature is between 25 °C and 26 °C during summer period, while the average minimum in winter can vary between 6 °C and 7 °C.

4.1 Building stock classification criteria

Building stock of Bilbao is characterised by the construction period in this study. Several factors act upon construction features, like social and financial situations and/or building regulations. As far as thermal requirements are concerned, after the Oil Crisis in the 70's, in Spain, like in many European countries, the requirements for insulation of buildings were considerably reinforced. With this aim in mind, the first thermal regulation was developed and came into force in 1979. Unlike in other European countries, there was no new Spanish thermal regulation till 2006, when the Spanish Technical Building Code (CTE) [27] came into force. Detailed data about the Building stock in Bilbao, based on Population and Housing Censuses developed by National Statistics Institute in 2001, by construction year, is shown in Fig. 2.

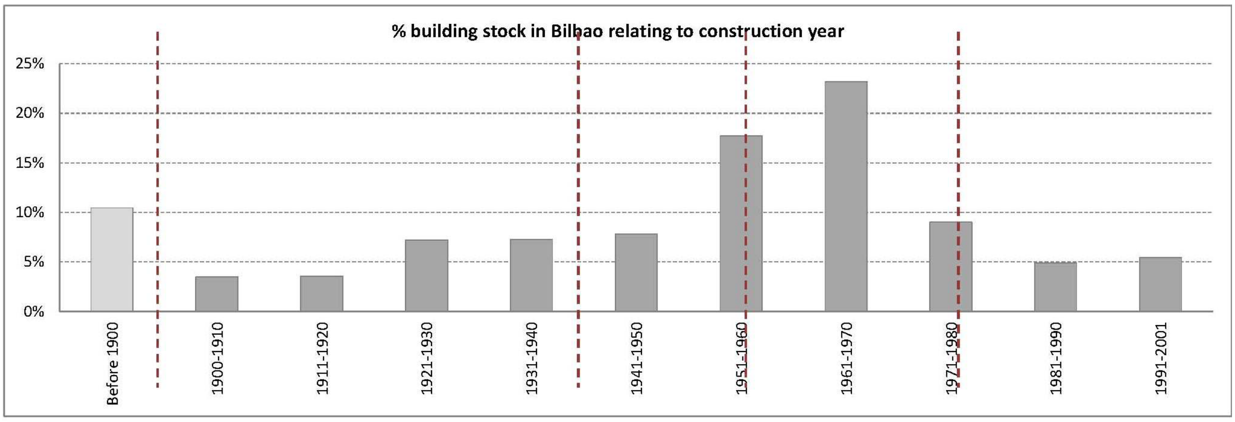

Fig. 2. Building stock in Bilbao in relation to construction year (Building Stock: 10044, year 2001, INE)

Based on the mentioned facts, 5 different periods have been identified since 1900, as depicted in Fig. 3 (Periods are numbered from 1 to 5 in the Fig. 3). Different representative constructive sections of façades in relation with each period are shown in Table 1. *C* (Heat Capacity) and *U-Value* are calculated as described in eq. 1 and eq. 2

$$U_i = \frac{1}{R_{in} + R_i + R_{out}}$$	**eq. 1**
$$C = \sum \rho_i \cdot c_{p,i} \cdot e_i$$	**eq. 2**

Where:

R_{in}: is the internal surface thermal resistance (0.13 m^2K/W) [28]
R_i: is the surface to surface thermal resistance of the construction element
R_{out}: is the external surface thermal resistance (0.04 m^2K/W) [28]
ρ_i: is the density of the *i* layer material.
$c_{p,i}$: is the specific heat capacity of the *i* layer material
e: is the thickness of the *i* layer

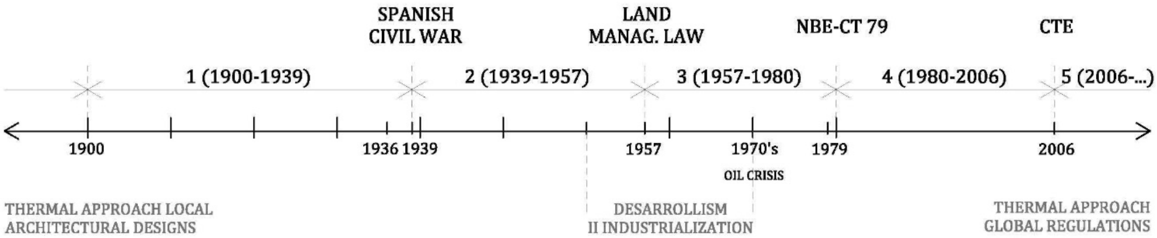

Fig. 3. Construction periods during twentieth century in Bilbao (Spain)

Table 1. Constructive Sections of Façades (according to data provided by Bilbao Social Housing)

4.2 Selection of study-cases

Each apartment of the sample (Fig. 4) was selected according to features defined in section 4.1. This way, all aforementioned periods are represented by at least two dwellings. One new dwelling, built in 2005 (only a year before the Spanish Technical Building Code came to force) is also included in this study.

As far as construction features are concerned, these dwellings can be considered representative not only of the social housing in Bilbao, but also of the social housing stock of the main urban areas in the region. Different aspects and features are taken into account for each dwelling, according to the approach described in section 3. Some of these aspects are summarized in Table 2. Occupation factors, such as occupant age, number of occupants or period of occupation, have been considered as well.

Table 2. Summary of the characteristics of the studied dwellings, according to the subsystems presented in Fig. 1 (Indoor Environment, Envelope, Windows, Energy Systems and Occupants)

Fig. 4. Location of the ten case-studies.

4.3 Field study

Based on aforementioned systemic approach, each dwelling is analyzed in situ. The data are combined in six groups based on the aforementioned six subsystems, as summarized in Table 3.

Table 3. Collected data

4.4 Data collection

4.4.1 Temperature and humidity

Several temperature and humidity monitoring studies can be found in literature. The criteria presented in [4] have been a reference for this study. According to this criterion, detailed measurements of temperature and humidity were collected using Temp-RH Hobo Data loggers (HOBO U12-011). Their resolution is 0.03 ºC (25 ºC) for temperature and 0.03 % for relative humidity, and their accuracy is ±0.35 ºC and ±2.5 % respectively. They were placed far away from direct heat or humidity sources and windows and approximately 1 m above the ground. These data loggers are programmed to collect data with a 10 min. frequency. Although longer time steps can be found in literature (from 20 min. [29] to 2 h. [20]), 10 min. time step has been used because it allows having information about some occupant actions, such as heating system activation or ventilation patterns. Temp-RH data loggers were previously calibrated and validated in the Laboratory for the Quality Control in Buildings (LCCE) of the Basque Government.

A TH (Thermo Hygrometer) was installed in the living room of each apartment and in some of them another TH was installed in the main bedroom, according to the indoor environment (Fig. 5). Similar criteria have been followed in other studies, e.g. in [17] or in [20]

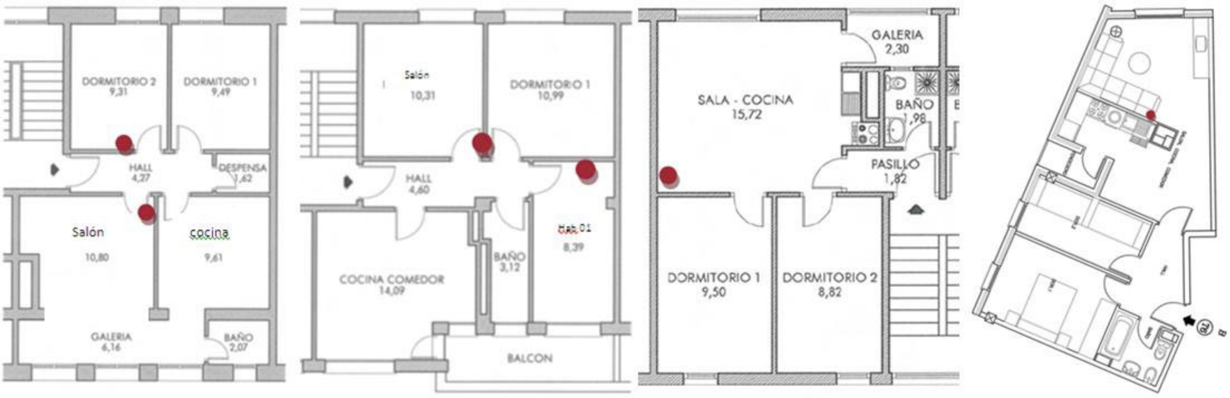

Fig. 5. Layout of some case studies (D1, D3-D4, D6 and D10).

Outdoor temperature and relative humidity were taken from a meteorological station of the Basque Government located in Deusto, Bilbao. This station measures variables such as air temperature, relative humidity, global horizontal irradiation and wind speed, among others, with a sampling frequency of 10-min.

4.4.2 Energy Consumption

Some assumptions have been made to estimate heating consumption in winter. The information sources are not the same in all the dwellings. In most of the cases (six of them) energy bills have been provided, but in two dwellings, heating consumption data have been collected in questionnaires. In the last case (D4) no heating system is used. Actually, a small electric heater is used punctually but its consumption has been considered negligible when summer and winter consumption are compared. In case D5 some meter readings have complemented the information from natural gas bills.

Collected data are presented for each dwelling in Table 4, where energy consumption related to the source during the indicated period is presented. However, it is necessary to standardize these data sets, because some of them are electricity consumption of the whole dwelling and others are natural gas consumption for Domestic Hot Water (DHW) and the heating system. In all the selected cases, this heating consumption has been extrapolated to the same period (1st Dec. – 1st Apr), due to the fact that the heating system has been working from the second or third week of December till the last days of March in every dwelling.

$$E_B = \frac{E_s}{n_s} \quad \textbf{eq. 3}$$

$$\mathrm{H_w} = E_w - n_w \cdot E_B$$	**eq. 4**

Eq. 3 and Eq. 4 are used to calculate the estimated heating consumption in winter, where E_B is the base energy consumption per day, E_S is the energy consumption in summertime, E_w is the energy consumption in wintertime, H_W is the estimated heating consumption in winter, n_s is the evaluated number of days of the summer period and n_w is the evaluated number of days of the winter period. E_B (kWh/day) is calculated considering the energy consumption in summer per day. This method is a good approximation to estimate the heating consumption, especially when heating and DHW is supplied by a natural gas boiler. DHW consumption is assumed to be similar for the whole year, so heating consumption, which only happens in winter, is calculated as natural gas consumption in winter (DHW + Heating) minus natural gas consumption in summer (DHW). This method is also used when the energy supply of the dwelling is purely electrical.

Therefore, the following assumptions have been made in order to estimate the heating consumption during winter period: *1)* 159 kWh / Butane Gas Cylinder; *2)* Base consumption (without heating) per day is calculated according to data from summer period, eq. 3. The estimated heating consumption in winter is obtained by means of eq. 4.; *3)* In this case, the base consumption is assumed according to IDAE[30] (due to variability of the dwelling energy consumption in summer). The estimated heating consumption in winter is obtained using eq. 4.; *4)* Using as reference 43400 kJ/kg for LHV of Kerosene. (9.4 kWh/l)

Table 4. Heating Consumption data collected

Moreover, the fact that not all rooms are heated in some dwellings is another problem to standardize the heating consumption estimation. As questionnaires and measurements show, in some dwellings only one or two rooms are heated (D1, D3 and D10, as summarized in the appendix). In order to adequate the consumption and having a more representative value of kWh/m^2, a relation between heat consumption and real heated area has also been calculated. These values, which are used as a reference to compare the studied dwelling with others, are presented in Table 5.

Table 5. Heating Consumption collected and calculation data

4.4.3 IR techniques

Thermal imaging inspection was also carried out during the investigation of two aforementioned subsystems: Envelope and Building Techniques. Thermography allows detecting thermal heterogeneities of the envelope, like thermal bridges, or variations of the U-Value of different areas of the façades (see Fig. 14).

Some aspects which have a strong influence in IR assessment are [31]: Emissivity (ε), Relative Humidity (RH).ΔT (It is recommended at least a 10-15 ºC temperature difference between indoors to outdoors when IR analysis is carried out) and Solar Radiation. IR images must be taken avoiding sunny hours, to avoid the effect of the sun on the walls. In this way, also the thermal inertia of the walls must be taken into account. Other factors, like distance of the measured element, air temperature, air relative humidity, wind or reflected temperature have to be considered as well, especially if quantitative analysis is carried out.

According to these parameters, the infrared thermographs were performed with a FLIR infrared Camera Model PS60 and were carried out during 2 nights: 28th February 2012 (01.00-04.00 AM) and 2nd March 2012 (00.00-01.00 AM). During the first night collection, the air temperature was 6,5 ºC and there was a RH of 88%. During the second night, the air temperature was 9 ºC and there was a RH of 88%. No rains were recorded in the previous days.

4.4.4 Thermal comfort

Special attention has been paid in this study to the thermal comfort. Thermal comfort and healthy indoor environment are two of the most important targets of any construction. In this approach, these aspects have been included in "Occupants" subsystem. Different factors determine a comfortable environment, such as air temperature, relative humidity, air movement, human activity and type of clothes, to name some of them. Predicted Mean Vote (PMV) or Predicted Percentage Dissatisfied (PPD) indexes are used to assess thermal comfort. PPD is defined in terms of the PMV. PMV depends on activity, clothing, air temperature, mean radiant temperature, air velocity and humidity [32]. As this long term monitoring study was carried out in occupied dwellings, there were some limitations with the used instrumentation, and all of the above mentioned parameters were not registered during the research. For this reason, a simplified method has been used to assess thermal comfort in dwellings, which is described in section 5.6.

4.4.5 Questionnaires

To complete this study, the occupants of each dwelling filled in some questionnaires during the monitoring period. The information supplied by the questionnaires is related to occupant behaviour and awareness, energy consumption, building services, indoor air quality and occupation patterns.

4.5 Data Analysis

Different analyses of the collected data were made according to different moments of the monitoring period:

- Seasonal values were analyzed for winter (Dec-Mar), tempered season (Apr-May) and summer (Jun-Aug).
- The coldest period of 15 days, (1-14 February)
- One period of 15 days in Spring.
- The hottest period of 15 days, (8-22 August)
- Short time periods (48h). The hottest (18^{th}-19^{th} August), the coldest (8^{th}-9^{th} February) and tempered (24^{th}-25^{th} April) short periods.

These values for each dwelling are provided: maximum and minimum values, average values, standard deviations and correlations between indoors and outdoors air temperatures.

5 Results

U-values of dwellings are clearly gathered in two defined ranges. One is the group related to the newest (Built after 80's) or energy renovated buildings, which have an U-value between 0.40-0.50 W/m^2.K. The other group refers to buildings built before the first thermal regulation (1979) with a U-value between 1.10-1.30 W/m^2K.

As expected there are two clear correlations. First of all the higher ΔT, the higher the heat consumption. As it was also expected, when two dwellings with similar heating consumption are compared, the higher ΔT corresponds to the lower U-value. This trend is clearly shown in the graph depicted in Fig. 6. A comfort zone has been assumed to this study. Even though comfort zone in winter is defined between 20 ºC and 24 ºC by ASHRAE in [33], the thermal comfort limits are selected according to [22] (18 ºC $\pm$2 ºC) Thus, red lines represent these comfort limits for winter, which makes 5.83ºC and 9.83ºC of ΔT). ΔT in this graph is the difference of the average indoor and outdoor temperatures in winter (see Fig. 8). The time-constant (τ) has been calculated dividing C [J/m^2.K] by U [W/m^2.K], so τ is presented in hours [h], according to [34]. This concept is considered useful in this graph since it encompasses both C and U in only one term.

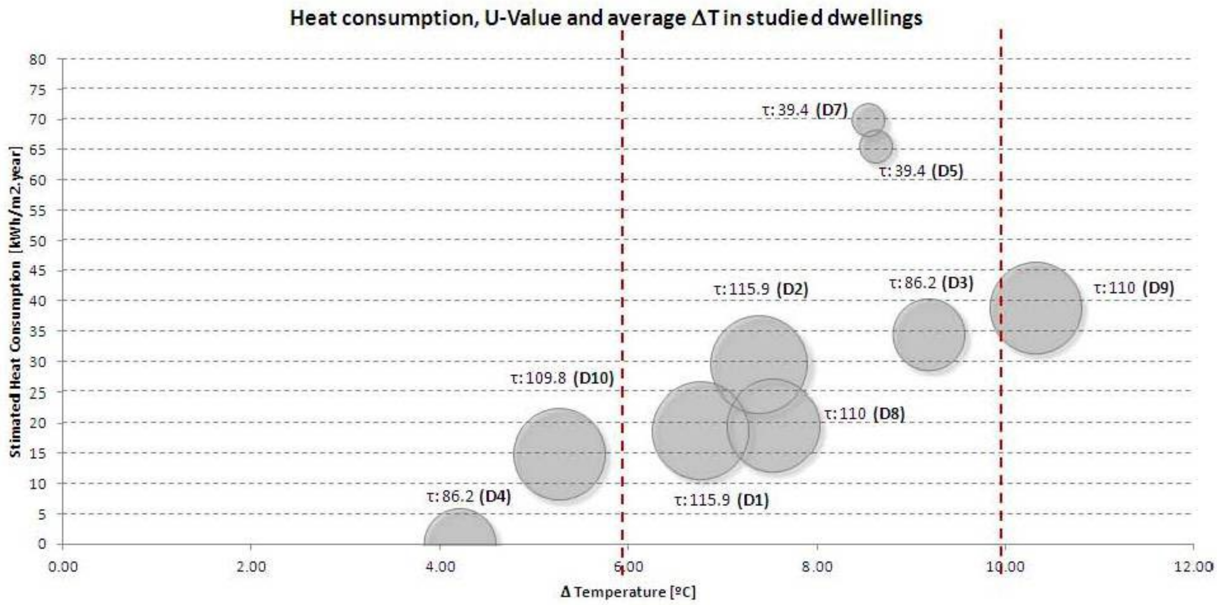

Fig. 6. Energy performance of the dwellings. Relation between yearly energy consumption per square meter of heated area, time constant and average ΔT. (Non available heating consumption data in D6) Outdoor Average: 10.17

However, if only these aspects are taken into account, an unexpected performance of two dwellings could be deduced looking at this graph: the highest heat consumption in each interval (D5 and D7, respectively) doesn't correspond with the highest ΔT. This point proves that other aspects, such as heat capacity of the façade, user behaviour, ventilation, windows quality and opaque walls and windows ratio or thermal bridges, to name but a few, play an important role in thermal performance in these dwellings. Both dwellings (D5 and D7) present not only a high U-Value (1.27 W/m^2K) but also a low heat capacity value in façade (180 kJ/m^2K), whilst other studied dwellings with low U value in their façades have, however higher heat capacity (360 kJ/m^2K - 423 kJ/m^2K); Differences between D5 and D7 could be explained when ventilation patterns are born in mind or user behaviour, in general.

Thus, these consumption differences should be evaluated and explained analysing more parameters. D3 and D4 are quite similarly constructed. Their differences can be explained when the used heating system is taken into account (D4 has no heating system) and when comparing the average monthly indoor temperatures (Fig. 7). Even using the same heating system (natural gas with high temperature radiators), significant differences can be found in heating consumption (about 50%), as Fig. 7 shows in graphs for D8 and D9. When D5 and D7 are compared, with similar average indoor temperatures during winter period, differences in heating consumption (Fig. 6) can be attributed in this case to occupants behaviour, as previously said.

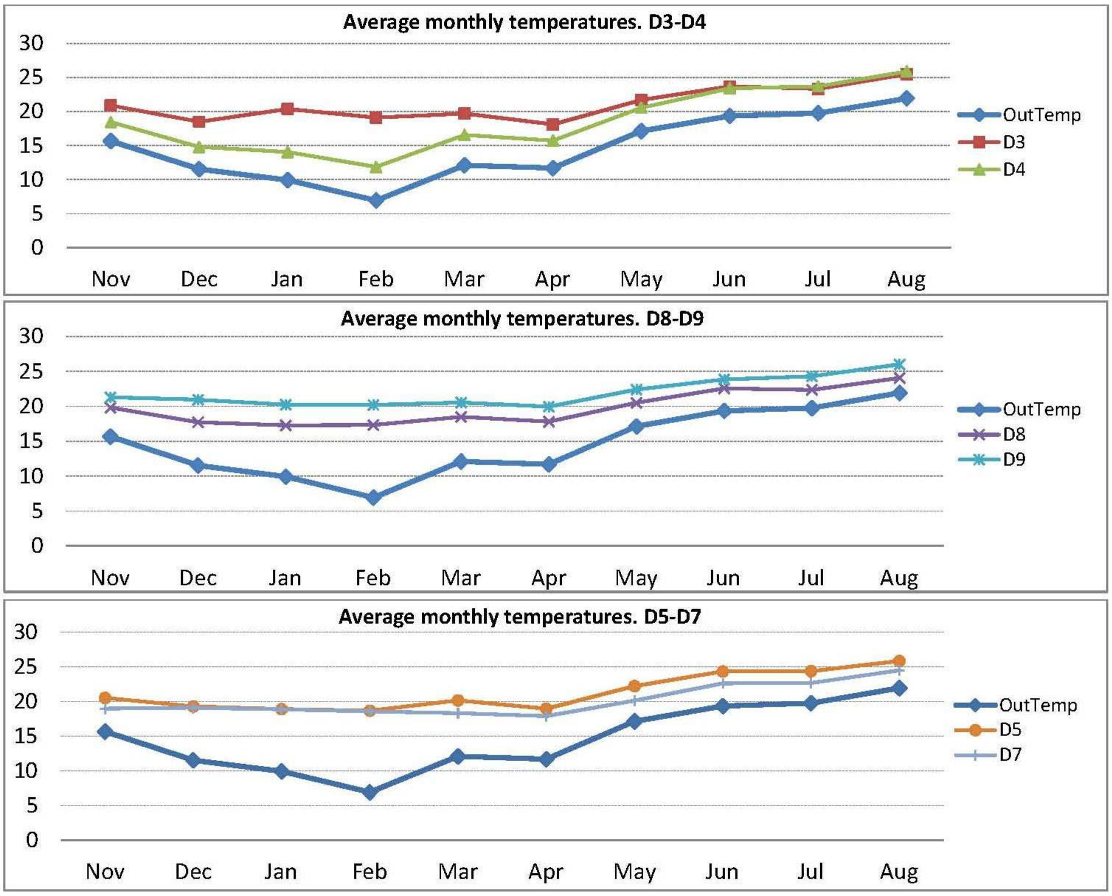

Fig. 7. Comparison of the monthly average temperatures in some studied dwellings.

5.1 Analysis of annual indoor environment

Social housing sector is a heterogeneous dwelling group when indoor thermal conditions are taken into account. In the studied group, significant differences are found for the average monthly indoor temperatures, especially in winter time, when heating systems are used and consequently, heat consumption is the highest (Fig. 8). This period will be studied in detail later.

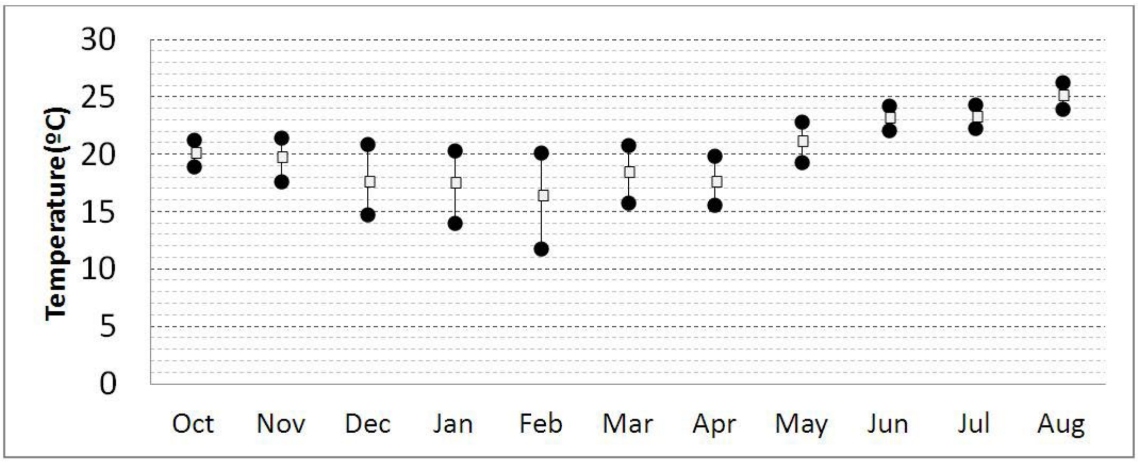

Fig. 8.Maximum, average and minimum monthly indoor temperatures for the 10 studied dwellings.

Fluctuations in indoor temperature are a consequence of several factors, such as the heat capacity of the building structure, the heating system control or ventilation patterns, to name but a few. Diurnal and Nocturnal Ranges give an idea of the indoor temperature stability. The ratio of internal to external temperature fluctuation ($\Delta t_i/\Delta t_o$) shows correlations between indoor and outdoor temperatures, and it will depend on the dwelling features (Building Techniques, Building Envelope and Energy Systems) and, on the other hand, on dwelling services and dwelling operation, related to occupant behaviour.

Table 6 shows the nocturnal and diurnal ranges by seasons. The higher diurnal and nocturnal ranges of indoor temperatures are in winter period, when heating systems are used. The average of diurnal range in this period is between 3.18 (D2) and 1.16 (D6), whilst the average of nocturnal range is between 3.63 (D10) and 0.82 (D6). In summertime, instead, these ranges are in general quite smaller, from 3.36 (D2) to about 0.8 (D4 and D6).

Table 6. Ratio of internal to external diurnal and nocturnal temperature fluctuation for the studied dwellings (main room data)

Differences can also be found when the two monitored rooms of the same dwelling are compared, especially in wintertime. If all rooms of the dwelling are heated by the heating system, nocturnal and diurnal ranges are similar in both rooms (e.g. D5, average diurnal range is 2.64 in the main room and 2.85 in the bedroom; and average nocturnal range is 2.84 in the main room and 2.70 in bedroom) When only some rooms of the dwelling are heated, the differences are quite bigger: in D3 the average diurnal range is 3.11 in the main room and 1.36 in the bedroom; and the average nocturnal range is 2.99 in the main room and 1.27 in the bedroom.

These results seem to be contradictory with that mentioned in [22], where it is affirmed that fluctuation temperature is closely linked to the heat capacity of the structure. However, this phenomenon can be explained with the fact that both studies have been carried out under different conditions (in this case, every monitored dwelling has been occupied during monitoring periods, whereas in [22] two dwellings out of the three were vacant). The way of using the heating system in winter, and ventilation management of the user in summer (both strategies regarding to occupants' behaviour) can increase significantly the indoor temperature range of the dwellings. As a matter of fact, this is proved with the result of diurnal range of temperatures in D4 in winter, (one of the lowest of the sample), which has no heating system, as well as in D6, (it presents the lowest temperature range) where the use of the heating system is very occasional, according to D6 questionnaire. This hypothesis is proved in summer as well. Dwelling D6, which is also the dwelling with the lowest temperature in summer, is vacant during this period. Other factors, such as the ratio of area of exposed envelope and dwelling area can complement the explanation of these results. Thus, the high values of D2 are also explained due to its location within the building, directly under the roof, whereas in D1 the effect of high C in the opaque walls could be counteracted by the low quality of the windows.

Indoor relative humidity (RH) has also been studied. The accepted range of RH for thermal comfort is from 30% to 70% [33]. Therefore, as shown Fig. 9, more than 99% of registered RH data were higher than 30% in all dwellings. However, the situation changes when the highest limit is observed. In four dwellings, more than 5% of registered data were out of comfort zone, and two of them gave especially high values: D6 (32.4% of the registered data out of comfort zone) and D7 (46.9% of the registered data out of comfort zone). Seasonal detailed information is presented in Table 7. The majority of collected data higher than RH 70% correspond to wintertime, except in D7 which has high RH values in every evaluated season.

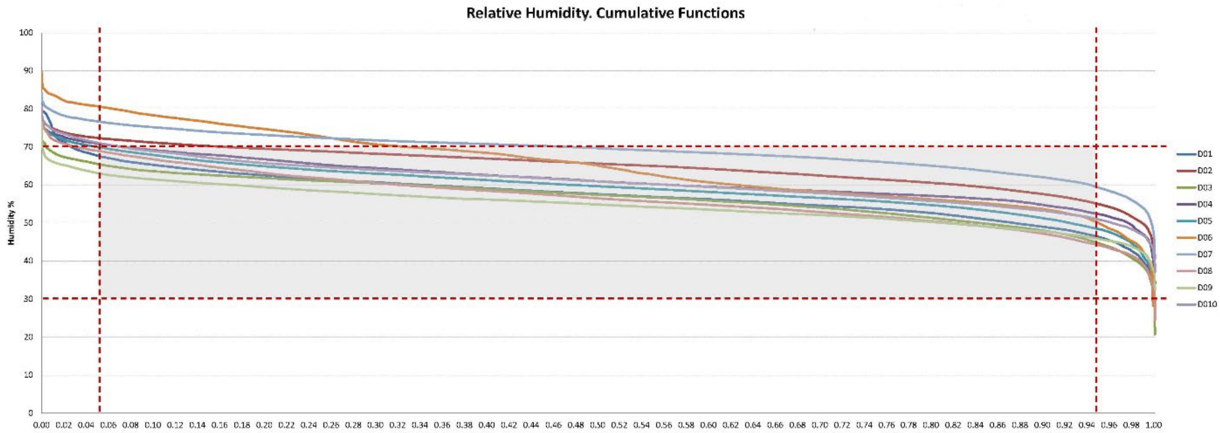

Fig. 9.Relative Humidity in the Dwellings. Cumulative Distribution Function.

Table 7. Summary of logged RH (%) during the whole period and by seasons: Winter (Dec 2011 - Mar 2012), tempered season (Apr-May 2012) and Summer (Jun-Jul-Aug 2012)

In occupied dwellings RH is directly affected by natural ventilation (there is no mechanical ventilation in the studied dwellings). Thus, this parameter can also give information about the ventilation rate, whether it has been enough or not. Indoor RH is related to outdoors RH, and with indoor humidity sources like cooking or human activity. Too high RH values could mean low ventilation rate, as well as low indoor temperatures.

5.2 Winter period

Winter period data (Dec 2011-Mar 2012) are presented in this section. Some temperature limits are defined to evaluate indoor temperatures in dwellings. For winter, thermal comfort limits have been set up around 18 ºC ±2 ºC based on the research presented in [22]. Moreover, the lowest limit (16 ºC) has been used as a reference in other studies for identifying "cold homes" when standardized temperatures are used [4].

Average indoor temperature in two dwellings in winter is lower than 16 ºC (D4 and D10). For dwellings D1, D2, D6 and D8 average indoor temperatures are also low (Table 8). The reasons of these low temperatures can be different in each case: recurring inoccupation of dwelling, inadequate heating equipment control, building and heating system characteristics, ventilation patterns…

Table 8. Summary of logged temperatures (ºC) in Winter (Dic-Jan-Feb-Mar)

5.2.1 15-day and 48-hour periods

48-hour period and 15-day period analysis (Fig. 10 and Fig. 11 respectively) allows complementing the information gathered by questionnaires with real data obtained by the thermo-hygrometers. Ventilation (opening windows) and heating consumption patterns are easily identified in these analyses. Opening windows in winter are identified in the graphs because RH and temperature drops suddenly. In a similar way, when heating system is activated, temperature increases and RH drops at the same time. Two examples of this behaviour for dwellings D3 (Heating system activation) and D5 (opening windows) are depicted in Fig. 10.

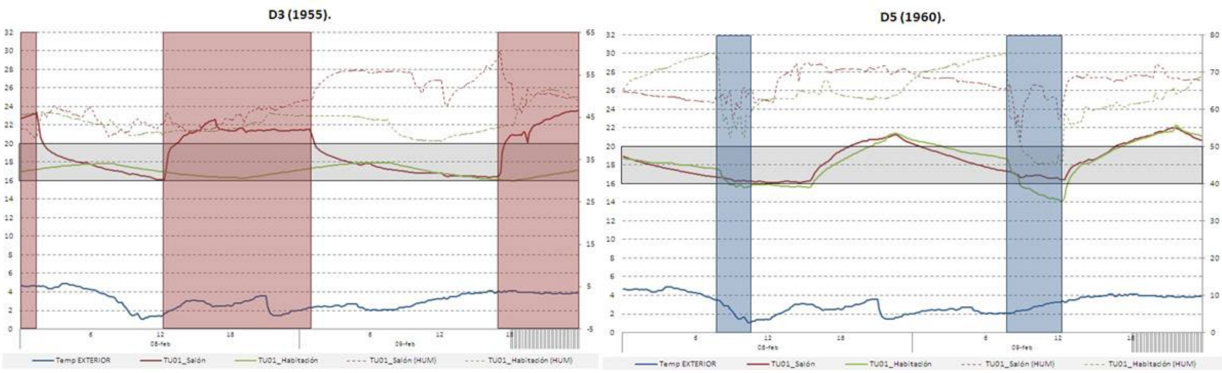

Fig. 10. 48-h analysis. Identification of heating system activation (left graph) or opening windows (right graph)

These analyses allow also comparing different heating systems, and the way of using them. For example, D1 and D3 use heaters only in some rooms of the whole dwelling. However, the results are quite different in each case (Fig. 11). Although both dwellings are occupied during the whole day, D1 only have some peaks with over 16 ºC in the heated area and in the 48-hour analysis there is a minimum of 12 ºC (in that moment, windows are open), whilst D3, a dwelling heated by a 2kW electric heater located in the living room, has a significant amount of logged data over 20 ºC in the heated area.

Several differences can also be found in the evolution of non-heated area temperatures in these dwellings. D4 (with no heating system) has a very low temperature during the coldest period. Temperature in the whole dwelling is stable and the same in the two studied points, and small peaks appear in the main room, due to the use of a small heater, whose consumption has been neglected in energy consumption estimations. Dwellings with natural gas and one radiator in each room have smaller temperature differences in the whole dwelling during the day (e.g. in D5 natural gas heating system with one heat radiator in each room is used. The system is commanded with a thermostat located in the living room). Energy consumption for heating is usually higher in these dwellings, but the whole dwelling works closer to comfort levels. Temperatures are similar in every room, and small variations are due to different ventilation patterns in each room.

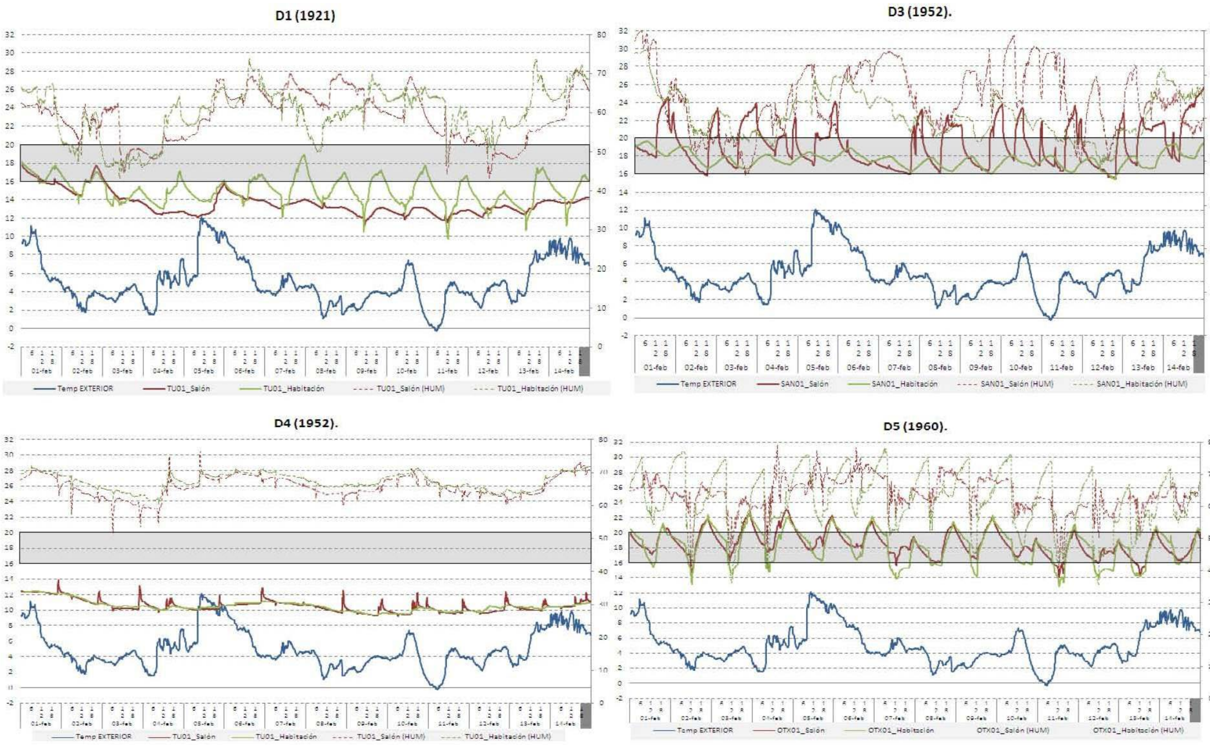

Fig. 11. Indoor RH and Temperature and outdoor temperature for D1, D3, D4 and D5 dwellings during 15-day period in winter.

In this analysed 15-day period, the 4 dwellings (D1, D4, D6 and D10) have an average temperature below 16 ºC and only one dwelling (D9) have an average temperature higher than 19 ºC (Table 9)

Table 9. Summary of logged temperatures (ºC) in the 15 coldest days (1-14 Feb 2012)

5.3 Summer period

In order to assess the thermal behaviour of each building without any heating or cooling system, monitoring measures have also been carried out in summer, from June to August 2012. As it was expected in this climatic area, indoor thermal comfort is satisfactory without any cooling systems,. As shown in Table 10, the range of indoor average temperatures is between 6.82 (D7) and 12.34 (D2), with a standard deviation between 1.31 (D7) and 1.86 (D4). These data show the capacity of these dwellings to attenuate the impact of the diurnal summer thermal variations.

Table 10. Summary of logged temperatures (ºC) in summer (June-August)

For this period, indoor temperatures are evaluated in detail as well (Fig. 12). Thermal comfort limits have been set up with a maximum value of 28 ºC. Even during the hottest period of the year, an optimised management of occupants (reduction of solar gains during day time and natural cooling at night) ensures a proper thermal regulation. This regulation is achieved thanks to the specific architectural designs of these dwellings, especially because its indoor distribution allows a cross ventilation and thermal draught created by existing temperature gradients between opposite façades, which allows adequate natural ventilation.

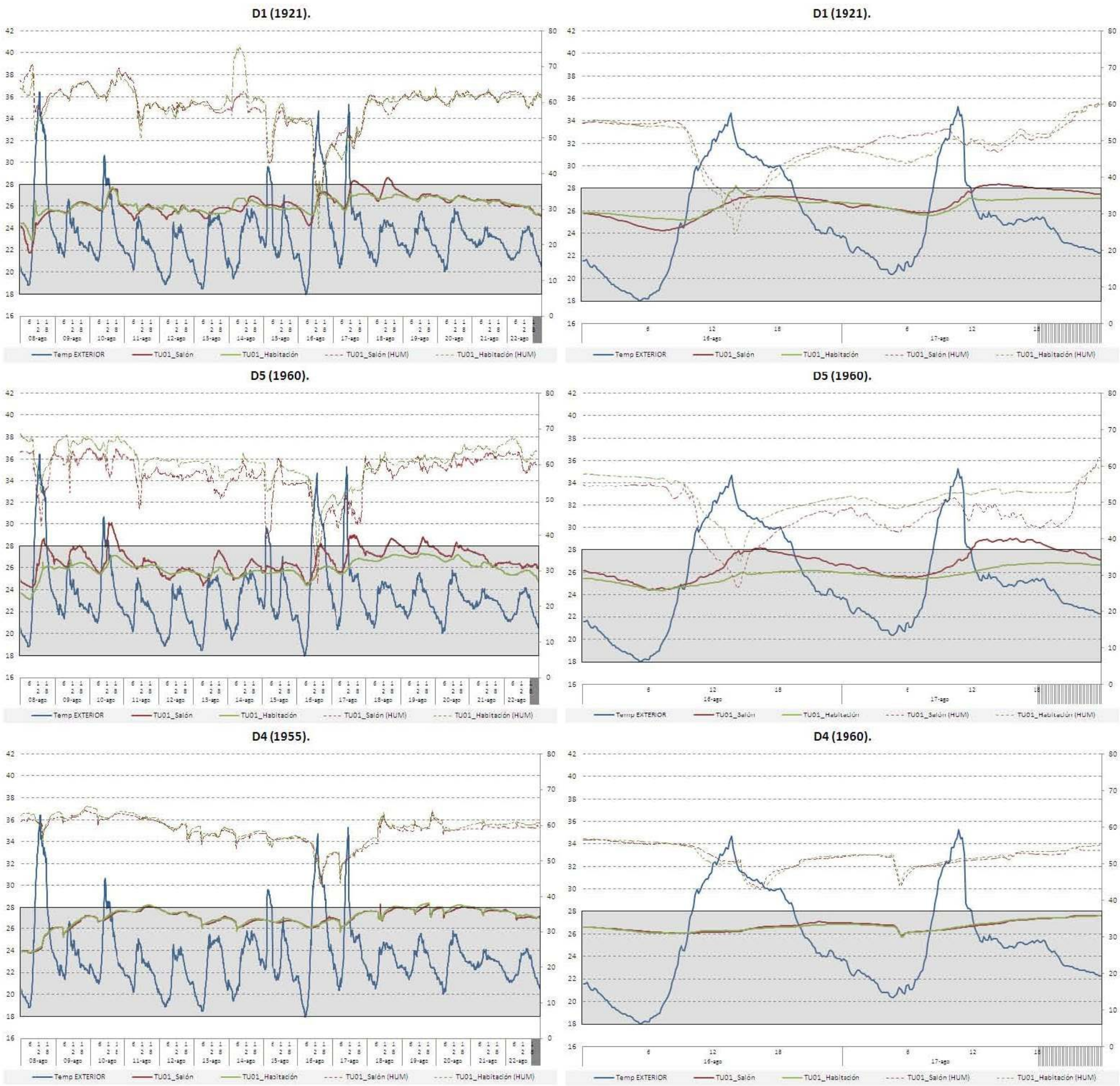

Fig. 12. 15-day and 48-hour period (the hottest period) analyses for D1, D4 and D5 in summer.

5.4 Spring period (tempered season)

Tempered season data (April-May 2012) have been assessed as well. Similar methodology has been followed to analyse these data. In this period, only in one dwelling (D10) the average indoor temperature is lower than 18 ºC. The other dwellings have average temperatures between 18.15 ºC (D4) and 21.19 ºC (D9). Standard deviations in this period are in general quite higher than those obtained in wintertime.

5.4.1 15-day and 48- hour periods

Although indoor thermal conditions between the dwellings are similar in this period, still several significant differences can be found. Some dwellings used the heating system during some days of this period.

5.5 Thermal imaging inspection

To analyse the heat consumption of a dwelling, another issue to take into account is the impact of thermal bridges. According to diverse consulted bibliography, the impact of thermal bridges on heat consumption can vary from 5% [35] (insulating the exterior of the building envelope) to 39% [36] (in many insulated single family houses with bad thermal bridge treatment).

Despite the complexity to carry out an accurate quantitatively IR inspection, the temperature profile in the thermal bridge created in the slab face of each building has been analysed, as shown in Fig. 13. The minimum temperature in the external surface of the façade (T_{min}) corresponds to a point far away from the thermal bridge, where the heat flux is supposed to be one-dimensional. The difference between the minimum and the maximum temperature (ΔT) indicates the level of the impact of the slab face thermal bridge. The higher ΔT, the higher the thermal bridge impact is.

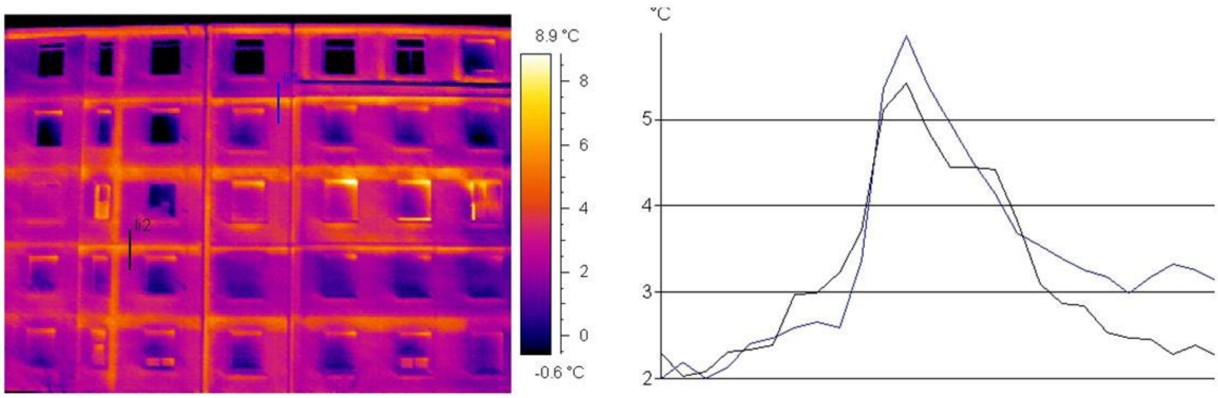

Fig. 13. Temperature profile in the slab face thermal bridge of dwelling D2.

The lowest difference of surface temperature (ΔT) has been found in the buildings corresponding to dwellings D3 and D7 (0,7 ºC), whilst the highest ΔT was registered in the façade of D2 (3,3 ºC). The possible effect of thermal bridges over the global thermal performance of the dwellings is not very well defined when these results and indoor temperatures or consumption in each dwelling are assessed together, due to the fact that the effect of other variables such as opening windows patterns, (see Fig. 10) make negligible the impact of thermal bridges. In this case, the fact that dwellings have been occupied during the monitoring period is a handicap to evaluate this effect. Studying quantitatively the thermal bridges effect on a dwelling requires to limit the effect of human behaviour, either by means of simulations, or by carrying out the study in vacant dwellings.

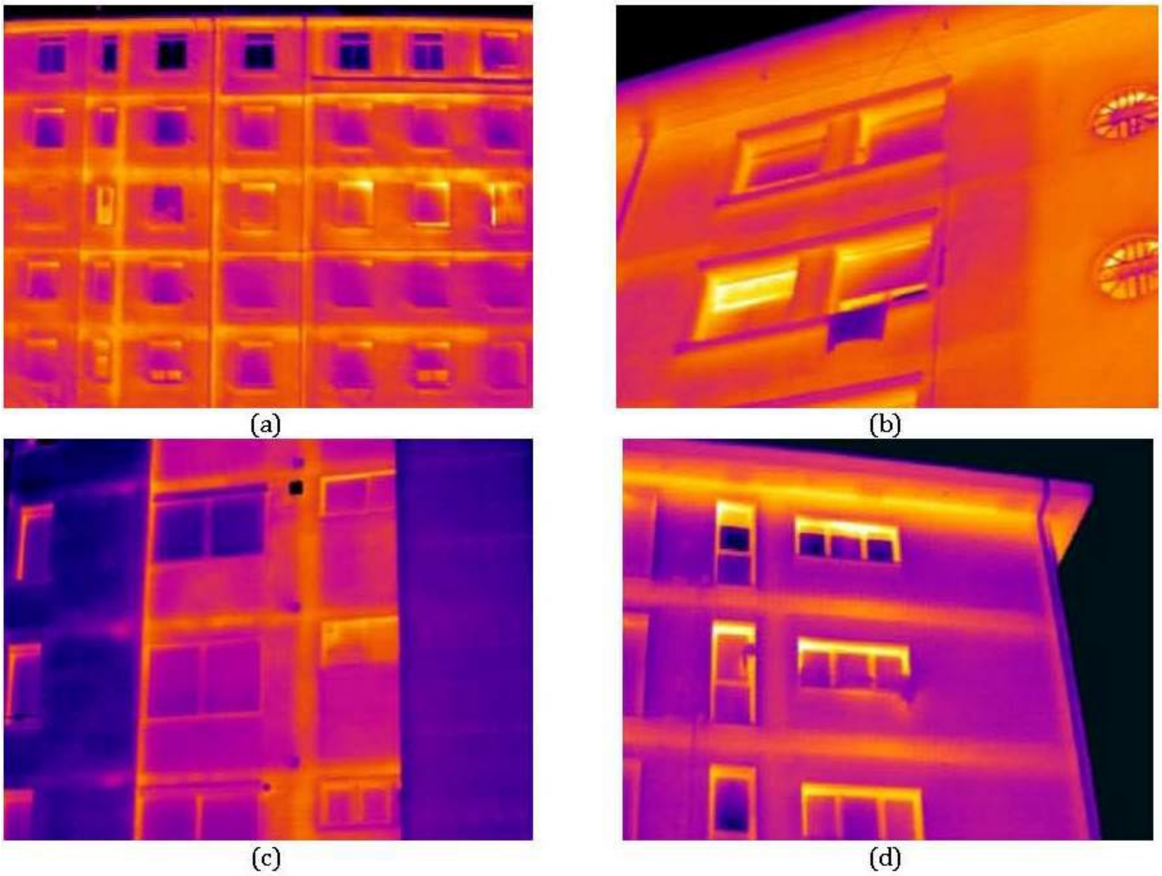

Fig. 14. Thermographs of some buildings studied (a) D2; (b) D3; (c) D5; (d) D8.

5.6 Indoor thermal comfort and risk of cold homes

Due to the fact that some of the logged temperature data in winter are much lower than expected, a study has been developed in order to evaluate indoor thermal comfort in winter, and the risk of cold homes. Thermal comfort is defined by ISO 7730 ([32]) as the mental condition expressing satisfaction with thermal environment. As it has been mentioned in section 4.4.4, recording all these parameters has not been possible. For this reason, an approximation based on the statistical analysis has been made, following the procedure presented in [22].

Cumulative distribution functions (CDF) were obtained with the series of registered temperatures in the studied dwellings during winter period, from 1st of December 2012 to 1st of April 2012 (Fig. 15). Significant differences can be found when CDF are compared. About 80% of the registered data in D4 in winter is lower than 16ºC. On the other hand, in D9 the share of the registered data below 16ºC is negligible, almost 70% of the time the temperature is over 20ºC, which could suggest that reducing the set point temperature would reduce energy consumption without reducing indoor environment comfort levels. CDF of D10, D1, D2 and

D5 are also presented in Fig. 15. CDF of D2 shows a balanced indoor temperature management, where less than 5% of the registered data is below 16ºC and less than 5% of the registered data is over 20ºC.

A summary of logged temperatures according to these criteria is presented in Table 11. In this table the thermal performance of D4 must be highlighted. It is not only the coldest dwelling in winter, but also one of the dwellings with higher temperatures in summer (see Table 10) if it is compared to other dwellings. D6 logged high temperatures in summer, but this is due to the fact that the dwelling was empty during this summer period and thus, there was no ventilation during this period. D5 presents higher temperatures over the whole year. Thermal performance of D4 could be explained because the high U-value of its façade and especially because it is located in the upper floor of the building and the U-Value of its roof is too high.

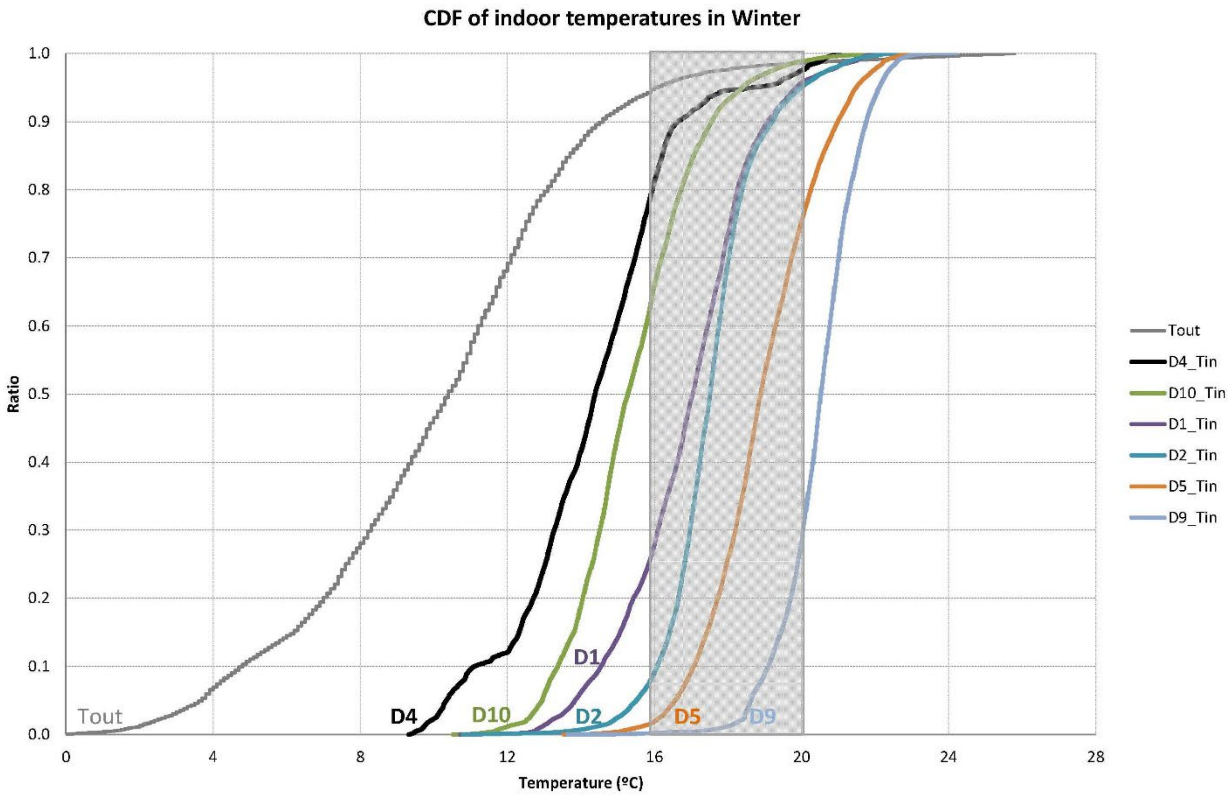

Fig. 15. Cumulative Distribution Function of 6 studied dwellings in winter (D4, D10, D1, D2, D5 and D9).

Table 11 Summary of logged temperatures in the main room (%) in winter (Dec 2011 - Mar 2012), tempered season (Apr-May 2012) and summer (Jun-Jul-Aug 2012)

These CDF analyses give quantitative information, but they don't describe the temperature evolution inside the dwellings. As described in [22] the difference between indoor and outdoor temperatures against outdoor temperature is analyzed (Fig. 16). The thermal comfort zone is marked in these graphs, so as to identify which measures are in the thermal comfort zone and which measures are not. The graphs also show the share of measures which are below 16 ºC. Previously mentioned thermal comfort limits are selected (18 ºC ±2 ºC) according to [22].

The CDF temperature in winter gives an idea of the heating system usage. Differences between D4, (where more than 80% of the measured temperatures are below 16 ºC), and D9, (where more than 99% of measured temperatures are higher than 16 ºC), are clear. In this case, one of the most influential factors is not the building envelop, the energy system or the building techniques but the building operation and specially, the way the heating system is used.

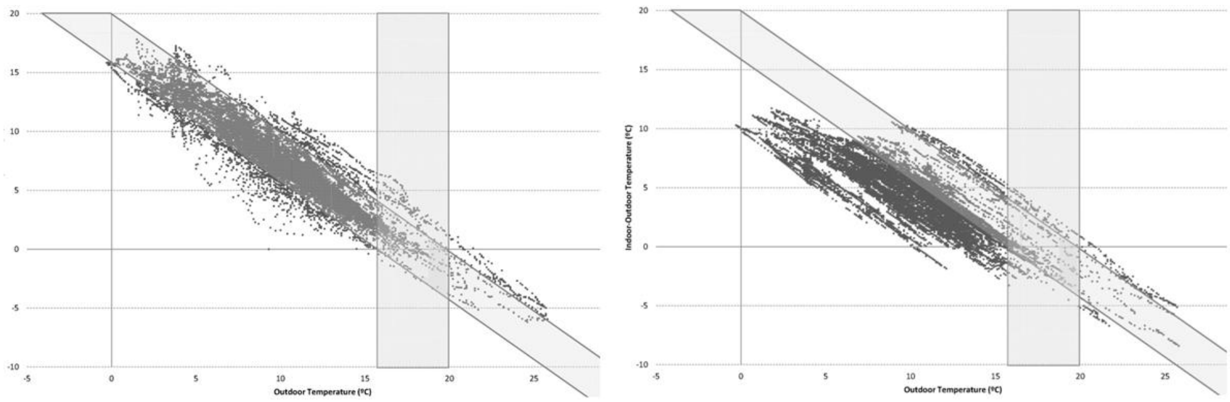

Fig. 16. Indoor-Outdoor temperature against outdoor temperatures in wintertime. (D2 and D4).

6 Discussion

Thermal behaviour of dwellings can be explained only when the building is studied under a global approach. In the case of the analyzed dwellings, occupants' behaviour (as affirmed in [37]) plays an important role in indoor thermal characteristics, moreover in summertime. In most of the studied cases, it can ensure a thermal regulation thanks to specific architectural design of the dwellings: crossing distribution of the indoor environment, distribution of rooms according to its uses and orientations or indoor distributions which allow natural ventilation. Thus, following the approach presented in Fig. 1, the results obtained may be summarized in the following points:

Outdoor environment and site. The studied dwellings are located in an area with a tempered climate, although sporadically peaks of temperature (both high and low) could be registered.

Heating systems. In the majority of the analysed dwellings the heating system efficiency could be improved, especially in rented ones, where the occupants usually decide not to invest on an efficient heating system.

Building envelope. In many dwellings windows have been replaced at least once, and *"Bilbao Social Housing"* have promoted and developed plans in this way, usually acting not on a building scale, but on a dwelling scale. However, there is still a great number of buildings and dwellings with envelopes displaying a poor thermal performance.

Building Techniques. The effects of the thermal bridges have not been appreciated due to their low impact compared to other effects, such as ventilation patterns.

Indoor design. In general, studied dwellings present a good indoor design, with crossing indoor distribution, adapted to uses and orientation.

Occupants. Occupation patterns, ventilation patterns or ways of using the heating system have a high repercussion in the comfort and in the energy consumption. This can be observed in Fig. 11, where the measured temperature profiles in three dwellings during two weeks in February are presented. The differences are not only in the heating system fuel, but also in ventilation patterns. In this way, strategies for increasing the occupants' awareness are recommended to be developed.

6.1 Indoor comfort

6.1.1 Winter period

Four of the studied dwellings have an indoor average temperature lower than 16 ºC during the coldest period in winter, and two of them present an average temperature lower than 16 ºC when the whole winter is analyzed. On the contrary four dwellings have an average temperature over 18 ºC. In three of these four dwellings (D5, D7 and D9), the occupants are the owners. In the fourth one, although the average indoor temperature is higher than 18 ºC, it is quite unstable. These three dwellings are the only ones which have natural gas based heating system, and the household incomes of these dwellings are also the highest of the ten studied cases. Other studies have also demonstrated that amongst other factors, household incomes and energy consumption and therefore, indoor comfort at home, are closely linked [38].

The majority of the analyzed dwellings have lower energy consumption than expected. This is not due so much to the building thermal performance itself, but to the indoor temperatures which take in some cases very low values.

Improving the thermal performance of the stock of social dwelling not only must aim at reducing energy consumption, but also at improving indoor comfort. For that reason, when the effectiveness of a renovation in a social dwelling is evaluated, indoor environment parameters, such as indoor temperature and RH, must be taken into account. The improvements on the indoor comfort should be considered as positively as energy savings itself. Factors which are out of the scope of our study, such as health and social factors will also be benefitted through a proper renovation of social dwellings.

6.1.2 Summer Period

Indoor conditions in summer have also been considered in this study. Similar methodology to the one used in section 5.6 to evaluate indoor comfort in winter could be followed to study the indoor thermal comfort in summer. In this case, it has not been accomplished because the registered indoor temperatures in summer are in general quite comfortable, rarely higher than 28 ºC even during the hottest days of the year, as expected in this climatic area.

7 Conclusions

In order to establish a good energy renovation strategy of the building stock, and to consider different priority criteria, it is necessary to have accurate data on the thermal performance of the building stock. This paper has shown a methodology for studying thermal performance of social dwellings based on a long term monitoring of 10 dwellings. Collected data have been used to define general trends on energy consumption and thermal performance of social housing sector, as well as enough data to define the operation conditions in social dwellings, based on this field study, and not in standards. Significant differences have been found comparing standard operation conditions and operation conditions based on gathered measurements. This study also provides qualitative and quantitative characterization of ten reference dwellings, representative of the Social Housing Sector in Bilbao.

The field investigation shows that energy consumption of these social dwellings is lower than expected. This situation is not due that much to a good thermal performance of the studied dwellings, but to a lowering of the indoor comfort levels, and low indoor temperatures in winter. This way, future energy retrofitting strategies will have to bear in mind this aspect when their effectiveness will be assessed. That is, sustainability on building renovations does not have to be evaluated only in terms of energy savings, but also under economic and social criteria. The aim of reducing cold homes (and this way the risks which they involve) must be considered as important as energy savings themselves, especially in social housing sector.

Differences on energy consumption for heating have been found amongst the studied dwellings. Those differences can only be explained properly when all subsystems and their interactions are considered in the study. Especially important is the indoor average temperature required by the occupants in winter, which is closely linked to household incomes. The highest indoor temperatures have been found in the dwellings with higher household incomes. These differences on indoor conditions also depend on the heating system and its use, as described in section 5.2.1. It proves the heating system influence on the indoor thermal comfort, both the kind of heating system itself and the use of it given by the occupant.

It could be interesting to carry out further researches about the influence of the occupants on energy consumption and indoor comfort. Many aspects which are strongly dependent on the occupants, such as the mentioned heating system usage, ventilation patterns, set point temperatures or closing the window shutters at night, involve great variations on the final energy consumption of a building.

The study also shows that the majority of dwellings have a good design, which can allow thermal regulation by means of the occupants' adaptive behaviour. Energy renovations in social dwellings in this city has to be leaded mainly to improve energy systems and building envelope, both walls and windows if necessary.

It is necessary to investigate accurately the different types of social dwellings before any retrofitting intervention, according to the classification previously mentioned. The best retrofitting strategy for improving thermal performance of a building constructed in 1920, with high thermal mass in façade will be different than the best one for a building constructed in 1960 with a light façade.

In this research, a sample of ten different dwellings has been studied. Some of them present a low U value in façade, some of them present a high C in façade, and two of them present high U value and low C in façade at the same time. However, none of them have a façade with both low U-Value and high C. It could be interesting to study the thermal behaviour of a dwelling with these features in further researches.

Finally, in another research line, the risk of cold homes in Spain is a factor to be taken into account. Although this problem could seem to be only linked to northern countries, this research has shown that, at least in social housing sector, cold home is a real problem. This problem will be aggravated in the near future due to the economic crisis and the steady increment of the energy prices. More studies focusing on cold home concept should be carried out.

In short, social dwelling stock is one of the sectors with more risk of energy poverty. Hence, social housing stock, especially those built before 1980, should be a priority in energy renovation strategies, both due to its potential of improvement and the need to fight against the risk of fuel poverty and cold homes.

8 Acknowledgements

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9 Appendix

A summary of geometrical and other features of the heating area in each studied dwelling are presented in Table A1.

Table A1. Geometrical features of the heating area in each dwelling. (EF: Envelope Factor= m^2 heated area /m^2 façade of heated area)

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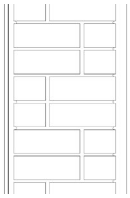
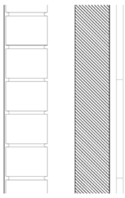
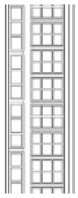
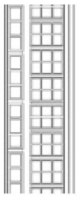
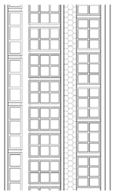
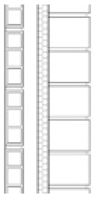
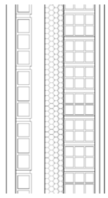
Tables with captions

Geometrical features of the heating area						
						
F.a	F.b	F.c	F.c.1	F.c.2	F.d	F.e
From Indoors (left) to Outdoors (right)						

U [w/m².K] C[kJ/ m².K]	Constructive Section (in-out)	Period	U [w/m².K] C[kJ/ m².K]	Constructive Section (in-out)	Period
F.a. **U: 1.11** **C:463.8**	Plaster Perforated Brick (37 cm) Cement Mortar	1	**F.b** **U: 1.16** **C: 359.8**	Plaster Hollow Brick (12.5 cm) Air gap Concrete Wall (10 cm) Cement Mortar (2cm)	1-2
F.c **U: 1.44** **C: 160.0**	Plaster Hollow Brick (4.5 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2cm)	3	**F.c.1** **U: 1.27** **C: 180.0**	Plaster Hollow Brick (4.5 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2cm) Lightened Cement Mortar (2cm)	3
F.c.2 **U: 0.43** **C: 238.4**	Plaster Hollow Brick (4.5 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2 cm) Thermal Insulation (4 cm) Hollow brick (9 cm) Lightened Cement Mortar (2 cm)	3	**F.d.** **U: 0.48** **C: 189.0**	Plaster Hollow Brick (4.5 cm) Thermal Insulation (3 cm) Air gap Perforated Brick (12.5 cm)	4
F.e. **U: 0.41** **C: 162.6**	Plaster Hollow Brick (4.5 cm) Thermal Insulation (6 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2cm)	4-5			

Table 12. Constructive Sections of Façades (according to data provided by Bilbao Social Housing)

		Indoor Environm	Envelope			Windows			En. Syst	Occ
Nº	Year	A. (m²)	Sec.	U_{wall} [W/m².k] (calc)	C_{wall} [kJ/m².K] (calc)	Wind.	U_{win} (calc)	Infiltr.	Heating System	Property type
D1	1921	53.33	F.a	1.11	463.8	Wood (f); Gass 6	5.35	High	Butane	Rented
D2	1921	45.68	F.a	1.11	463.8	PVC (f); Glass 4/6/4)	2.38	Low	Elect. heater	Rented
D3	1952	51.5	F.b	1.16	359.8	Al (f); Glass 6 – Wood (f); Gass 6	5.35-5.70	High - Med.	Elect. heater	Rented
D4	1952	51.5	F.b	1.16	359.8	Al (f); Glass 4/6/4)	3.37	High	None	Rented
D5	1960	47.68	F.c.1	1.27	180	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Owner
D6	1960	39.7	F.c.2	0.43	238.4	PVC (f); Glass 4/6/4)	2.38	Low	Elect. Heater	Rented
D7	1960	47.65	F.c.1	1.27	180	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Owner
D8	1995	68.3	F.d	0.48	189	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Rented
D9	1995	87	F.d	0.48	189	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Owner
D10	2005	58.5	F.e	0.41	162.6	PVC (f); Glass 4/6/4)	2.38	Low	Kerosene	Rented

Table 13. Summary of the characteristics of the studied dwellings, according to the subsystems presented in Fig. 1 (Indoor Environment, Envelope, Windows, Energy Systems and Occupants)

Subsystem	Data	Information sources
Outdoor Environment and Site	Geographical parameters (Lat, Long)	Field measurements, Bibliographical sources
	Climatic area, solar radiation	Field measurements, Bibliographical sources
	Microclimate, outdoor temperature and RH	WEB Data, Recorded Data. Visual inspection
Building Techniques	Thermal Bridges	Thermal imaging
Building Envelope	Thermal characteristics of the walls	Bibliographical sources
Energy Systems	Energy Systems, Energy consumption	Questionnaires, Energy bills
Indoor design	Indoor distribution	Plans, field measurements, visual inspection.
Occupants	Indoor Environment: Plans, sections, Façades	Field measurements
	Activities, Behaviour, environmental quality	Questionnaires, Field measurements

Table 14. Collected data

		Data collected		Estimated consumption 1 Dic- 1 April
	Source	Period	Consumption	Assumptions
[D1]	Questionnaires	Whole Winter	4 butane gas cylinder	1)
[D2]	Electricity Bills	24 Nov-20 Mar	1840 kWh	3) (Base consumption: 4,16 kWh/day)
[D3]	Electricity Bills	12 Dec-11 Apr	863 kWh	3) (Base consumption: 4,16 kWh/day)
[D4]	N/A	N/A	NEGLIGIBLE	NEGLIGIBLE
[D5]	Natural Gas Bills	18 Dec-17Apr	3600 kWh	2) (Base consumption: 6 kWh/day)
[D6]	Electricity Bill	Not enough data available		
[D7]	Natural Gas Bills	15Nov-14Mar	3936 kWh	2) (Base Consumption: 6 kWh/day)
[D8]	Natural Gas Bills	15Nov-14Mar	2145 kWh	2) (Base Consumption: 6.7 kWh/day)
[D9]	Natural Gas Bills	15Nov-14Mar	3990 kWh	2) (Base Consumption: 5 kWh/day)
[D10]	Questionnaires	Whole Winter	20 l kerosene	4)

Table 15. Heating Consumption data collected

	Estimated consump. [kWh]	Heated rooms	m² (heated area)	Consumpt. [kWh/m².year]	Corrected Consumpt. [kWh/m².year]
[D1]	636	Bedroom (x2), Kitchen	33.87	11.93	18.78
[D2]	1354	Whole dwelling	45.68	29.64	29.64
[D3]	356	Living room	10.31	6.91	34.52
[D4]	NA	NA	NA	NA	NA
[D5]	2880	Whole dwelling	47.65	60.44	60.44
[D6]	Not enough data available				
[D7]	3210	Whole dwelling	47.65	67.37	67.37
[D8]	1335	Whole dwelling	68.3	19.55	19.55
[D9]	3385	Whole dwelling	87	87	38.91
[D10]	188	Living room	12.6	3.21	14.92

Table 16. Heating Consumption collected and calculation data

		Winter Period (Dec-Mar)		Spring Period (Apr-May)		Summer Period (Jun-Aug)	
	C *(kJ/ m²K)*	Diurnal Range (8-20h) (Δt_i)	Nocturnal Range (20-8h) (Δt_i)	Diurnal Range (8-20h) (Δt_i)	Nocturnal Range (20-8h) (Δt_i)	Diurnal Range (8-20h) (Δt_i)	Nocturnal Range (20-8h) (Δt_i)
(T_o)		5.53	4.01	4.58	4.02	5.19	4.38
D1	*463.8*	2.14	2.15	1.23	1.33	1.07	0.99
D2	*463.8*	3.18	2.87	2.53	2.49	3.36	3.68
D3	*359.8*	3.11	2.99	1.32	1.39	0.91	0.93
D4	*359.8*	1.19	1.68	1.03	1.46	0.81	1.08
D5	*180.0*	2.64	2.84	1.98	1.85	2.03	1.80
D6	*238.4*	1.16	0.82	0.89	0.89	0.79	0.85
D7	*180.0*	2.98	2.55	1.63	1.33	1.03	0.93
D8	*189.0*	1.79	1.41	1.64	1.12	1.75	1.38
D9	*189.0*	2.18	1.92	1.43	1.58	1.17	1.27
D10	*162.6*	2.02	3.63	1.54	1.56	1.11	1.23
Average of dwellings		2.24	2.29	1.52	1.50	1.40	1.41

Table 17. Ratio of internal to external diurnal and nocturnal temperature fluctuation for the studied dwellings (main room data)

R.H.	Dec 2011 – Sept 2012		Winter	Tempered season	Summer
	Measures up to 30% (%)	**Measures higher than 70% (%)**	Measures higher than 70% (%)	Measures higher than 70% (%)	Measures higher than 70% (%)
D1	**0.02%**	**3.7%**	8.1%	0.14%	0.36%
D2	**0.00%**	**16.2%**	27.5%	12.1%	3.9%
D3	**0.06%**	**0.3%**	0.82%	0.00%	0.1%
D4	**0.00%**	**7.2%**	16.2%	0.19%	0.02%
D5	**0.02%**	**4.9%**	9.2%	3.5%	0.02%
D6	**0.2%**	**32.4%**	63.2%	18.6%	0.81%
D7	**0.00%**	**46.9%**	40.6%	58.8%	47.5%
D8	**0.00%**	**3.0%**	0.85%	1.76%	6.9%
D9	**0.00%**	**0.08%**	0.03%	0.00%	0. 2%
D10	**0.00%**	**7.0%**	10.1%	2.3%	6.0%

Table 18. Summary of logged RH (%) during the whole period and by seasons: Winter (Dec 2011 - Mar 2012), tempered season (Apr-May 2012) and Summer (Jun-Jul-Aug 2012)

	Maximum Temp. (ºC)	Minimum Temp. (ºC)	Average Temp. (ºC)	Range (ºC)	Standard Deviation
Outdoors	25.80	-0.30	10.17	26.10	3.87
D1	24.46	9.73	16.94	14.73	1.85
D2	22.71	10.79	17.56	11.92	1.32
D3	26.13	14.36	19.35	11.77	1.86
D4	21.27	9.21	14.38	12.06	2.26
D5	23.86	12.94	18.79	10.91	1.59
D6	23.69	13.81	17.67	9.88	1.61
D7	22.39	14.27	18.71	8.13	1.25
D8	22.66	11.13	17.70	11.53	1.20
D9	24.22	13.64	20.48	10.58	1.04
D10	23.28	10.52	15.43	12.76	1.68

Table 19. Summary of logged temperatures (ºC) in Winter (Dic-Jan-Feb-Mar)

	Maximum Temp. (ºC)	Minimum Temp. (ºC)	Average Temp. (ºC)	Range (ºC)	Standard Deviation
Outdoors	12.10	-0.30	5.08	12.40	2.54
D1	19.01	9.73	14.38	9.28	1.55
D2	21.10	12.99	16.95	8.11	1.43
D3	25.72	15.51	18.46	10.21	1.99
D4	13.91	9.21	10.57	4.69	0.76
D5	23.16	12.94	18.38	10.22	1.97
D6	17.68	13.81	15.04	3.87	0.84
D7	22.39	14.27	18.86	8.13	1.52
D8	18.60	12.85	16.75	5.76	0.92
D9	24.22	14.96	20.24	9.26	1.01
D10	22.32	10.52	14.81	11.81	1.97

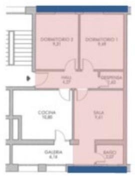
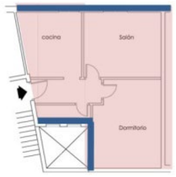
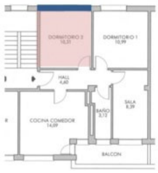
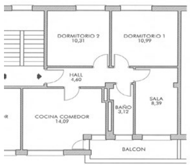
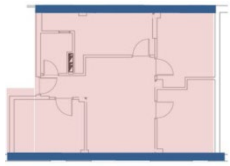
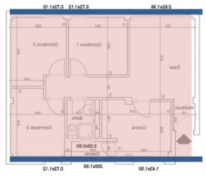
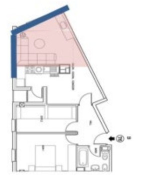
Table 20. Summary of logged temperatures (ºC) in the 15 coldest days (1-14 Feb 2012)

	Maximum Temp. (ºC)	Minimum Temp. (ºC)	Average Temp. (ºC)	Range (ºC)	Standard Deviation
Outdoors	36.90	12.40	20.35	24.50	3.53
D1	28.64	17.80	23.81	10.85	1.60
D2	29.12	16.77	23.87	12.34	1.70
D3	28.15	20.75	24.06	7.40	1.43
D4	29.99	20.25	24.32	9.75	1.86
D5	30.14	19.75	24.54	10.40	1.43
D6	28.72	20.32	24.62	8.40	1.78
D7	26.97	20.15	23.25	6.82	1.31
D8	29.57	18.89	22.99	10.68	1.38
D9	27.85	20.60	24.72	7.25	1.43
D10	26.72	18.46	23.27	8.26	1.42

Table 21. Summary of logged temperatures (ºC) in summer (June-August)

	Winter		Tempered season		Summer	
	Measures below 16 ºC	Measures over 20ºC	Measures below 16 ºC	Measures over 20ºC	Measures below 20 ºC	Measures over 28ºC
OUT	94.67%	1.41%	69.96%	10.43%	52.00%	3.43%
D1	24.6%	5.68 %	11.69%	41.69%	0.20%	0.02%
D2	9.06%	4.94 %	3.13%	39.77%	2.42%	0.17%
D3	0.83%	30.25%	1.15%	49.24%	0.00%	0.00%
D4	81.86%	2.27%	33.15%	29.33%	0.00%	1.36%
D5	0.94%	29.20%	0.00%	52.53%	0.00%	2.33%
D6	12.92%	5.96%	0.14%	46.69%	0.00%	5.07%
D7	1.09%	16.99%	0.31%	26.94%	0.00%	0.00%
D8	5.20%	4.75%	0.92%	30.26%	0.28%	0.03%
D9	0.26%	71.85%	0.00%	76.58%	0.00%	0.00%
D10	65.90%	1.13%	25.41%	18.27%	0.08%	0.00%

Table 22 Summary of logged temperatures in the main room (%) in winter (Dec 2011 - Mar 2012), tempered season (Apr-May 2012) and summer (Jun-Jul-Aug 2012)

Geometrical features of the heated areas				
				
D1	D2	D3	D4	D5
				
D6	D7	D8	D9	D10

	m² façade (of heated area)	EF		m² façade (of heated area)	EF
[D1]	*Apartment Façade:* 32.5 (Façade) 6.5 (Windows; 20%) *Heated Area Façade:* 22.5 (Façade) 4.5 (Windows; 20%)	1.67	[D6]	*Apartment Façade:* 27.9 (Façade) 7 (Windows; 25%)	1.43
[D2]	*Apartment Façade:* 29.75 (Façade) 5.55 (Windows; 20%) *Heated Area Façade:* 29.75 (Façade) 5.55 (Windows; 20%)	1.51	[D7]	*Apartment Façade:* 41.25 (Façade) 10.23 (Windows; 25%) *Heated Area Façade:* 41.25 (Façade) 10.23 (Windows; 25%)	1.16
[D3]	*Apartment Façade:* 35 (Façade) 8.75 (Windows; 25%) *Heated Area Façade:* 7.5 (Façade) 1.95 (Windows; 26%)	1.37	[D8]	*Apartment Façade:* 46.8 (Façade) 11.5 (Windows; 25%) *Heated Area Façade:* 46.8 (Façade) 11.5 (Windows; 25%)	1,71
[D4]	*Apartment Façade:* 35 (Façade) 8.75 (Windows; 25%)	N/A	[D9]	*Apartment Façade:* 42.9 (Façade) 10.7 (Windows; 25%) *Heated Area Façade:* 42.9 (Façade) 10.7 (Windows; 25%)	1.59
[D5]	*Apartment Façade:* 41.25 (Façade) 10.23 (Windows; 25%) *Heated Area Façade:* 41.25 (Façade) 10.23 (Windows; 25%)	1.16	[D10]	*Apartment Façade:* 35.9 (Façade) 7.7 (Windows;21%) *Heated Area Façade:* 14.95 (Façade) 2.72 (Windows; 18%)	0.86

Table A1. Geometrical features of the heating area in each dwelling. (EF: Envelope Factor= m² heated area /m² façade of heated area)