Please cite as:
J. Terés-Zubiaga, C. Escudero, C. García-Gafaro, J.M. Sala. Methodology for evaluating the energy renovation effects on the thermal performance of social housing buildings: Monitoring study and grey box model development. Energy and Buildings 2015, 102, 309-405

ENERGY AND BUILDINGS

https://doi.org/10.1016/j.enbuild.2015.06.010.

Methodology for evaluating the energy renovation effects on the thermal performance of social housing buildings: monitoring study and grey box model development

J. Terés-Zubiaga[(1,)], C. Escudero [(2)], C. García-Gafaro[(3)], J.M. Sala[(2)]*

(1) ENEDI Research Group, Department of Thermal Engineering, University College of Technical Mining and Civil Engineering, University of the Basque Country UPV/EHU, Rafael Moreno "Pitxitxi", 2, Bilbao, Spain

(2) ENEDI Research Group, Department of Thermal Engineering, Faculty of Engineering of Bilbao, University of the Basque Country UPV/EHU, Alda Urquijo S/N, Bilbao, Spain

(3) ENEDI Research Group, Laboratory for the Quality Control in Buildings, Basque Government, C/Agirrelanda N 10, 01013 Vitoria-Gasteiz, Spain

Abstract

Grey box models are a solution for evaluating and quantifying the effect on building thermal performance of different energy saving measures. They are usually used to predict a building thermal performance, and applied to energy systems. This paper presents the application of a grey box model to evaluate the thermal performance of a reference social housing building, focusing on its potential to evaluate the thermal performance of building passive elements (building envelope). A methodology to be used by public administration (to evaluate the effectiveness of a given energy renovation work) is also proposed. Firstly, a monitoring carried out in an empty social housing dwelling during 3 months is presented. Afterwards, a grey box model development is carried out using obtained monitoring data. Model development as well as some general model results are presented and evaluated. Finally, a methodology proposal to be applied by public administration is presented. By monitoring and developing a grey box model of a social housing building, this

[*] Corresponding Author: Jon Terés-Zubiaga. jon.teres@ehu.eus; +34 94 601 77 82

research aims to explore the possibilities of grey box models as a tool to represent in an accurate way the thermal performance of a dwelling, focusing on evaluating building passive elements and their effects on building energy consumption.

KEYWORDS: Experimental data; energy renovations; Building simulations; Thermal performance; Grey Box model; Simplified Methodology; Social housing; Passive Elements; Building Envelope;

1 Introduction

Buildings play an important role in energy consumption all over the world. Nowadays, the built environment uses over 40% of the final energy consumption in the European Union, where a significant part is used for fulfil their thermal demand [1]. For that reason, understanding the thermal performance of a given building is one of the aims of many references found in literature, both by means of monitoring studies such as [2, 3], and/or by model simulations [4-6].

Knowing the thermal performance of a building allows predicting the effect of potential energy renovation measures, and then, identifying the optimal option in terms of energy, comfort or taking into account economical issues. In fact, amongst the main barriers of the penetration of new technologies in the market it can be found the uncertainties related to payback periods. Public administrations also found this problem frequently when they try to evaluate the effect on energy savings of a specific energy saving measure carried out with financial help from them.

Thus, literature shows how building models have been widely used with this aim as a useful tool in the last years, and many kind of models are devoted to analyze thermal performance of a dwelling [7]. Some tools to define that building models are currently widely spread and validated (such as TRNSYS or Energy Plus) [8-14]. However, this kind of models usually requires a significant computational time to perform yearly simulations and they need very detailed data related to the building characteristics.

Other type of simulation is the black box approach. It is commonly used when limited information is known about the building. It implies to define a mathematical function which represents the building thermal behaviour. To do that, measured data (input and outputs) are used to define the model parameters. Mathematical correlations which define the performance are identified based on mentioned measured data, and then, once those correlations have been fixed, model is fed using new input data, in order to obtain the corresponding output data. Many examples of this kind of models applied to different aspects related to energy performance in buildings can be found in literature, such as [15-18].

Finally, grey box models combine both approaches. A simple physical model is used and its parameters are fixed using measured data. Several designs and developments of grey box models applied to building environment (with very different objectives) are available in literature [19-22].

In addition, many researchers have shown differences between the expected and the actual performance of buildings, both in terms of energy consumption and indoor comfort, which are caused by faults in the building envelop and systems, and by the influence of occupants' behaviour in the operation of the building [23]. Faults in the building envelope or systems, which occur often during construction process, are usually not taken into account in simulations, which lead to inaccurate results. The influence of human behaviour is more difficult to predict due to the heterogeneity of the occupant typologies and the interaction between them and the building. As many studies in literature have shown (such as [24] for example), the human behaviour influences significantly the energy performance of the building, and it will be affected not only by indoor comfort, but also by different occupant's features (household incomes, culture, age…) as well as other external factors such as rebound effect [25-27]. For that reason, human behavior and operating conditions are often included in building simulations using standardized profiles.

Then, for a better understanding of differences between expected and real performance of buildings, it is necessary to monitor the building thermal performance. Monitoring can be carried out in occupied or empty building (in order to avoid the user influence), long or short-term monitoring, and it can be focused on energy consumption, the behaviour of the occupants and/or the resulting indoor comfort. A profuse number of papers focused on monitoring studies (with different level of detail) can be easily found in literature. An interesting overview of data collection methods has been recently presented in [23]

Many of the grey box models' developments (related to building environment) found in literature aim in general terms, to optimize the operation of the energy systems, but there are not many papers which using grey box models to assess the thermal performance of the envelope.

However, for all mentioned above, grey box methodology can be a very useful tool in order to quantify the real effect of a specific energy saving measure (global or partial) in a specific building. On the one hand, it has the advantages of the simulations (it makes possible to comparing two different scenarios, before and after retrofitting works, under the same operating conditions). On the other hand, it is necessary to carry out a monitoring in order to define the grey box model, and thus, aforementioned possible faults in envelope or systems will be implicitly taken into account, whereas they would be unnoticed when a typical simulation program is used.

Then, this methodology can be useful in different sectors. In this case, it will be applied in social housing, as a tool to quantify the real effect of energy saving measures carried out with public funding, which allows identify the best energy renovation practices in order to define optimal long term strategies.

At the same time, having a quality data sets obtained in building monitoring is useful to develop, validate and calibrate different kind of models. However, experimental data often are not possible to obtain for different reasons (availability of a case study, availability of required equipment…). Besides, it is hardly found available this kind of data of a representative dwelling or building, so many model developers found an important problem to validate and adjust its model using experimental data, and data obtained by simulation tools (TRNSYS, energy plus...) are usually used. Taking into account these considerations, this paper aims:

- To provide high quality data sets of experimental data gathered in a representative empty dwelling during three months, which can be used as useful tool to validate and/or adjust the building model by means of comparison between monitoring data and calculated data. Moreover, data presented in this paper, may be useful when the objective of a research is to study the effect of a specific energy saving measure (thermal improvement of the envelope, a new heating system…) on a standard building, since this study provides enough data to define a model of the selected building and to validate it, regardless of the kind of model used.
- To explore the grey box models possibilities as a useful tool for tenants and public administrations to assess the real effect of energy saving measures focused on passive elements (although also is applicable to active ones) with two main objectives: identify the optimal solution amongst all the possibilities, or evaluate the real effect of a specific energy saving measure.

To reach these objectives, a reference dwelling was selected as case-study to carry out a monitoring and a grey box model of the selected dwelling was developed using the measured data. Firstly, selection and a detailed description of the dwelling are presented. Secondly, description of the monitoring is shown. Results of the monitoring are presented afterwards, and, the Grey Box Model development and calibration are described. Once the thermal performance is validated, just occupation profiles and operating conditions must be fixed in order to represent in a global way the energy consumption of the dwelling.

2 Case study and Methodology

2.1 Building general description

A social dwelling located in a district of Bilbao was selected for this study. Selection was carried out taking into account a previous classification of the building stock presented in [28]. It is well known the complexity and heterogeneity of the building stock and the consequent difficulty to define a "standard building". However, the chosen dwelling is quite representative in the region of a specific construction period of the 20th century, the 60s. A significant number of today's buildings were built up in that decade, especially in industrial cities.

The studied dwelling is located in a multi-family building built in 1959-1961, in the fourth floor. Some pictures are presented in Figure 1 and the layout of the dwelling is shown in Figure 3. The net floor area is 52.5 m^2 and the floor to ceiling height is 2.47 m. The considered dwelling has 3 external façades, orientated East, West and South, but only two of them (E and W) have windows. The following description of the construction features corresponds to the state of the dwelling when the monitoring period was carried out, in the first months of 2012.

2.2 Building construction features

External walls of the dwelling are composed by two layers of hollow bricks separated by an air gap. The indoor surfaces of walls are plaster over gypsum. The external surface is currently the result of renovation works carried out in 1987, when an addition of other façade layer was executed in the chosen building. The assumed addition of a new layer in façade is depicted in Figure 2. The thickness of thermal insulation is very small, even negligible in some cases. Detailed section of the façade, as well as indoor partitions (both between two rooms and between the dwelling and other dwelling or staircase) is defined in Table 1.

As far as windows are concerned, two different kinds of windows are found in the dwelling, both of them with aluminium frame without thermal break. The window of room 5 (see Figure 3) was a single glazing window whereas the rest of windows were double glazing.

The building was constructed with reinforced concrete structure, like many buildings built up in the region during those years. Horizontal structure is composed by hollow-tiled floors, as usual in that construction period.

2.3 Monitoring study

2.3.1 Measurement equipment

Detailed measurements of indoor and outdoor temperatures were collected using 53 PT100. Surface and air temperature were measured with these sensors. Reflexive tape was used to protect the sensors from direct solar radiation. Surface sensors were fixed using conductive plaster, in order to guarantee a good surface-sensor contact. Four heat flux plates were also used in the study to measure values of the heat flux through façades, floor and ceiling. A meteorological station was installed to measure solar radiation, wind velocity and atmospheric pressure. Data obtained by Euskalmet meteorological station were also taken into account in this study.

The indoor spaces of the monitored dwelling were numbered 1-8 (five rooms, a toilet, a hall and a drying area) as shown in Figure 3. The heat supply in the monitored dwelling during this field study was purely electrical. Five electrical space heaters were placed in room 1-5 (one heater in each room), and each heater was rated at 360 W. Thus, dwelling heating supply was measured by means of monitoring the electrical supply to the heaters. Their heat inputs were measured using a SINEAX M561 single phase power meter.

An Agilent 34980A Data Acquisition and Switching system was used for logging measured values, with 34921A channel armature multiplexer and 34921T terminal block. All sensors were previously calibrated and validated in the LCCE of the Basque Government by means of international patterns, all of them with traceability. Detailed information on instruments characteristics is presented in Table 2.

2.3.2 Data acquisition procedure and data treatment

Monitoring was carried out during three months (February – April, 2012). This way, monitoring guarantees to provide a quality data set of the cold season. The monitoring is carried out during the winter season, because is the season when energy systems (heating systems, in this case) are working. Summer period in this region has a temperate climate, and no cooling systems are used in residential sector, so summer conditions have no influence in the annual thermal energy demand of residential buildings. The dwelling was empty during the monitoring period.

Measurements were taken with 1 minute frequency. Data acquisition system had an integrated filter. Thus, data were passed through this filter to improve the signal quality. Sampling rate should be chosen according to the response time of the studied object. Mentioned 1-min. frequency allowed checking the measurements in detail. After this first checking, data were integrated in 10 minute periods (more suitable frequency for buildings), by calculating the average value of each period. Outdoor conditions were also measured with a 10 minute frequency. This way heating demand, outdoor and indoor conditions were measured simultaneously, guaranteeing the quality of the obtained data. A layout of the dwelling can be seen in Figure 3, where room numbers and sensor positions are also shown. A list of corresponding sensors for the first scenario, classified according these data groups, is detailed in Table 3.

2.3.3 Test-Routine

It must be taken into account that the monitoring does not aim to take measures under operating conditions, but identifying the building thermal response related to different thermal situations. Thus, the resulting model (defined using obtained data) allows calculating accurately the thermal response of the building under the different possible realistic operating conditions. In order to measured aforementioned thermal response, a controlled heat input routine was designed.

The controlled heat input was designed as a combination of a Randomly Ordered Logarithmic distributed Binary Sequence (ROLBS, a high frequency routine, with a 30 min. step) and a Pseudorandom Binary Sequence (PRBS, a low frequency routine, with a 60 minute step). The resulted routine, which has no correlations with the other inputs, was designed to excite the heat dynamic at several ranges of frequencies in which the time constant of the building is expected to be [29]. Thus, it allows uncoupling the different effects which have influence on building thermal performance, such as thermal capacity or thermal resistance. Those time constants varied from 60 minute steps to 12 hour steps. An example of resulted heat input routine for a week is depicted in Figure 4.

2.3.4 Assessment of results

Acquisition system generated a data file daily. Each file (raw data) was firstly treated and measurements given by each sensor were passed by calibration factors. These calibration factors were obtained by the aforementioned calibration procedure. Calibrated results were assessed as follows. First of all, they were studied day-per-day. This procedure allows to identify unexpected behaviour in any sensors, and assessing it in detail or to check if all sensors had been measuring and correctly connected, for instance. Then, they were integrated in ten minute periods, and average values for each element (indoor air temperature, outdoor surface temperature of façade…) were obtained.

2.4 Grey Box Model definition

Obtained experimental data can be used for developing and adjusting different building models. This paper presents the use of these data in a definition of a grey box model, based on a RC Network.

2.4.1 Inputs affecting a node in a building model

Grey box model was designed in an iterative procedure. This procedure started with the most single model and its complexity was progressively increasing untill achieving a good model adjustment. Thus, the final model was represented with the RC-network depicted in Figure 5, as well as a representation of the different branches. As shown in the figure, the model was divided in different branches which represent different energy fluxes: energy flux through structure (the upper branch), through the windows (the middle one), through the façade and from heating system. All thermal nodes considered in the model are presented in Table 4. All parameters identified during the learning process are presented in Table 5. Also the influence of solar radiation was considered in the model (A_iG_h and A_eG_h).

2.4.1.1 Solar irradiation. Effective area

Solar irradiation has a strong influence on the thermal performance of the dwelling, both incident solar irradiation that passes through a window and the mentioned incident solar irradiation on the outdoor surfaces of opaque walls. Solar gains are easily accessible in building energy simulation tools such as TRNSYS, but difficult to obtain in a real building. Different methodologies can be found in literature in order to include direct and global solar radiation in this kind of models [22, 30].

In this paper, a simplified method has been used based on the effective area, both for windows and walls. The introduced mathematical correlation aims to calculate the solar radiation effects in the building, taken into account implicitly the geometric features of the building, solar masks, and cloud cover data.

The effective window area (A_{w-e}) is a parameter which considers an average surface exposed factor (f), G-value of the windows (g) and the real area of the window (A_w). Then, A_{w-e} is obtained by multiplying those three values, f, g and Aw. Thus, the solar flux that passes through windows is calculated as shown in Eq. 1.

$$\phi_s = A_{w-e} \cdot G_h = f \cdot g \cdot A_w \cdot G_h \qquad \text{Eq. 1}$$

Where G_h is the horizontal beam radiation [w/m^2].

Likewise, the effective façade area (A_{f-e}) is a value which considers a surface exposed factor (f), and the real area of the façade (A_f). The inclusion of this term in the governing equations of the developed model is presented in the following (indoor air model and opaque walls model).

2.4.1.2 Infiltration and ventilation

Infiltration losses are neglected. A tracer gas test was carried out in the dwelling, and obtained values were lower than 0.5 ACH. In fact, these losses are actually included in the uncertainty component of the model. As far as ventilation losses are concerned, no ventilation happened in the dwelling during the monitoring period. Therefore, it was not represented in the dwelling scheme. However, since ventilation may involve important heat losses in a dwelling during its usage, it will be considered in the model afterwards, as defined later.

2.4.2 Model coupling

Therefore, heat transfer in the dwelling is described by means of a lumped parameter model, formulated by a deterministic type, linear time state - space model. Non described effects by mentioned deterministic model are added as a noise, obtaining thus a stochastic model. The mathematical correlations of this kind of model are described in detail in [29, 31].

Thus, the coupling of the different elements of the model is presented in Figure 5. The indoor environment was represented by an indoor air temperature T_{in} and a heat capacity of the indoor air mass C_{in}. This node is also affected by solar gains through semi-transparent elements. It was obtained by taking horizontal global radiation (G_h) weighted with the effective window area factor, as previously mentioned.

Connection with the outdoor environment is through thermal resistances and temperature – capacity nodes. Two different kinds of thermal resistances are presented: those which represent combined heat exchange (R_{str-in}, R_{str2}, R_{w1}, R_{w2}, R_{e-in} and R_{e-out}); and those which are purely conductive resistance, such as R_{est1}, R_{e2} and R_{e3}. C_{str} represents the heat capacity of the structure, whilst C_e quantifies the envelope heat capacity.

Solar gains on the envelope outdoor surface were also taken into account, in a similar way to solar gains of the indoor air node through semi-transparent elements. No heat capacity was assumed in windows. Heat input from the heaters was not directly included on the indoor air node, but as a small branch which included its thermal resistance and heat capacity.

In short, the model took into account thermal capacity of the dwelling and thermal resistance of the envelope. The envelope was divided into the windows component (with the solar gains related to them) and opaque walls component. The influence of the structure on thermal behaviour (heat capacity and thermal bridges) was therefore also considered in the model (upper branch).

2.4.2.1 Identification process of parameters

As previously mentioned, the developed model is a grey box model in which the physical part is a stochastic linear state-space model where the dynamics of the states can be written as shown in Eq. 2.

$$\begin{aligned} \{dT\} &= [A]\{T\}dt + [B]\{U\}dt \\ \{Y\} &= [C]\{T\} + [D]\{U\} \end{aligned} \qquad \text{Eq. 2}$$

Where [A] is the matrix which contains thermal properties of the model; {T} is a state vector formed by the temperature at each node; [B] is the matrix which defines the way that excitements affect the model; {U} is the entry vector, formed by excitement variables, such as air temperatures, solar irradiation, etc; {Y} is the measurement vector, formed by registered data, such as measured temperatures and heat fluxes; [C] is the matrix which connects measured variables with state variables; and finally [D], the matrix which connects measured variables with entry variables. More detailed information about this procedure can be found in [29].

Then, the full model includes five state variables, that each represents the temperature in an element of the building: Temperature of the heater (T_h), Temperature of the indoor air (T_{in}), Temperature of indoor surface of façade (T_{e-in}), Temperature of outdoor surface of façade (T_{e-out}), Temperature of windows (T_w) and Temperature of indoor surface of structure (T_{str-in}). Similarly, the parameters of the model represent different thermal properties of the building. This point includes thermal resistances and heat capacitances, which are presented in Table 5.

Finally effective areas in which the energy from solar radiation enters the building are included by means of aforementioned effective area of façade and windows. The set of differential equations describing the heat flows in the full model are:

$$dT_{in} = \frac{1}{C_{in}} A_{in} G_h dt + \frac{1}{C_{in}(R_{e-in} + R_{e2})}(T_e - T_{in})dt + \frac{1}{C_{in}(R_{w-in} + R_{w-out})}(T_{out} - T_{in})dt + \frac{1}{C_{in}(R_{str-in} + R_{str2})}(T_{str} - T_{in})dt + \frac{1}{C_{in} \cdot R_h}(T_h - T_{in})dt + \sigma_{in} d\omega_{in} \quad \text{Eq. 3}$$

$$dT_e = \frac{1}{C_e(R_{e-in} + R_{e2})}(T_{in} - T_e)dt + \frac{1}{C_e(R_{e-out} + R_{e3})}(T_{out} + A_e G_h R_{e-out} - T_e)dt + \sigma_e d\omega_e \quad \text{Eq. 4}$$

$$dT_{str} = \frac{1}{C_{str}(R_{str-in} + R_{str1})}(T_{in} - T_{str})dt + \frac{1}{C_{str} R_{str2}}(T_{out} - T_{str})dt + \sigma_{str} d\omega_{str} \quad \text{Eq. 5}$$

$$dT_h = \frac{1}{C_h} P dt + \frac{1}{C_h R_h}(T_{in} - T_h)dt + \sigma_h d\omega_h \quad \text{Eq. 6}$$

And the measurement equation is:

$$T_{i,k}^m = T_{i,k} + e_k \quad \text{Eq. 7}$$

The parameters presented in Table 5 were initialized with geometrical observations and using as reference Spanish thermal standards. The model was calculated by means of the software CTSM. It is a computer program for performing Continuous Time Stochastic Modelling. The program was developed at Informatics and Mathematical Modelling (IMM) at the Technical University of Denmark (DTU) [32]. The software package LORD, which was developed during the PASLINK projects, can also be used with the same aim. It allows the modelling and identification of thermal systems, in particular building components [33].

3 Experimental data

Results obtained by monitoring are briefly presented in this section. Due to the amount of data obtained, results of a reference day are presented as an example. Firstly, results of each sensor are presented. Secondly, average results of that typical day are presented, as well as the plot of the average values of the selected period (1st-21st of February).

3.1 Results per sensor

Daily results were assessed, gathering them by systems and subsystems (Opaque walls, single glazing window, double glazing window, indoor walls…). As Guerra-Santin and Tweed mentioned in [23], this kind of long term measurements can say a lot about the performance of the building, and visual examination of the measurements can give the researcher a good idea of temperature problems in the building, such as rooms that are too cold or too warm). In this study, for example, results showed that one of the bedrooms (room 1) presented a low temperature in comparison with the others, which suggested that there were significant heat losses in there.

3.1.1 Indoor air temperature

Indoor air temperature was measured in the centre of the room, in every location where the occupant spends most of their time, according to ASHRAE Standard 55 [34]. Thus, measured temperatures in each room, as well as average temperature and ΔT (difference between maximum and minimum temperature) are depicted in Figure 6.

3.1.2 Temperature of envelope indoor surface

Daily data sets belonging to temperatures of envelope indoor surface are depicted in Figure 7. All measured indoor surfaces performed in a similar way. In this case, differences amongst measured temperatures were about 0.5 ºC.

3.1.3 Temperature of envelope outdoor surface

Temperature of the envelope outdoor surface was measured in two different points: one sensor was located in the western façade (T_e12) and the other one in the eastern façade (T_e42). Data obtained from the sensors placed on the outdoor surface of the façade are graphed in Figure 8. The inclusion of plots related to outdoor temperature and solar irradiation (dotted lines, blue and yellow respectively) has been considered interesting, since envelope outdoor surface is obviously the element more affected by climate conditions. The influence of radiative heat exchange between the outdoor surface of façade and sky, and the effects of solar irradiation over façade are clearly identified when these data is analyzing.

3.1.4 Temperature of floor and ceiling surface

In this case, temperatures measured in room 1 showed also in this case values significantly lower than the others. Average values of ΔT for the other rooms graphed in figures in red line (data set corresponding to room 1 has not been taken into account), were 0.4 ºC in the case of floor surfaces, and 0.6 ºC in the case of ceiling surfaces. As also expected, ceiling surface is more sensible than floor surface to heat input variations, and, in general, to indoor air temperatures.

3.1.5 Temperature of pillars

Two different behaviours were observed amongst measured temperature in pillars. On the one hand, pillars which are in the middle of the dwelling (T_p41 and T_p7) presented the highest surface temperatures. On the other hand, all the pillars placed in façade (T_p1, T_p3 and T_p8) showed measurements lower than the average values. However, while T_p41 and T_p7 did not show great differences and measurements of both pillars were quite similar, measurements obtained from T_p1, T_p3 and T_p8 displayed significant differences. In the case of T_p8, this disparity can be explained because the pillar is placed in a non-heated room. T_p1 measurements should be similar to T_p3, since they both are in the same orientation, and in a heated room. In a similar way to other temperatures measured in room 1 (as shown before), data obtained from this room were about 0.5 ºC lower than those obtained in room 3, which, presumably had similar conditions.

3.1.6 Temperature of indoor partitions

Surface temperature measurements of indoor partitions for the 1st of February are depicted in Figure 9. If temperatures corresponding to sensors placed in room 1 (T_m11 and T_m12) and room 6 (T_m61 and T_m62) are not taken into account, ΔT (depicted in Figure 9 in red line) presented an average value for that day of 0.7 ºC.

Interesting information can be obtained when focusing on data sets whose performance differs from the rest, i.e. T_m11, T_m12, T_m61 and T_m62. In relation to data collected in room 6, low temperatures registered in T_m61 and T_m62 can be explained mainly since this room has no heat input.

Regarding to data logged in room 1, temperatures measured in this room were lower than the rest of the heated room. Analyzing in detail these values, one can come to the conclusion that these low values were not a consequence of the low temperatures of the room, but they were the cause itself of the low temperature in room 1. It was observed that the lowest indoor partition temperatures were logged in T_m11 (this is the wall that separates the dwelling with the contiguous one) and temperature values obtained from T_m12 (this wall separates the dwelling and the staircase) were especially low. These low temperatures may suggest that there were important heat losses through these walls to contiguous dwelling and, mainly, to staircase. In the first case, a limited use of the heating system (if there were) in the contiguous dwelling can explain the losses through T_m11. Losses through T_m12 are the most significant, as it can be concluded when at Figure 9 is observed.

This hypothesis is also reinforced by the fact that the higher differences between heated rooms' temperatures are registered when the heater is switched on, i.e. the higher ΔT was (between room 1 and contiguous dwelling or staircase), the higher heat flux was, and then, the higher heat losses were. That's to say, explained in a simplified way, when two similar rooms have the same heat input, temperature differences between them will be closely linked with the differences on heat outputs, i.e. heat losses.

3.1.7 Windows temperatures

Five sensors were placed to obtain the temperatures related to windows, as presented in Figure 10. Two different types of windows were evaluated, single glazing window, and one double glazing window (in room 2). Temperatures in glazing area and frames were logged. In the case of the double glazing window, temperatures were measured both in the indoor and outdoor surface of the glass, whereas in the single glazing window only indoor surface temperature was logged. Sensors' nomenclature is presented in Table 6.

Being both types of windows low thermal quality windows, significant differences were appreciated between single and double glazing (differences of more than 2 ºC were found when indoor surface temperatures were compared).

3.2 Average data per day

After analyzing the different elements separately, average values were obtained, with the aim of having a representative value for each one. Previously, ΔT (between maximum and minimum logged values in each moment) for each element had been studied in order to ensure the representation of every sensor, and 1 min. frequency data had been integrated in a 10 min. frequency data set. Average indoor air temperature was calculated using measurements obtained with the eight sensors (T_a1-T_a8). Data set of each sensor was weighted using the room area where each sensor was located, as Eq. 8 shows.

$$\overline{T_a} = \frac{\sum T_i \times A_i}{\sum A_i} \quad \text{Eq. 8}$$

Where T_a is the weighted average indoor air temperature; T_i is the indoor air temperature logged by each sensor; and A_i is the area of each room. This way, calculated values are more representatives, because the problem found when the room area was not taken into account was that the two small rooms without heating (drying area and bathroom) caused an average temperature lower than actually was. The rest of average values ($T_{f,in}$, $T_{f.out}$, T_w, T_{str}, T_{fs}, T_{fi} and T_p) were obtained using the measurements logged by the sensors pointed out in Table 7.

Taken into account the assumptions exposed above, average values for each day were calculated. As a way of example, average values for the same day (1st of February 2012) are presented in Figure 11. Looking at the graph, some points should be remarked. First of all, the "heat chain" is clearly shown in the figure. Heat flows from the hottest point (heater resistance) to the coldest point (outdoor environment).

Thermal inertia of each element is shown as well in the graph. It can be seen that, when heater is switched on, indoor air temperature presents a fast response, whereas indoor surface of façade, or especially structure temperature (T_{est}) are much more stable.

Influence of heater or outdoor environment on each element can also be explained with this graph. Indoor air temperature and indoor surfaces are, obviously, more sensible to heater influence, especially when it is not a sunny day. Two different performances were shown by windows, depending on their glazing area. Single glazing windows (T_v2, in the graph) presented, in the main, glazing area temperatures about two degrees below the double glazing windows (T_v1).

3.3 Learning data for parameters identification procedure

Once daily data sets were obtained, they were gathered into periods of three weeks data sets. Thus, data sets corresponding to the first three weeks of monitoring (1st-21st February 2012) are presented in Figure 12. These data were used for grey box identification and validation.

4 RC model results

How monitoring data allowed detecting some performances that in other way they would have gone unnoticed has been presented in section 3.1. However, it must be highlighted the fact that the grey box model does not make differences on that information, but that information, as well as infiltration or possible thermal bridges, are added in the sum of the components. That is, even though apparently, some effects which affect the thermal performance of the dwelling are missing, they are implicitly included in the different parameters of the model.

4.1 Characteristic parameters

Following the procedure previously presented, the RC model of the dwelling was developed. To do that, firstly, the parameter identification ($f_{(x)}$) was carried out using measured data (*x, y*). Different data periods for identification process can be found in literature, from 4 days [35] to 60 days [36]. As mentioned before, in this case, data corresponding to the period 1st-21st, February (21 days, depicted in Figure 12) was used as learning data for identification process.

This way, characteristic parameters of the model (thermal capacitances and resistances) were obtained. Secondly, once inputs (*x)* and characteristic parameters ($f_{(x)}$) had been known, direct use of the model was made to verify the model first checking the model represented the real thermal performance of the dwelling by comparing the calculated results to measured data. Finally, the model was used to make simulations under different given conditions (*x'*) obtaining the sought results (*y'*). The data series presented in Table 8 were used.

Wind velocity was measured as well. However, due to the low values logged during the monitoring period, it was not considered as a significant parameter. Characteristic parameters ($f_{(x)}$) obtained for the model are presented in Table 9. $R_{str,1}$ and $H_{str,2}$, as well as H_e2 and H_e3 are presented together, since actually, both values are calculated separately for methodology reasons (to include between them the capacity; those values separately are just the best adjustment of the model, based on statistical procedures), but the sum of them is representative of the R value of the structure and the opaque walls respectively (assuming that other "hidden effects" of the building can be also included in this value).

Some general considerations can be stated taking into account the values presented in Table 9. First of all, values of the thermal transmittance of the envelope (H), both for windows and opaque walls. If the value of each element is multiplied by the element area, an average value of the transmittance [$W/m^2.K$]. In fact, this is the important information which the model provides, since these values can be useful as reference to feed other models later (for instance, to adjust a more detailed TRNSYS model). The scope of these values will be closely linked to the detail level defined in the grey box model. Similarly, C values give information about the thermal inertia of the building. That is, these values show the response time of the dwelling or building to the variations of outdoor conditions.

Finally, A1 and A2 values (effective area) provide information of the dwelling gains related to solar radiation, both through opaque walls and windows, assessing the ratio between that value and the real area of the element (opaque wall, windows or roof if there were). In short, the higher effective area, the higher solar gains the dwelling has.

4.2 Model validation

A model validation, by means of a comparison between calculated values of the model and those obtained in the experimental observation was carried out. A graph with both sets of data, as well as the residuals is depicted in Figure 13. As observed in a first sight, obtained residuals were very low values and around zero.

The autocorrelation function (ACF) and integrated periodogram of the residuals were assessed to verify that residuals presented a random pattern related to white noise of measuring instrumentation. Thus, the analysis of ACF of residuals of indoor air temperature is depicted in Figure 14. It was evaluated at a maximum lapse of 50 h. Analysis showed that coefficients took low values, close to zero, alternately, without a defined pattern. This performance means the dwelling thermal performance is correctly represented by the model.

Similar conclusions were obtained when the integrated periodogram of residuals (shown in Figure 15) was checked. In this analysis, an ideal time serial purely at random would present cumulative relative amplitudes for each frequency which would draw a diagonal straight line. The Kolmogorov-Smirnov test (K-S test) was used to determinate if both data sets differed significantly. Confidence intervals for 95% and 99% certainties are presented in the aforementioned mentioned graph in red line (inside and outside, respectively). Since obtained periodogram was amongst the confidence intervals, it can be assumed that those correlations were low and therefore they could be neglected.

4.3 Model results

One of the most interesting points of using this model, is the fact that the building can be simulated changing the conditions existing during the monitoring period, using other weather conditions for example, or fixing some operating conditions in the setpoint comfort temperature.

Heating consumption of the dwelling during the winter period (November-March) was obtained using the developed RC model. Weather conditions of Bilbao, were assumed for the simulation. The required weather data (Outdoor temperature and G_h) were obtained from Meteonorm data base, which represent a typical meteorological year. Thus, heating consumption during the winter period was calculated as 3098 kWh, which represents around 60 kWh/m^2 during those five months. Obtained monthly results for those months are depicted in Figure 16.

5 Discussion and final considerations

5.1 Pros and cons of RC Models

The methodology developed in this paper is devoted to evaluate the thermal performance of existing buildings, based on measured data, and comparing different scenarios (before and after renovation works, for example) under the same conditions.

Then, this paper allows identify the main pros and cons of RC models (comparing them to white models). The main identified advantages are the lower amount of data required and the fact that uncertainties of data are more controlled. On the other hand, its main drawback comparing to white models is its lower flexibility to change building features, building heating systems and the aspects related to solar gains (blinds, shadows...).

Taking into account mentioned pros and cons, it was observed that RC models can be a very useful tool to owners, investors and public administration to quantify and evaluate the real effect of a given energy saving measure on a specific residential building (both in partial and global energy renovations): It can be adapted to residential building features, required monitoring period to obtained learning data for parameter identification process is no longer than a month, and the methodology takes into account the possible faults in building envelope or energy systems (which are found quite often in this kind of buildings) whereas at the same time, allows to difference the human behaviour effects, which can be included in the model afterwards. These effects can be then included both by considering indoor gains according to a given occupation profile and by assuming different setpoint temperatures. This last point is a key factor when thermal performance of social housing buildings is assessed: due to user profile the influence of the rebound effect is more significant, and moreover, many of them are usually rented, so it is usual that the user of the building before renovation is not the same that the user which will live in the dwelling after renovation process.

5.2 Improvements, methodology proposal and suggested application

Finally, for all the mentioned above, an application methodology is proposed in this section. The main motivation of it is the necessity of a local public administration of assessing and quantifying the effectiveness of the energy saving measures developed using public funding. For that reason, this section is focused on the application of mentioned methodology on social housing sector.

First of all, it must be highlighted that the study shows that monitoring can be carried out using a lower amount of sensors. For that reason, is proposed to use 2 sensors per dwelling to measure indoor air temperature (in two significant rooms), 4 sensors to measure temperature of opaque envelope (2 in the indoor surface, and 2 in the outdoor surface), 2 sensors in windows, 2 temperature sensors related to heating system, 4-6 sensors to monitoring surface temperatures of the structure, and the required equipment to measure the outdoor conditions (solar irradiation and temperature, mainly).

Regarding to monitoring period, as shown in this paper, a 21 day-period is enough to obtain the learning data required to define an RC model which predicts accurately the thermal performance of the dwelling.

Then, taken into account the mentioned consideration, a methodology proposal is suggested and presented in Figure 17. As shown, two short monitoring periods (21 days) are proposed, before and after renovation works. Obtained data in those monitoring are used in the parameter identification procedure, and then, parameters of the model corresponding to thermal performance of the building or dwelling before and after renovation works are obtained. Both RC models are fed with the same operating conditions in order to compare the thermal performance of the building under the same conditions. That comparison allows evaluating the real effect of the carried out energy renovation quantitatively.

6 Conclusions

This paper has provided high quality data sets of experimental data obtained by means of a detailed monitoring study carried out in a representative empty dwelling during three months. Moreover, a RC model development using measured data has been also presented in this paper, and showing that this kind of models can be a very useful tool to represent in an accurate way the thermal performance of a dwelling. The study has confirmed that the RC model represents with high accuracy the thermal performance of the studied dwelling, as the validation procedure has shown. It must be also highlighted that the strongest point of this kind of models is the fact that it gives information of the building as actually is and performs, taking into account all the interactions and all specific details of the construction, not only based on data “as projected” but on real project data.

A methodology has been proposed to be applied to quantify the real effects of energy saving measures carried out with public funding, which can be easily adapted to requirements and constraints of social housing and public administration. It allows defining a mechanical procedure for parameter identification and its applicability covers all the range of the energy renovation possibilities carried out by public administration in social housing, from partial energy renovation of building envelope or energy systems, to global building energy renovations.

Building values related to its thermal performance (H and C) are usually defined in other tools (like TRNSYS or Energy Plus, to name but a few) based on literature. But in some cases, especially in those buildings where information about façade construction or renovation works is not very accurately (this situation is usual in building renovations), the differences between the theoretical values based on literature and the real ones can be quite significant, reducing then the accuracy of the obtained results. This problem is avoided using the methodology presented in this paper.

7 Acknowledgements

Special thanks to Bilbao Social Housing of Bilbao City Council for allowing us to undertake the measurements of this research in one of its dwellings, and for its collaboration. Many thanks also to the Laboratory for the Quality Control in Buildings (LCCE) of the Basque Government.

8 References

[1] Eurostat, Statistics Database - Energy statistics - Supply, transformation, consumption (2010).

[2] O. Guerra-Santin, C. Tweed, H. Jenkins, S. Jiang, Monitoring the performance of low energy dwellings: Two UK case studies, Energy Build. 64 (2013) 32-40.

[3] R. Cantin, J. Burgholzer, G. Guarracino, B. Moujalled, S. Tamelikecht, B.G. Royet, Field assessment of thermal behaviour of historical dwellings in France, Build. Environ. 45 (2010) 473-484.

[4] F. Stazi, A. Vegliò, C. Di Perna, P. Munafò, Experimental comparison between 3 different traditional wall constructions and dynamic simulations to identify optimal thermal insulation strategies, Energy Build. 60 (2013) 429-441.

[5] S. Heiple, D.J. Sailor, Using building energy simulation and geospatial modeling techniques to determine high resolution building sector energy consumption profiles, Energy Build. 40 (2008) 1426-1436.

[6] J. Terés-Zubiaga, A. Campos-Celador, I. González-Pino, C. Escudero-Revilla, Energy and economic assessment of the envelope retrofitting in residential buildings in Northern Spain, Energy Build. 86 (2015) 194-202.

[7] D.B. Crawley, J.W. Hand, M. Kummert, B.T. Griffith, Contrasting the capabilities of building energy performance simulation programs, Build. Environ. 43 (2008) 661-673.

[8] L.T. Terziotti, M.L. Sweet, J.T. McLeskey Jr., Modeling seasonal solar thermal energy storage in a large urban residential building using TRNSYS 16, Energy Build. 45 (2012) 28-31.

[9] C. Buratti, E. Moretti, E. Belloni, F. Cotana, Unsteady simulation of energy performance and thermal comfort in non-residential buildings, Build. Environ. 59 (2013) 482-491.

[10] N. Aste, A. Angelotti, M. Buzzetti, The influence of the external walls thermal inertia on the energy performance of well insulated buildings, Energy Build. 41 (2009) 1181-1187.

[11] I. Ballarini, V. Corrado, Analysis of the building energy balance to investigate the effect of thermal insulation in summer conditions, Energy Build. 52 (2012) 168-180.

[12] I. González-Pino, A. Campos-Celador, E. Pérez-Iribarren, J. Terés-Zubiaga, J.M. Sala, Parametric study of the operational and economic feasibility of Stirling micro-cogeneration devices in Spain, Appl. Therm. Eng.

[13] Á Campos-Celador, E. Pérez-Iribarren, J.M. Sala, L.A. del Portillo-Valdés, Thermoeconomic analysis of a micro-CHP installation in a tertiary sector building through dynamic simulation, Energy (2012).

[14] I. González-Pino, E. Pérez-Iribarren, A. Campos-Celador, J. Las-Heras-Casas, J.M. Sala, Influence of the regulation framework on the feasibility of a Stirling engine-based residential micro-CHP installation, Energy. (in press; DOI information: 10.1016/j.energy.2015.03.030) (2015).

[15] A. Afram, F. Janabi-Sharifi, Black-box modeling of residential HVAC system and comparison of grey-box and black-box modeling methods, Energy Build.

[16] M. Killian, B. Mayer, M. Kozek, Effective Fuzzy Black-Box Modeling for Building Heating Dynamics, Energy Build.

[17] V. Logar, Ž Kristl, I. Škrjanc, Using a fuzzy black-box model to estimate the indoor illuminance in buildings, Energy Build. 70 (2014) 343-351.

[18] J. Ruschenburg, T. Ćutić, S. Herkel, Validation of a black-box heat pump simulation model by means of field test results from five installations, Energy Build. 84 (2014) 506-515.

[19] S.F. Fux, A. Ashouri, M.J. Benz, L. Guzzella, EKF based self-adaptive thermal model for a passive house, Energy Build. 68, Part C (2014) 811-817.

[20] G. Reynders, J. Diriken, D. Saelens, Quality of grey-box models and identified parameters as function of the accuracy of input and observation signals, Energy Build. 82 (2014) 263-274.

[21] D.A. Coley, S. Schukat, Low-energy design: combining computer-based optimisation and human judgement, Build. Environ. 37 (2002) 1241-1247.

[22] T. Berthou, P. Stabat, R. Salvazet, D. Marchio, Development and validation of a gray box model to predict thermal behavior of occupied office buildings, Energy Build. 74 (2014) 91-100.

[23] O. Guerra-Santin, C.A. Tweed, In-use monitoring of buildings: An overview of data collection methods, Energy Build. 93 (2015) 189-207.

[24] M. Eguaras-Martínez, M. Vidaurre-Arbizu, C. Martín-Gómez, Simulation and evaluation of Building Information Modeling in a real pilot site, Appl. Energy. 114 (2014) 475-484.

[25] P.H.G. Berkhout, J.C. Muskens, J. W. Velthuijsen, Defining the rebound effect, Energy Policy. 28 (2000) 425-432.

[26] L. A. Greening, D.L. Greene, C. Difiglio, Energy efficiency and consumption — the rebound effect — a survey, Energy Policy. 28 (2000) 389-401.

[27] F. Jaume, Methods to empirically estimate direct and indirect rebound effect of energy-saving technological changes in households, Ecol. Model. 223 (2011) 32-40.

[28] J. Terés-Zubiaga, K. Martín, A. Erkoreka, J.M. Sala, Field assessment of thermal behaviour of social housing apartments in Bilbao, Northern Spain, Energy Build. 67 (2013) 118-135.

[29] P. Bacher, H. Madsen, Identifying suitable models for the heat dynamics of buildings, Energy Build. 43 (2011) 1511-1522.

[30] F. Kasten, G. Czeplak, Solar and terrestrial radiation dependent on the amount and type of cloud, Solar Energy. 24 (1980) 177-189.

[31] J. Bloem, System identification applied to building performance data. (1994).

[32] N.R. Kristensen, H. Madsen, Continuos time stochastic modelling CTSM 2.3 - user's guide., 2003.

[33] O. Gutschker, Parameter identification with the software package LORD, Build. Environ. 43 (2008) 163-169.

[34] ASHRAE, Thermal environment conditions for human occupancy, in: ASHRAE Standard 55, Atlanta, 2007.

[35] H. Madsen, J. Holst, Estimation of continuous-time models for the heat dynamics of a building, Energy Build. 22 (1995) 67-79.

[36] I. Hazyuk, C. Ghiaus, D. Penhouet, Optimal temperature control of intermittently heated buildings using Model Predictive Control: Part I – Building modeling, Build. Environ. 51 (2012) 379-387.

Figures

Figure 1. General view of the building where the case study dwelling is located

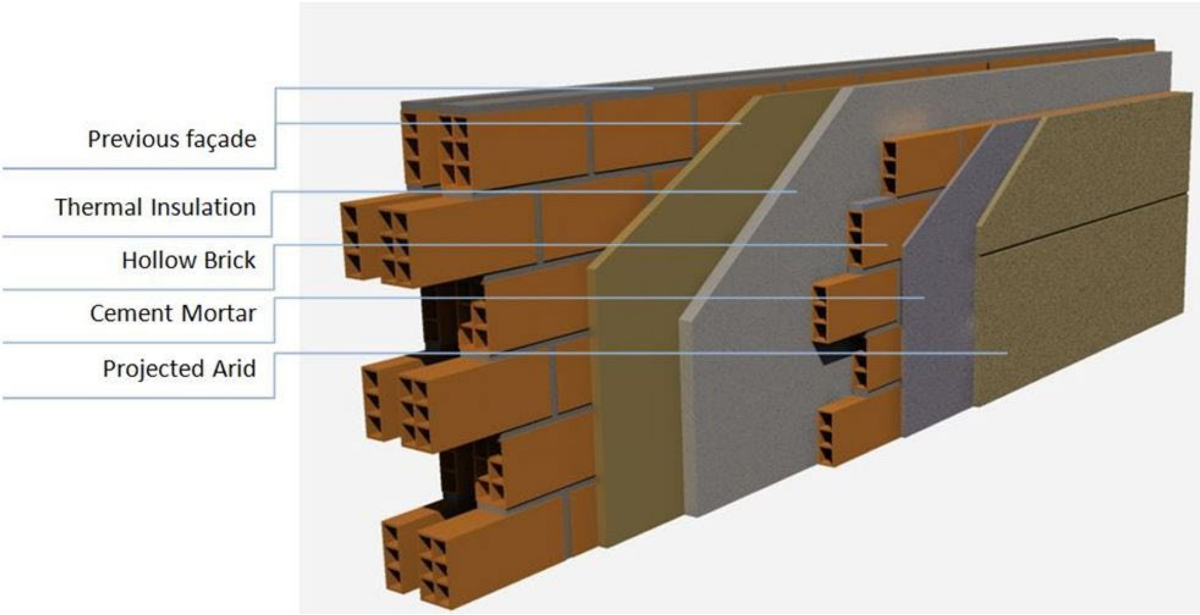

Figure 2. Façade constructive section (according to Bilbao Social Housing renovation in 1989)

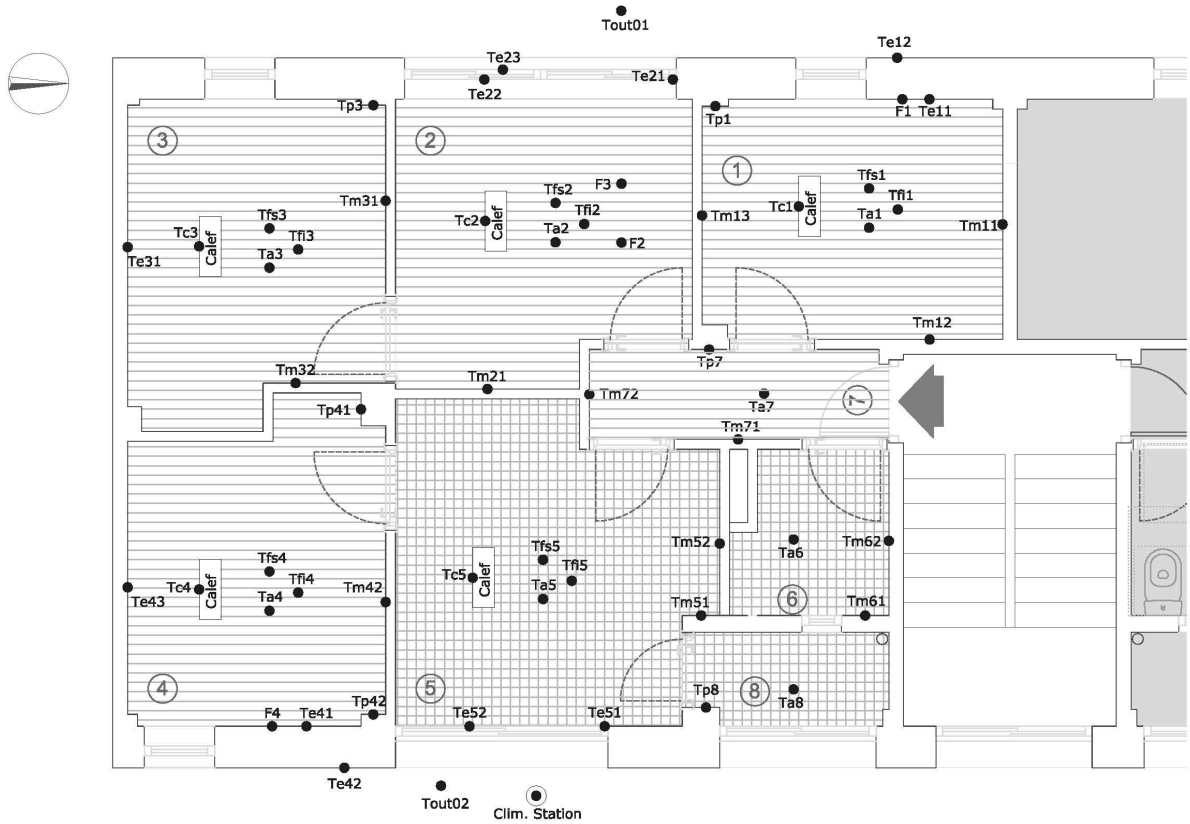

Figure 3. Layout of the studied dwelling before retrofitting works

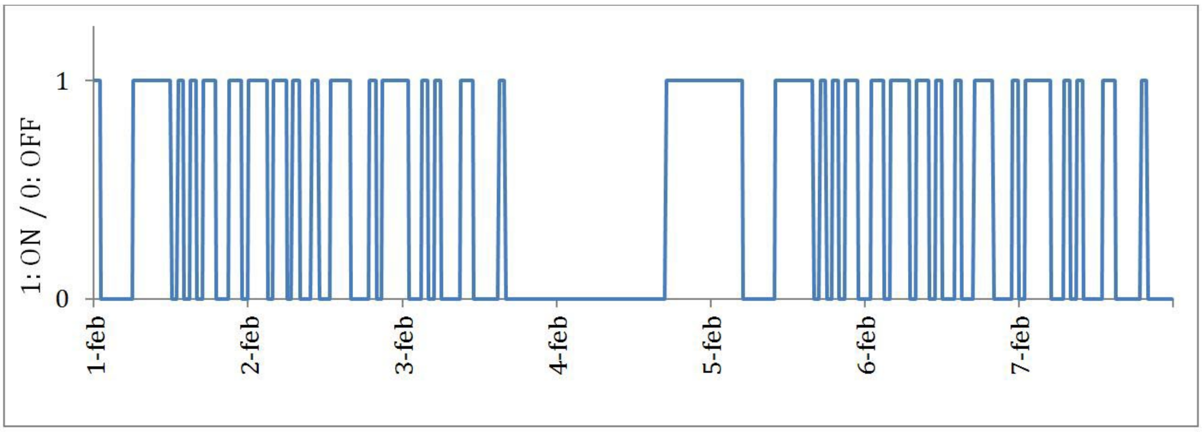

Figure 4. Heat input control signal in the dwelling from 1st-7th of February

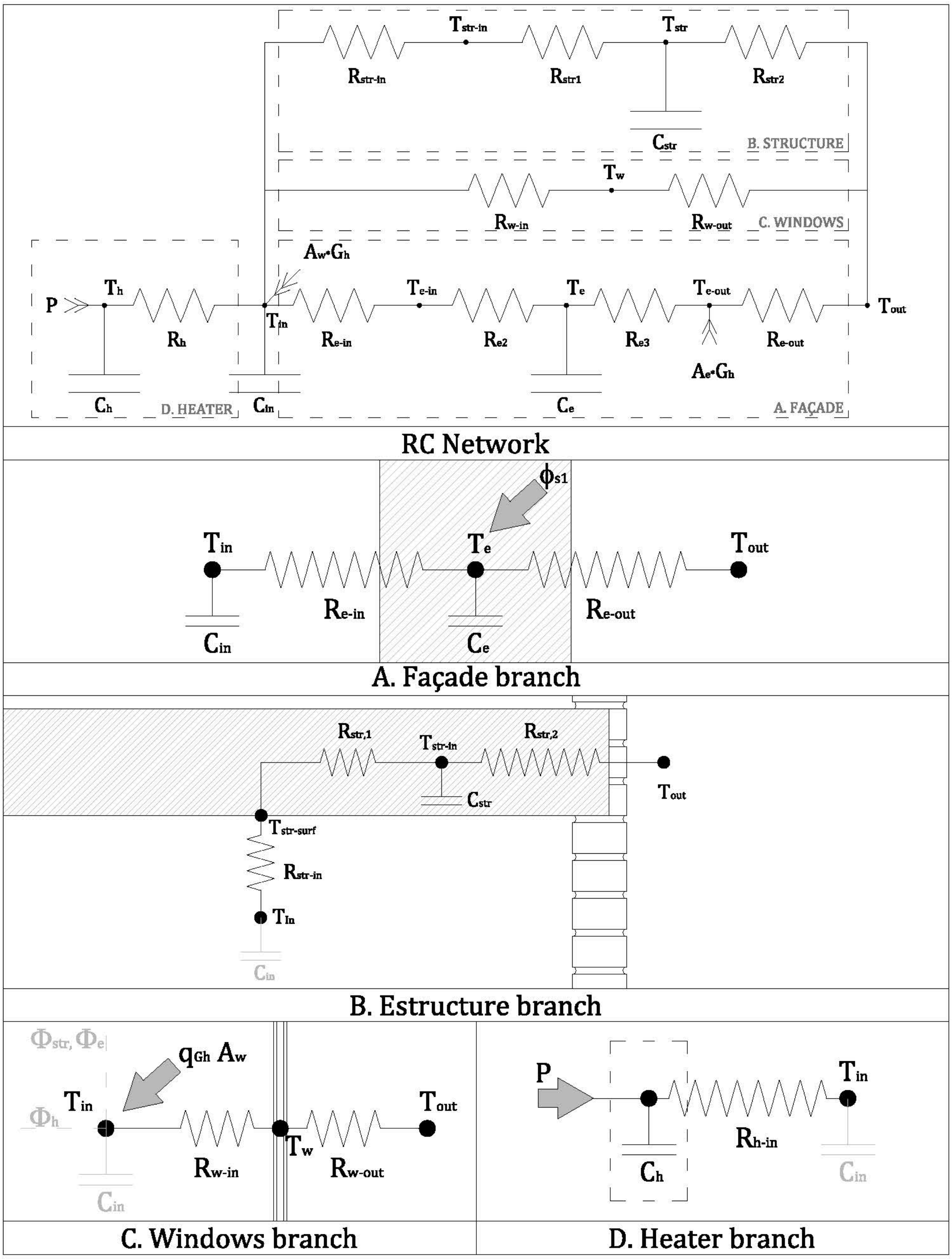

Figure 5. RC network of the selected model, with the different branches highlighted

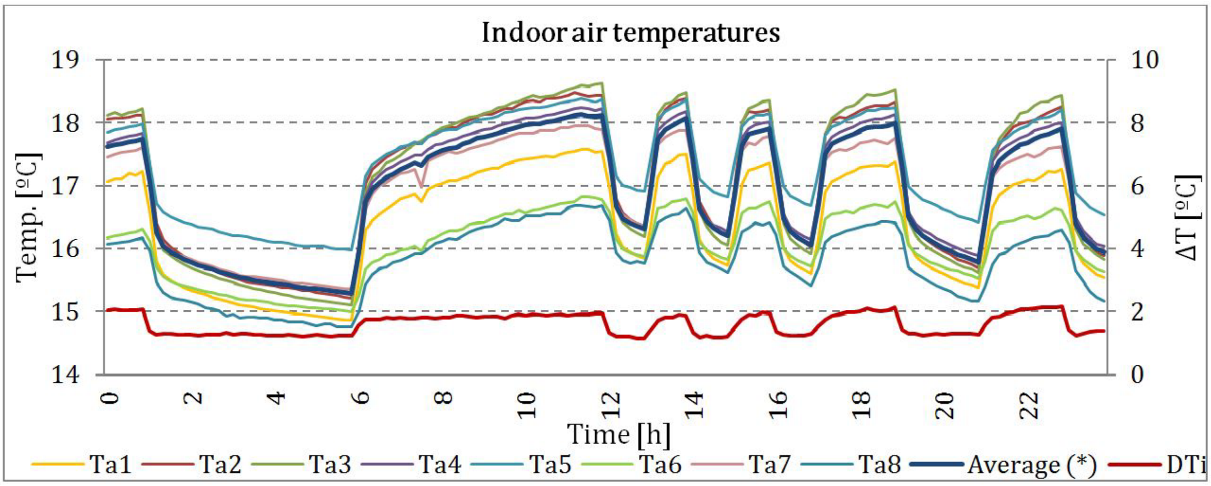

Figure 6. Indoor air temperatures in 1st of February 2012

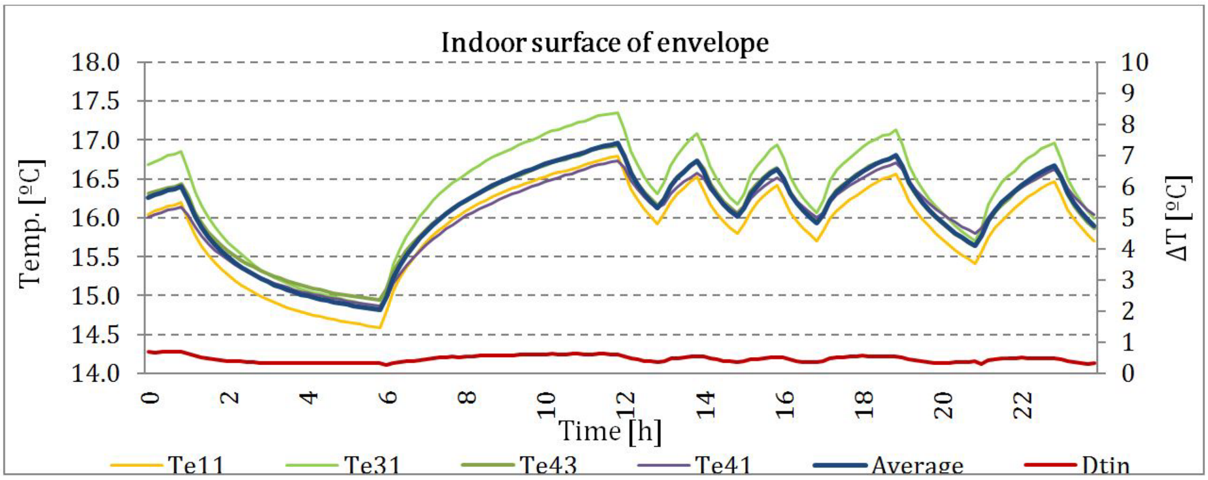

Figure 7. Temperature of indoor surface of envelope in 1st of February 2012

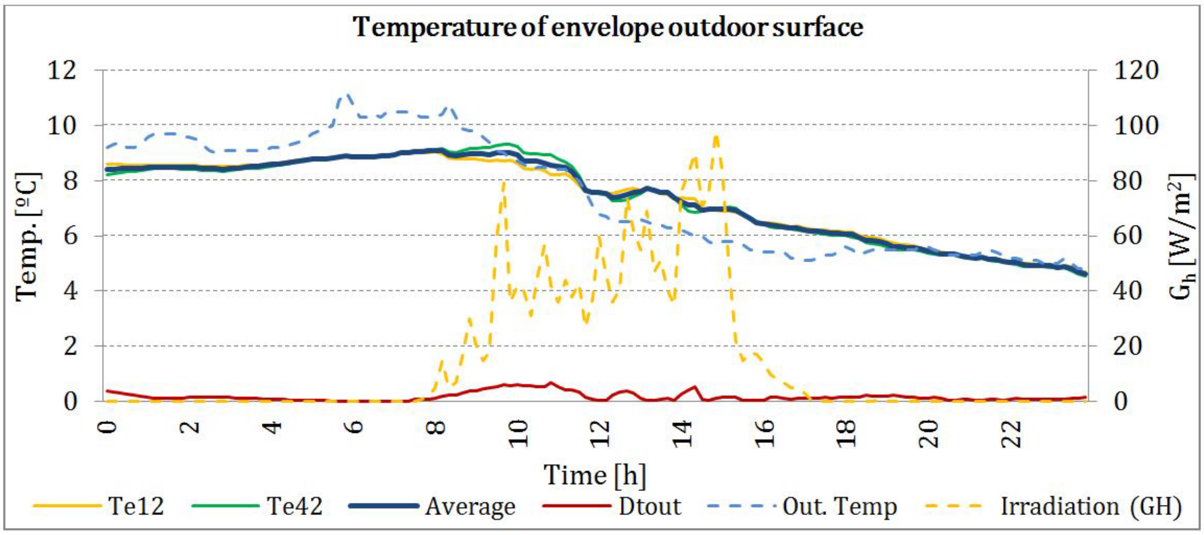

Figure 8. Temperature of envelope outdoor surface in 1st of February 2012

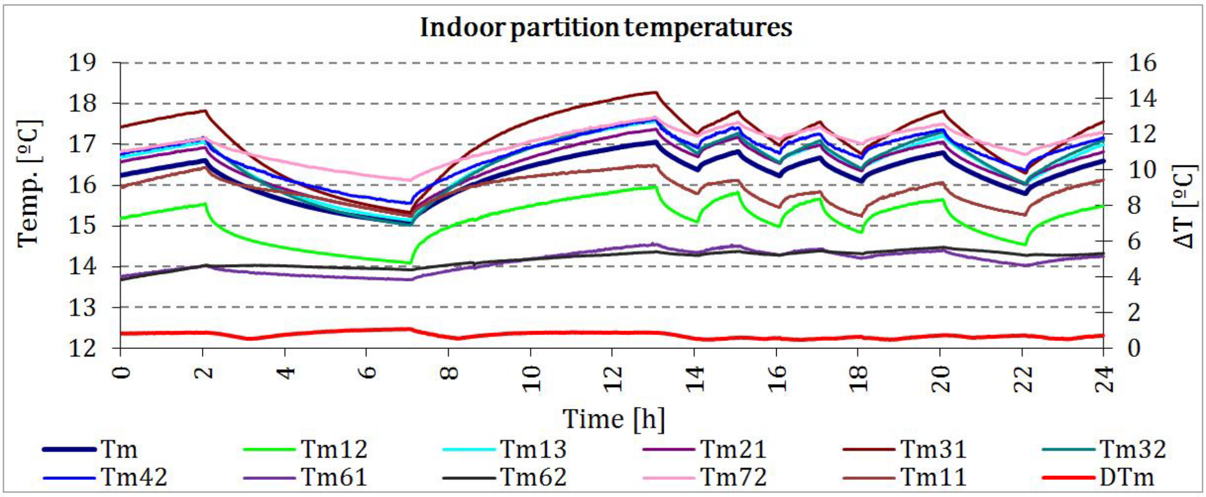

Figure 9. Temperature of indoor partitions in 1st of February 2012

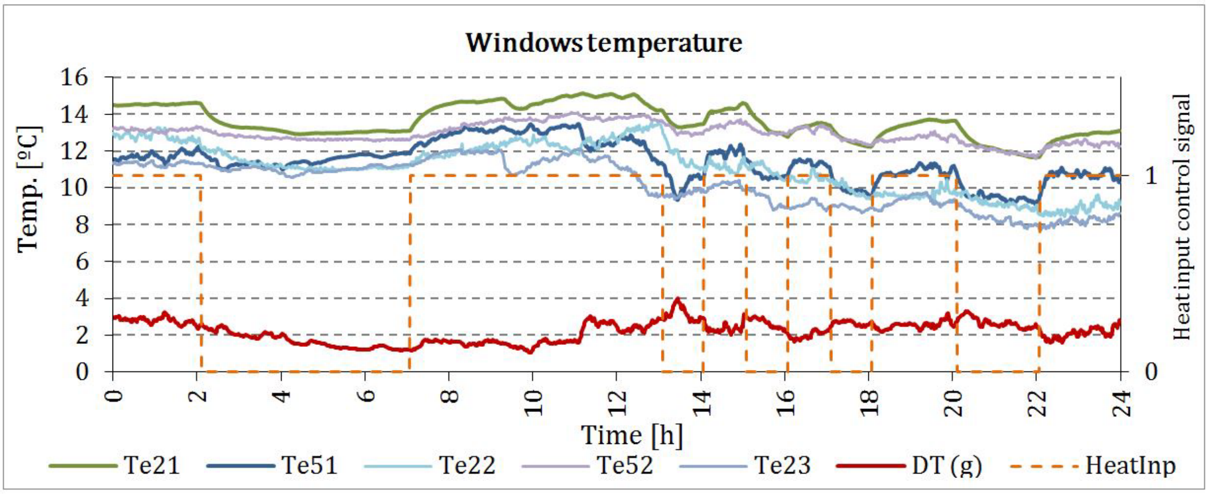

Figure 10. Window surface temperatures in 1st of February 2012

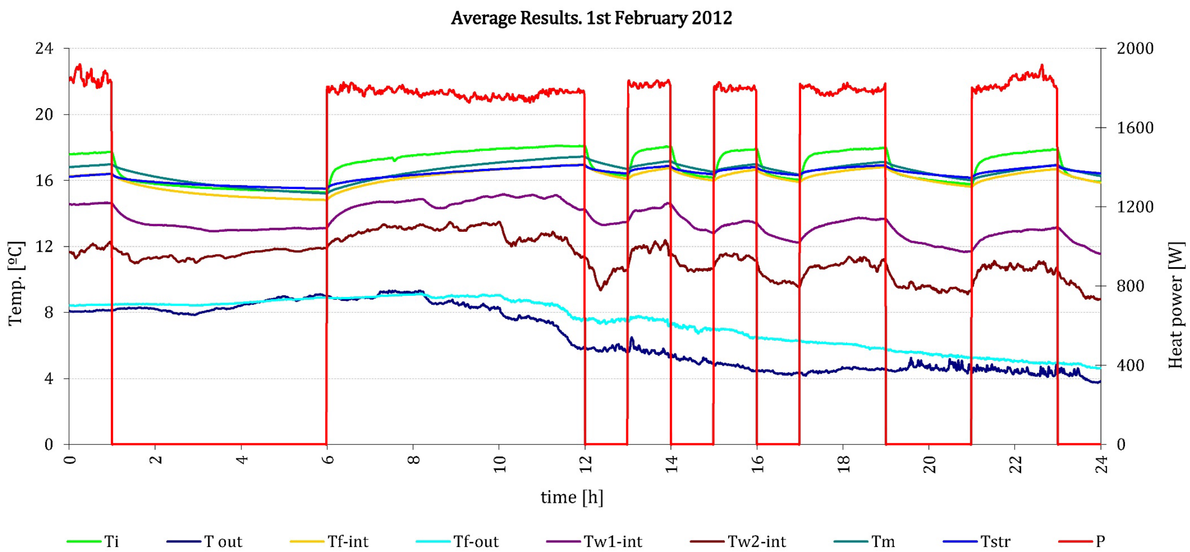

Figure 11. Results obtained for 1st February 2012

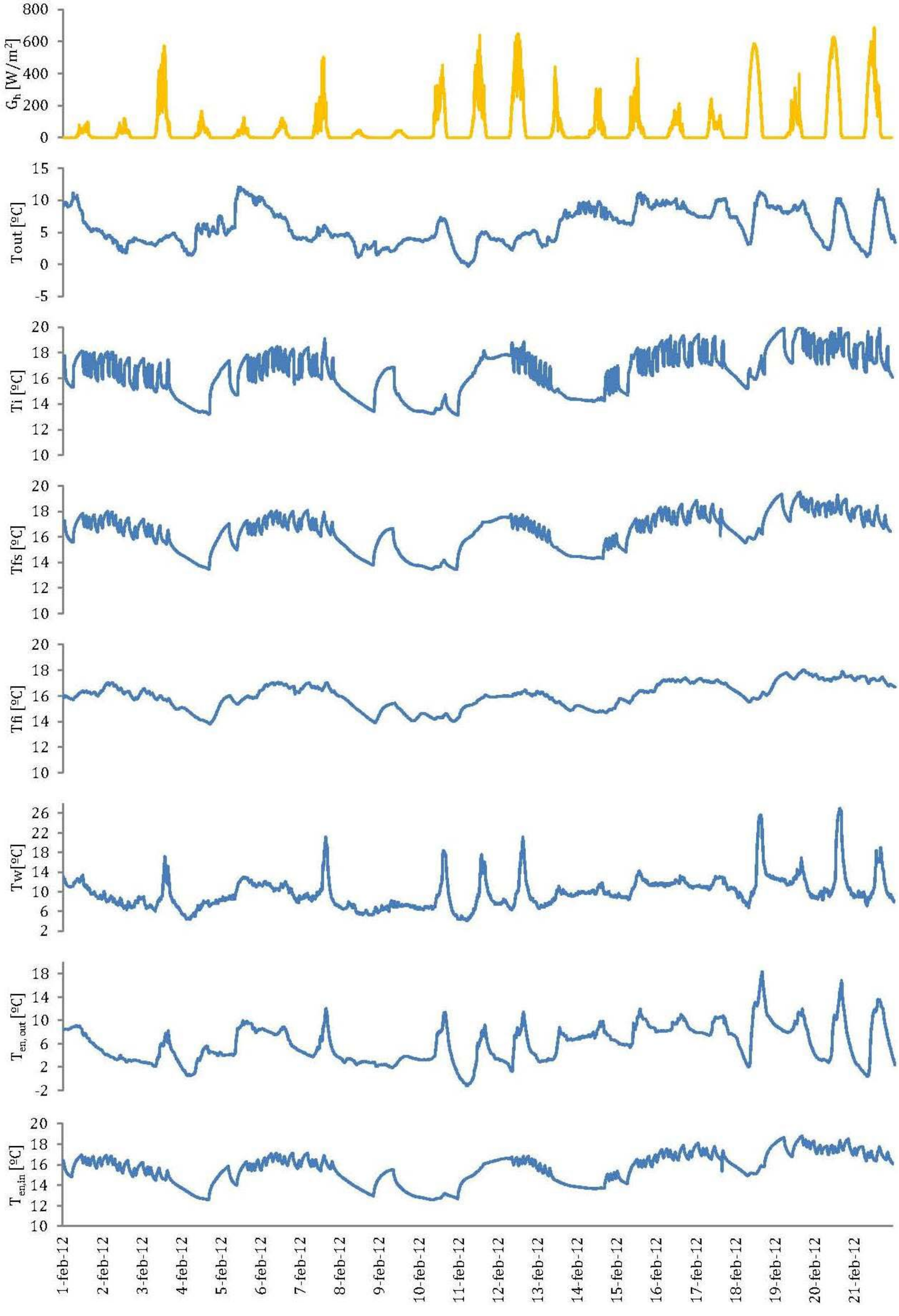

Figure 12. Plots of the data used in co-heating method and RC model (1st -21st Feb 2012)

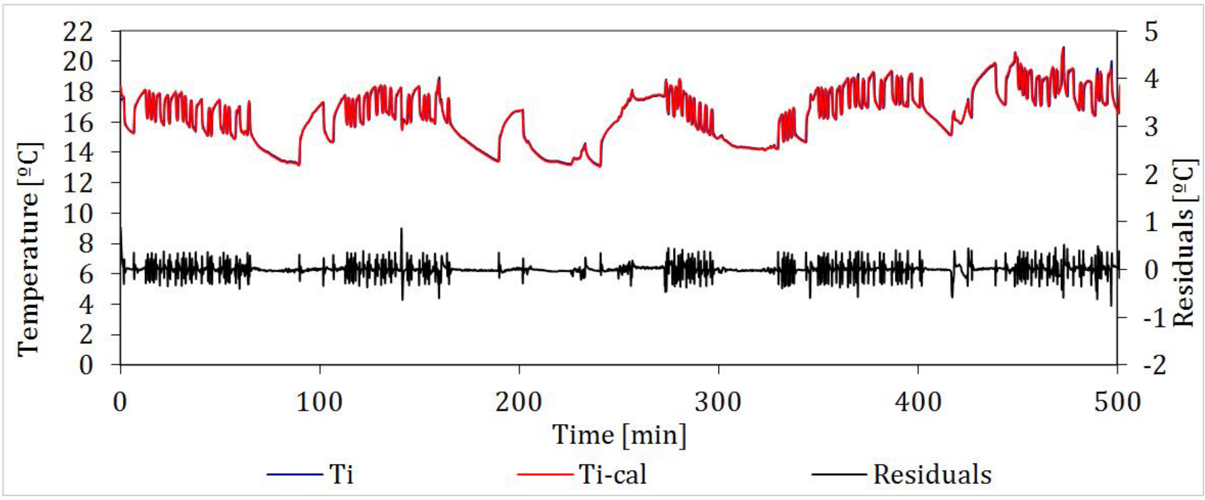

Figure 13. Indoor temperature calculated (red) Vs. observed (blue), and residuals (black)

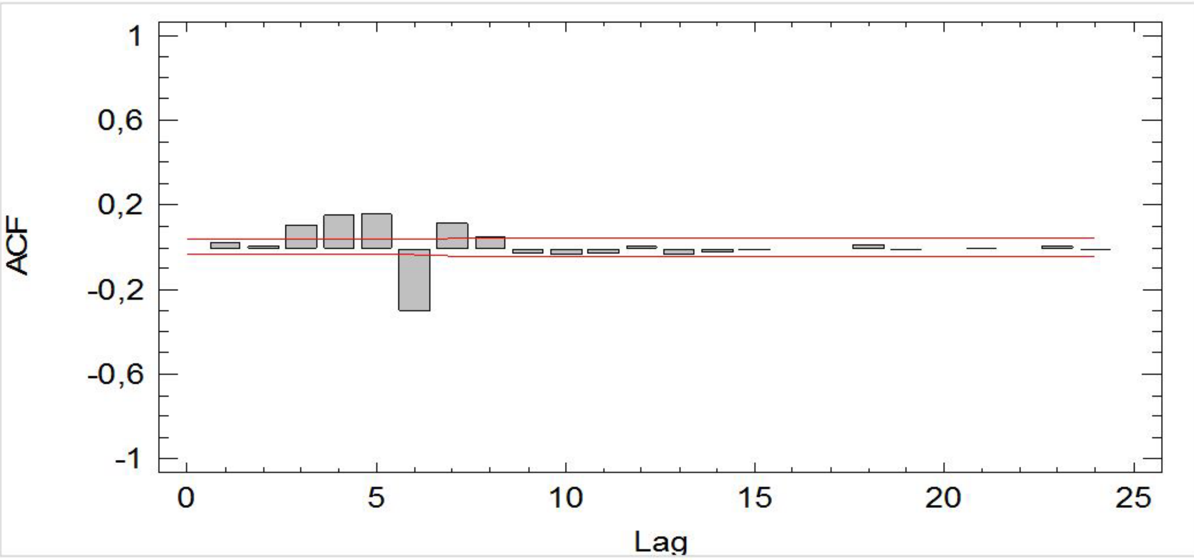

Figure 14. Autocorrelation Function (ACF) of residuals

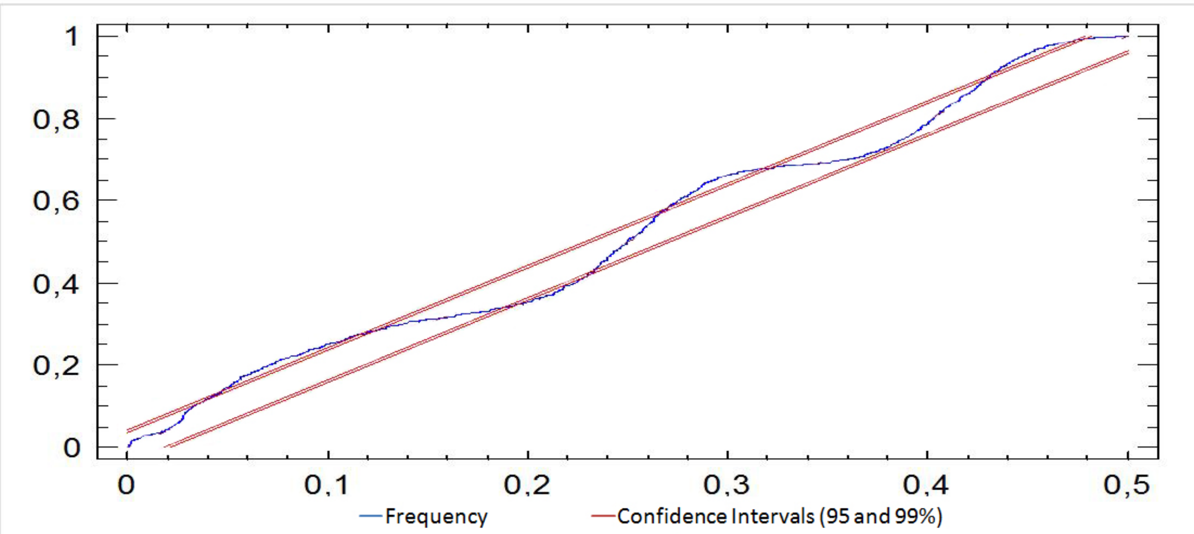

Figure 15. Cumulated periodogram of residuals

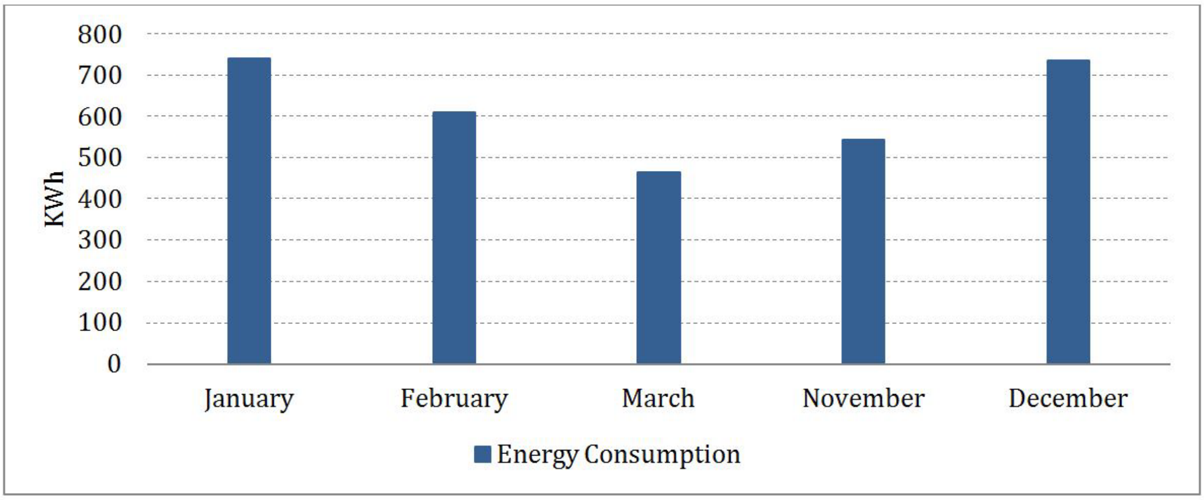

Figure 16. Energy consumptions obtained by the RC model

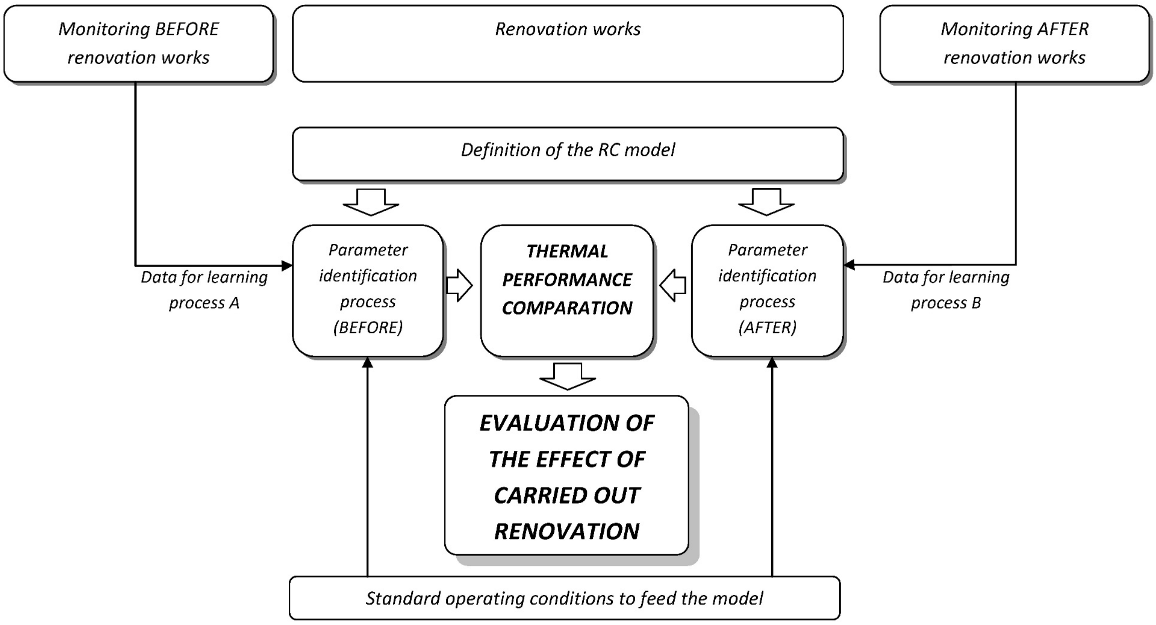

Figure 17. Methodology proposed to evaluate energy renovation effect in social housing

Tables

Kind of wall	Constructive section	U – value (calculated) [W/m2K]
External Walls	Gypsum Hollow Brick (4.5 cm) Air gap Hollow Brick (12.5 cm) Thermal Insulation (2 cm) Hollow Brick (4.5 cm) Cement Mortar (2cm) Projected arid (1,5 cm)	0.74
Dwelling Partitions	Plaster Hollow Brick (4.5 cm) Plaster	3.59
Dwelling-Staircase/other dwelling	Plaster (1 cm) Hollow Brick (12.5 cm) Plaster (1 cm)	2.26

Table 1. Construction of the main elements of the dwelling envelope

Parameter	Units	Sensor	Uncertainty
Temperature	[°C]	PT100. A class (4 wire)	± 0,2 °C
Heat Flux	[W/m^2]	Ahlborn FQA-0801-H	± 5 %
Anemometer	[m/s]	Meteo Multi FMA510	± 0,5 / ± 0,3 m/s
Barometric pressure	[bar]	Meteo Multi FMA510	± 0,5 mbar
Relative humidity	[%]	Meteo Multi FMA510	± 3 %
Solar Irradiation	[W/m^2]	Kipp and Zonen CMP11	± 3 %
Electrical power (heaters)	[W]	Sineax M561 single phase power meter	± 0,2 %

Table 2. Characteristics of the used sensors

Collected data group		Number of sensors	Collected data group		Number of sensors
Indoor Air Temperature	[T_a]	8	Surface Temperature of Structure	[T_{str}]	16
Surf. Temp. of opaque env.	[T_e]	6	- *Ceiling*	[T_{fs}]	5
- *Indoor surface*		4	- *Floor*	[T_{fi}]	5
- *Outdoor surface*		2	- *Pillars (in)*	[T_p]	2
Surface Temp. of windows	[T_e]	5	- *Pillars (out)*	[T_p]	4
Surface Temp. of partitions	[T_m]	13	Heater Temperature	[T_c]	5
Flux meters	[F]	4	Outdoor Conditions	-	4

Table 3. Highlights of the dwelling

Element	Nodes (subscript)	Description
Indoor air	in	C_{in} is linked to this node. Other direct inputs, such as solar gains or internal gains must be also included in this node.
Opaque walls	e-in; e; e-out	It includes the different resistances and capacitances considered in the opaque walls, as well as other collateral fluxes, such as solar irradiation, which affects which affects the heat flux indirectly, since it heats up the envelope, and it can modify it significantly.
Windows	w	This element has no capacity associated, since in residential buildings thermal inertia of windows can be neglected when comparing to opaque façade thermal inertia.
Structure	Str-in; str	Since the case study is a dwelling, and not a whole building, some heat losses occurs to other adjacent dwellings. Structure branch represents the heat flux through the rest of the envelope elements (thermal bridges, indoor partitions...). The balance in this node is expressed in Eq. 5.
Heating system	h	It is linked to the heater capacitance. The balance of this node is expressed as shown in Eq. 6.

Table 4. Thermal nodes considered in the RC model

Name	Description
C_h	Heater capacitance
C_{in}	Internal air and furniture capacitance
C_e	Wall capacitance
C_{est}	Structure capacitance
R_h	Convective resistance between heater and indoor air
R_{e-in}	Internal convective resistance (walls)
R_{e2} and R_{e3}	Wall conductive resistances
R_{e-out}	External convective resistances (walls)
R_{w-in}	Internal convective resistance (Windows)
R_{w-out}	External convective resistance (Windows)
R_{str-in}	Internal convective resistance (structure)
R_{str1} and R_{str2}	Structure conductive resistances

Table 5. Description of grey box model parameters

Element	**Surface**	**Room 2 (Double Glazing)**	**Room 5 (Single Glazing)**
Glass	Indoor surface	T_{e21}	T_{e51}
	Outdoor surface	T_{e22}	-
Frame	Indoor Surface	T_{e23}	T_{e52}

Table 6. Sensor's temperature placed in windows

	Initials	Nomenclature	Values taken into account
HEAT.	**T_c**	Reference heater temperature	T_{c1}
	P	Input heat power	Measured power of the 5 heaters
	T_a	Average ind. air temperature (weighted)	T_{a1}-T_{a8}
FAÇADE	**T_{fin}**	Average ind. surface temperature of façade	T_{e11}, T_{e31}, T_{e41}, T_{e43}
	T_{fout}	Average outd. surface temperature of façade	T_{e12}, T_{e42}
	T_w	Average surface temperature on windows	T_{e21}, T_{e51}
STRUCT.	**T_{str}**	Average temperature of structure	T_{fs1}-T_{fs5}, T_{fi1}-T_{fi5}, T_{p1}, T_{p3}
	T_{fs}	*Average temperature of ceiling surfaces*	*T_{fs1}-T_{fs5}*
	T_{fi}	*Average temperature of floor surfaces*	*T_{fi1}-T_{fi5}*
	T_p	*Average temperature of pillars surface*	*T_{p1}, T_{p3}*
OUT	**T_{out}**	Outdoor temperature	Web data (Euskalmet)
	G_h	Global horizontal irradiation	Web data (Euskalmet)

Table 7. Measured data sets

Variables		Description
Independent variables *x* (excitements of the system)	*G_h*	It is the observed irradiation at the climate station
	T_{out} [ºC]	It represents outdoor temperature
	P [W]	It represents the power of the heater
Dependent variables *y* (system variables)	*T_{in}* [ºC]	It is the objective function of the model. It is a single value which is the average indoor temperature measurements.
	T_{fi} and T_{fs} [ºC]	They are the average surface temperature of indoor floor and ceiling respectively
	T_P [ºC]	It is the average temperature measured in pillars
	T_w [ºC]	It is the average temperature obtained from temperature sensors placed in windows
	T_F [ºC]	It is the average temperature obtained from temperature sensors placed in indoor and outdoor surface of façade. Two different averages were calculated, corresponding to the indoor and outdoor surface temperatures

Table 8. Data series used in the RC model

	C [MJ/K]	H [W/K]		R [K/W]		
Structure	29.411	H_{str-in}	820	R_{str-in}	1/820	0.558
		$H_{str,1-2}$	1.8	$R_{str,1-2}$	1/1.8	
Windows	-	H_{w-in}	305	R_{w-in}	1/305	0.007
		H_{w-out}	255	R_{w-out}	1/255	
Opaque walls (envelope)	1.975	H_{e-in}	1259	R_{e-in}	1/1259	0.007
		$H_{e,2-3}$	169	$R_{e,2-3}$	1/169	
		H_{e-out}	1679	R_{e-out}	1/1679	
Heater	0.001	$H_{h,1}$	15.5	$R_{h,1}$	1/15.5	0.06
Indoor air	0.667	-				
		A1: 3.1 m^2 ; A2: 8.66 m^2				

Table 9. Characteristic parameters of the model