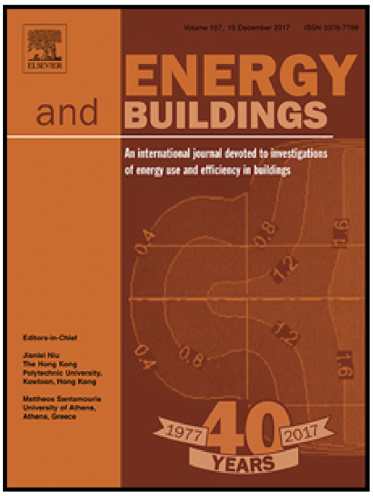

Understanding the performance gap in energy retrofitting: measured input data for adjusting building simulation models

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Highlights:

- Methods for monitoring buildings, testing and adjusting energy simulation software are developed.
- Factors influencing energy building performance are investigated in two case studies.
- Mixed-method approach helps to define building simulation templates and users' patterns.
- Adjusted simulation models allow a reliable building energy consumption evaluation.
- Weather data and occupancy patterns are the most influential factors in the adjustment of models.

Understanding the performance gap in energy retrofitting: measured input data for adjusting building simulation models

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Keywords: Residential buildings, Performance gap, Monitoring, Occupancy patterns, Building energy modelling

ABSTRACT

This paper focuses on exploring methods for reducing the gap between the expected and actual building energy performance by using simulation tools. The study has two purposes. The first is to quantify **the relative effect of the different building parameters measured on the energy heating and cooling consumption compared with standard parameters** through the adjustment of simulation models. The second is to develop an **approach, based on three methods, for monitoring residential buildings, while also testing and calibrating methodologies for the simulation software**. The approach developed is applied and tested in two real case studies (two apartments in two identically constructed buildings, one refurbished and the other not) in the city of Madrid, Spain. The analysis of the case studies shows that there is a **four-fold difference in potential savings in energy for heating** between models adjusted with standard and actual parameters. Moreover, the results reveal the significant **impact of the use of actual weather data and users' behaviour** in the adjustment of simulation models and **demonstrate the utility of the application of these methods**.

1. Introduction

The European Union is currently pursuing energy efficiency improvement in the refurbishment of domestic buildings in order to reach a 27% energy efficiency improvement target by 2030 [1], in keeping with the 2050 long-term strategy [2].

Retrofit interventions usually pursue the goal of reducing the energy demand of buildings while providing occupants with more comfortable indoor environments and lower energy bills. This “expected” performance is calculated using energy simulation programs. However, recent research has shown significant differences between the simulated and actual energy consumption in dwellings with similar characteristics [3-5]. This so-called performance gap can be the result of poor adjustment of simulation models to actual (measured) data. Commonly, normalized and standardized data are used but this information does not always correspond to the actual building and user characteristics [3, 6-8]. This, in turn, reduces the usefulness of energy performance simulation tools (EPST) to predict the energy consumption of buildings.

1.1. The performance gap in building performance simulation (BPS)

Building simulation programs are normally used to predict the building's energy performance and the users´ thermal comfort [9-12]. In recent decades interest in the usefulness of these tools, in search of more energy efficient buildings, has brought about an increase in the number of simulation programs but EnergyPlus [13], TRNSYS [14] and ESP-r [15] continue to be the most widely used software among the scientific community. Information regarding construction, occupancy patterns, HVAC and boundary conditions such as climate information is included within the building model. Inevitably, many assumptions are made when the model is to represent a complex energy flow-path and interactions [9, 16]. For this reason, numerous studies have shown that there is a performance gap between the expected and the actual performance of buildings [3, 5, 17-20]. These differences are attributed to different factors such as rebound [21] and pre-bound effect [22], the interaction between occupants and building technologies [23], as well as the accuracy of the input values used in the simulation models [24, 25].

In order to reduce the performance gap, different studies use monitoring data to calibrate [26] simulation models or to compare predicted vs. actual building energy performance. Coakley [24] present a review of the actual methods used by the research community to calibrate energy models focusing on the uncertainty on the calibration models. He categorised these approaches as “manual” and “automated”. Manual approaches are those that rely on iterative pragmatic intervention by the modeller, using characterization techniques, advanced graphical methods, model simplification techniques and procedural extensions. Automated approaches employ mathematical and statistical techniques and have some form of automated techniques such as optimization or alternative modelling techniques such as artificial neural networks. He concludes that there is no consensus regarding the approach to be used or the validation criteria needed to calibrate the energy model based on the purpose of individual cases. The methodological proposal presented in this paper falls within the category of manual approach. Regarding manual approaches, Royapoor [27] conducts an energy calibration with an EnergyPlus model of a 5-storey office building case study in order to generate an accuracy model to predict the building’s energy performance. Menezes demonstrates how the Post-Occupancy evaluation can be used to produce more accurate energy performance model through the data collected on electricity consumption and occupancy pattern monitoring in an office building in Central London [19]. Zakula [28] analyses the accuracy and limitations of the new ISO 52016 standard in comparison to dynamic simulation models of various building types and climates using the TRNSYS program. Shiel [29] proposes a methodology to identify the groups of most influential parameters in the predicted energy usage within a design stage BPS model in new buildings. However, there is a lack of approaches providing empirical evidence to understand the link between monitoring data, occupancy patterns and performance of residential buildings, and the use of these types of data to adjust the building simulation models and aid retrofit interventions.

The performance gap can be considered an `artificial´ issue due to the fact that the gap is the result of a definition of an `expected´ energy consumption. Therefore, it is important to establish how this expected energy consumption was calculated, what assumptions have been made [30, 31], which input values have been selected for introduction into the simulation models, and the sources from which they have been obtained [11].

1.2. Building envelope quality, weather data and occupant´s behaviour

The literature identified building envelope, weather data, and occupant behaviour as the main influencing factors in the building's energy performance. The data collected from both the building envelope and the weather monitoring campaign can be used as input values when defining building models in order to reduce uncertainty in identifying building envelope quality [20, 32, 33] and the differences between the standard weather simulation files and the actual local weather data [34, 35]. It is known that occupants' behaviour is one of the main factors determining the gap between actual and predicted building performance [8, 36-41]. The stochastic nature of the user´s behaviour results in standard and normative data being used as input data in energy simulation models.

Past research studies have shown deficiencies in building fabric leading to heat loss. For example, the Zero Carbon Hub [38] compiled data from several studies using co-heating tests to assess the total heat loss of new dwellings. It was found that only 5 of the 16 dwellings studied had a reasonable (10-15%) match between measured and predicted heat loss, while others showed differences of up to 100%. In other studies, by measuring the U-value, researchers discovered heat loss rates ranging from 20% to 300% higher than calculated [38, 42-44].

There are a number of techniques that can be used individually or in combination to monitor the performance of buildings' fabric and systems, including coheating tests, tracer gas tests, air permeability (or pressurization) tests, infrared surveys, in-situ U-value measurements, and air movement tests. Monitoring techniques for fabric and system performance are usually used to evaluate a specific aspect (e.g. air tightness) [45-49] or component (e.g. ventilation system) [50] of a building. Subsequently, these techniques have been applied more often to case studies where the performance of the building has been assessed [33, 51-53].

Accurate weather data also play an important role in reducing the gap between the predicted and actual energy building performance [54]. The monitoring of weather data is not always possible as the expense of installing a weather station near the case study is considered prohibitive, although a technique for calibrating building simulation models with real information is considered necessary. Some studies have even gone beyond actual data predicting future urban climates in order to focus on the consequences of climate change [55]. For example, Demanuele et al. [34] generated weather files which take into account the heat island effects in relation to the overheating risk in the city of London.

Regarding the user´s behaviour, the predefined occupancy profiles (a conventional family of 4 members working or studying during the central hours of the day) which are usually used in simulation software do not apply to the household studied [56-59]. The complexity of occupant behaviour requires an interdisciplinary approach in order to understand the different influence factors, that is: external factors such as cultural, economy, and climate; internal factors such as individual comfort preference, physiology, and psychology; and, occupants' interactions with building systems [60]. Other studies reveal the importance of collecting as much data as possible on the occupation of the house and the preferences of its users [36, 61, 62] as well as information regarding the age and number of occupants in the building studied [63].

The **goal of this paper** is to develop a methodological proposal in order to adjust the simulation models from experimental data and reduce the level of uncertainty of the results. Its application allow us to determine the relative effect of the parameters measured by comparing them with the standardized parameters in the building's energy consumption and thus identify which of them need to be further explored when undertaking an energy rehabilitation project. The parameters studied are weather data (outdoor factors), actual building constructive characteristics (envelope factors) and occupancy patterns (indoor factors). These data are compared to standardized ones, commonly used to perform dynamic simulation studies. This approach is applied in two experimental case studies in the city of Madrid, Spain. Two identically constructed buildings have been selected but one is refurbished and the other not.

This work tests and proposes a robust methodological proposal aiming to reduce the gap between models adjusted with standard or real data on the energy consumption. The findings of this investigation are relevant in terms of proposing a coherent methodology to inform interventions based on the collection of data/evidence on the use of quantitative and qualitative methods. The results obtained are not intended for general application, but rather to demonstrate how practitioners can use these methods in real renovation cases. The aim of this investigation is to provide an approach which can be replicated in actual renovation projects to reduce the uncertainty of the energy consumption results, and to determine the parameter or parameters requiring more attention. Furthermore, this work constitutes an advance in future rehabilitation plans with the application of the proposed methodology, in which the use of energy simulation models of homes can be promoted from the design phase, adjusted with real data of buildings and their occupants. Its application will allow simulation programs to be used as predictive tools to estimate reliably the energy savings that occur after the intervention and, consequently, more accurate amortization periods.

The paper is structured as follows: Section 2 outlines the methodology used for this research, including the description of case studies, the parameters selected, the methodological approach (three-step methodology) made up of three methods - monitoring campaign, mixed-methods, and building simulation; Section 3 presents the results of the application of the three methods to the case studies, before using building models to analyse the energy consumption results; Section 4 introduces the discussion; and Section 5 presents the conclusions.

2. Methodology

This section introduces the case studies and presents the methodological approach.

2.1. Case studies

The case studies are two dwellings located in different blocks in the social neighbourhood “Ciudad de los Ángeles” (Figure 1) in the south of Madrid.

Figure 1 Case studies located in Ciudad de los Angeles.

The two identical residential open buildings were built at the same time although one (CP17) was refurbished between 2009 and 2011. The dwellings selected both occupy the same position inside the building: in the middle of the third floor, in order to replicate the influence that the position inside the building has on energy performance [64]. The floor plans can be seen in the appendix (Figure A1 and Figure A2).

Table 1 Building and household characteristics

	Dwelling CP17	Dwelling CP18
Dwelling characteristics		
Dwelling type	Apartment	Apartment
Household size	1	1
Floor area	62m^2	62m^2
HVAC	Individual gas boiler (Heating and water) / Air conditioning	Individual gas boiler (Heating and water) / Air conditioning
Construction year	1972	1972
Last renovation	Between 2099-2011	Non-renovated
Refurbishment features	Double glazing, floor insulation, façade insulation	–
Household characteristics		
Tenure type	Owner	Owner
Age	83 years old	82 years old
Gender	elderly woman	elderly woman
Occupation	Employed- part time	Retired
Education	Without higher education	Without higher education
Physical condition	Very good physical condition	Good physical condition
Personality features	Dynamic and caring	Quiet and calm

Table 1 shows the main building and household characteristics. Both buildings have the same HVAC systems with individual boiler and split air-conditioning system, controlled by the occupants, who turn them on and off when they feel too warm or cold. The residents of the buildings are female senior citizens living alone. This type of household is becoming more common in Spain. In 2015 [65], single households already accounted for 25% of dwellings. The main differences between both residents are that the resident of the refurbished building (CP17) works part-time during the week, while the resident of the non-refurbished building (CP18) is retired and absent from home some weekends when she visits her son for several days at a time. These dwellings have been selected based on the similarities of both households, the relevance of this type of household, and the willingness of their occupants to be part of the study.

For practical reasons, the monitoring campaign was carried out in both a renovated and a non-renovated building, instead of a pre-renovation and a post-renovation campaign. This allowed us to perform a simultaneous field assessment of thermal and energy behaviour in both buildings under equal external conditions. This facilitates the comparison of the results of both buildings.

2.2. Methodological approach

The methodology of this paper is divided into three main parts (three-step methodology): 1. Monitoring approach, 2. Mixed-method approach and 3. Simulation approach. Each section includes its own method, application and results. This organization is proposed since the results of each approach serve as starting point for the one following. The three-step methodology aims to collect real information from the building’s characteristics (quantitative data) and users´ habits and customs (qualitative data). In combination with the application of the mixed-method approach, this has allowed us to develop adjusted simulation templates and occupancy patterns. Thus, the adjustment of simulation models with actual and standard data in the buildings' energy consumption has been evaluated, as has their impact on the building renovations. Figure 2 shows the methodological approach and the sections into which the paper is divided.

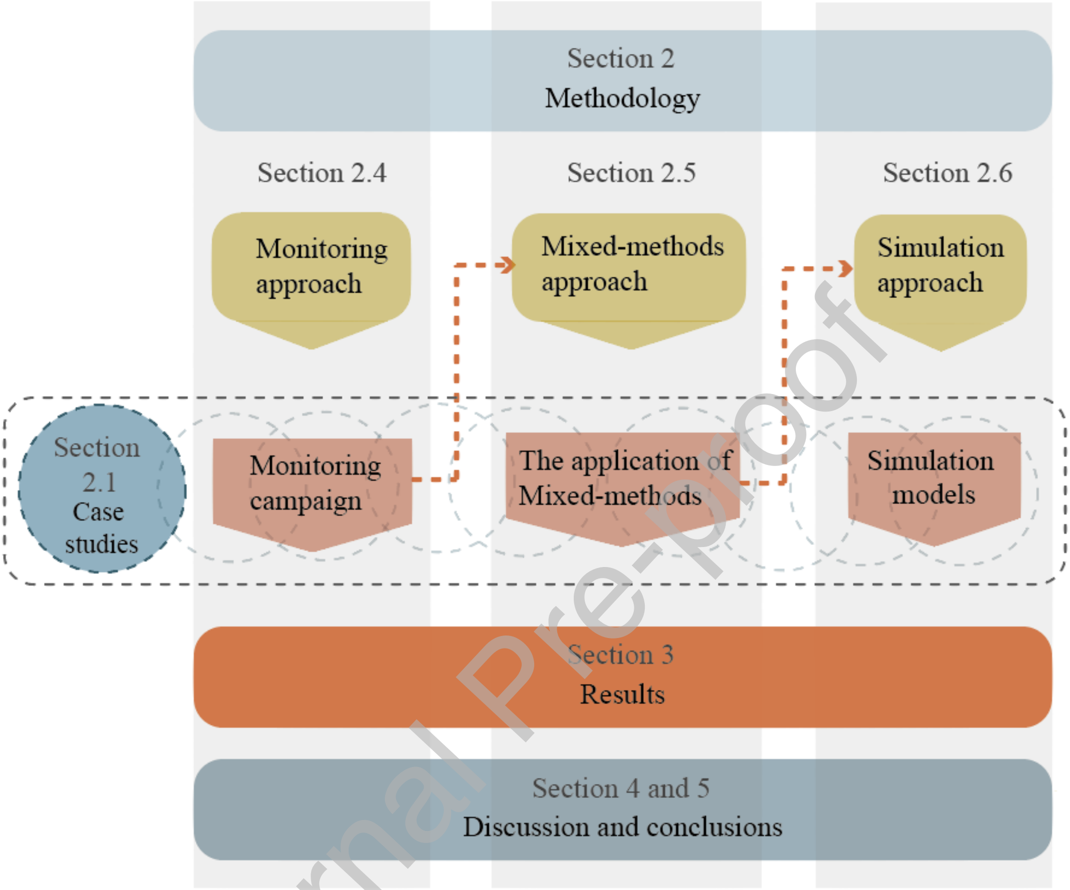


Figure 2 Methodological approach

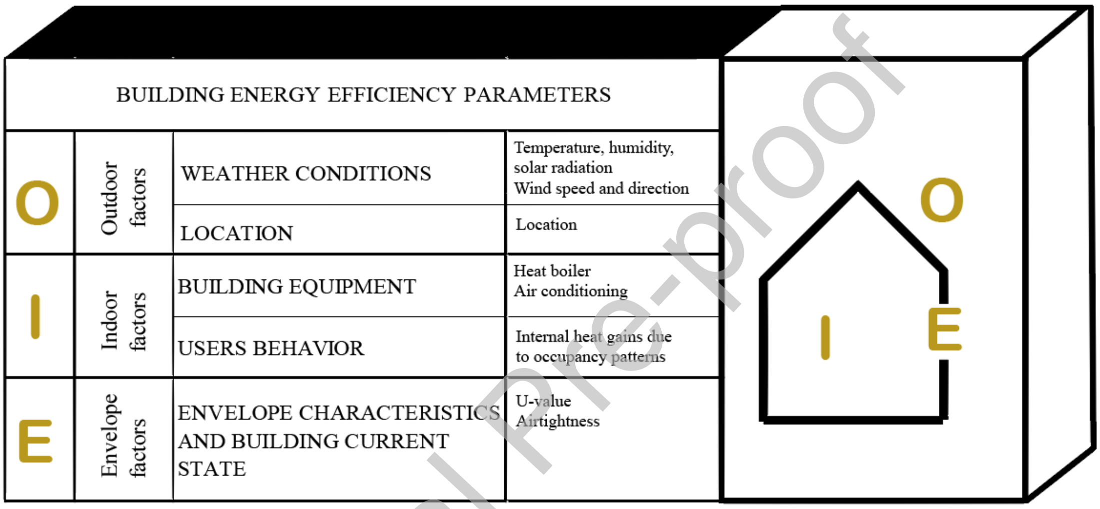
2.3. Local weather data, building envelope, and occupancy parameters

In this section, the parameters with the greatest influence on the energy performance of buildings have been listed and classified. A description is then provided of the measurement process of these parameters through the definition of the monitoring campaign, which instruments have been used, where the sensors have been located and what the purpose of the collection of each variable was.

In Annexes 53 [66] and 58 [67] the International Energy Agency defines the parameters with the greatest influence on the energy performance of buildings, as shown in Figure *3*: climate and location, building equipment, user behaviour, and envelope characteristics. However, given the lack of procedures which consider the interaction and combination of these parameters, their influence on the energy and thermal behaviour of buildings is limited.

This study presents a classification of these parameters, proposing a series of variables for to be measured during a monitoring campaign, and the collection of in situ data for the two case studies selected. These variables will be introduced and modified as input data in energy simulation models. These parameters are organized into three groups:

- Outdoor factors (O) take into account the surrounding environment (buildings and vegetation) of the case study: the weather conditions and the location.
- Indoor factors (I) are the parameters related to user occupancy, the interaction between users, and building technologies such as heating and cooling systems.
- Envelope factors (E) are those related to the building envelope characteristics and conservation status.



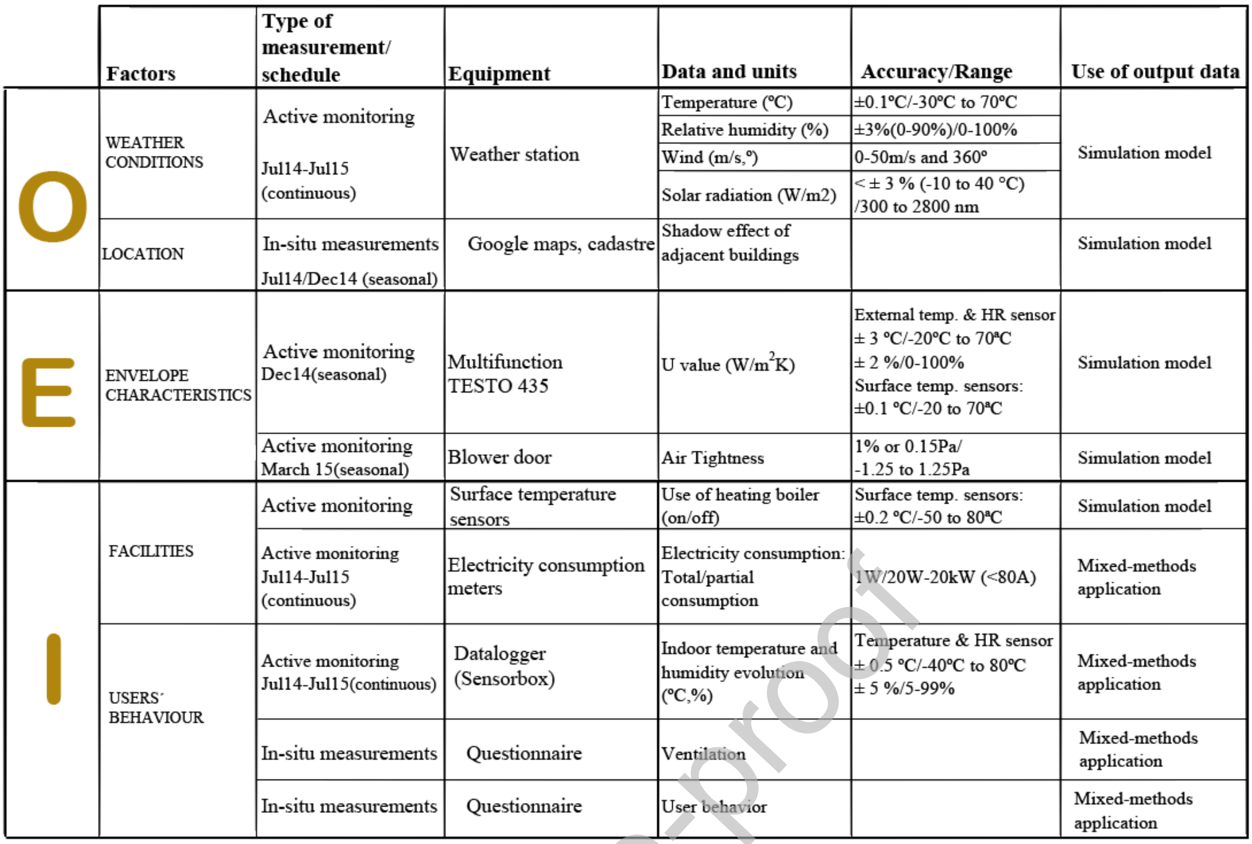
BUILDING ENERGY EFFICIENCY PARAMETERS			
O	Outdoor factors	WEATHER CONDITIONS	Temperature, humidity, solar radiation Wind speed and direction
		LOCATION	Location
I	Indoor factors	BUILDING EQUIPMENT	Heat boiler Air conditioning
		USERS BEHAVIOR	Internal heat gains due to occupancy patterns
E	Envelope factors	ENVELOPE CHARACTERISTICS AND BUILDING CURRENT STATE	U-value Airtightness

Figure 3 *Building energy efficiency parameters*

2.4. Monitoring campaign

The aim of the monitoring approach is to gather actual input data for the characterization of the building simulation models. On the one hand it focuses on the identification of occupancy profiles for specific occupants, combining quantitative data from sensors and meters, and qualitative data from interviews in order to understand household practices. On the other, it focuses on identifying the current state of the envelope and building characteristics in order to create a building model which represents the actual thermal behaviour of the building under study.

The monitoring campaign was performed for one year, between July 2014 and July 2015, aided by the willingness and cooperation of the residents. Figure 4 shows the different parameters measured, the type of measurement, the measurement instruments used, and the monitoring campaign timetable.



	Factors	Type of measurement/ schedule	Equipment	Data and units	Accuracy/Range	Use of output data
O	WEATHER CONDITIONS	Active monitoring Jul14-Jul15 (continuous)	Weather station	Temperature (°C)	±0.1°C/-30°C to 70°C	Simulation model
				Relative humidity (%)	±3%(0-90%)/0-100%	
				Wind (m/s,°)	0-50m/s and 360°	
				Solar radiation (W/m2)	< ± 3 % (-10 to 40 °C) /300 to 2800 nm	
	LOCATION	In-situ measurements Jul14/Dec14 (seasonal)	Google maps, cadastre	Shadow effect of adjacent buildings		Simulation model
E	ENVELOPE CHARACTERISTICS	Active monitoring Dec14(seasonal)	Multifunction TESTO 435	U value (W/m^2K)	External temp. & HR sensor ± 3 °C/-20°C to 70°C ± 2 %/0-100% Surface temp. sensors: ±0.1 °C/-20 to 70°C	Simulation model
		Active monitoring March 15(seasonal)	Blower door	Air Tightness	1% or 0.15Pa/ -1.25 to 1.25Pa	Simulation model
I	FACILITIES	Active monitoring	Surface temperature sensors	Use of heating boiler (on/off)	Surface temp. sensors: ±0.2 °C/-50 to 80°C	Simulation model
		Active monitoring Jul14-Jul15 (continuous)	Electricity consumption meters	Electricity consumption: Total/partial consumption	1W/20W-20kW (<80A)	Mixed-methods application
	USERS´ BEHAVIOUR	Active monitoring Jul14-Jul15(continuous)	Datalogger (Sensorbox)	Indoor temperature and humidity evolution (°C,%)	Temperature & HR sensor ± 0.5 °C/-40°C to 80°C ± 5 %/5-99%	Mixed-methods application
		In-situ measurements	Questionnaire	Ventilation		Mixed-methods application
		In-situ measurements	Questionnaire	User behavior		Mixed-methods application

Figure 4 Data collection methods, equipment, type of data and use of output data.

Regarding the **outdoor factors**, a weather station was installed on a building rooftop in the neighbourhood of Los Angeles, close to the case studies (100m). The information collected on **weather data** examines external air temperature, external relative humidity, solar radiation and wind speed and direction. These data allow us to generate a specific weather data file for the case studies.

Figure 5 and Figure 6 show the location of the sensors and equipment in apartments CP17 and CP18 respectively. The distribution of the equipment was identical in both apartments. All equipment was wireless, positioned to avoid disturbing the residents. Router and connect ports were installed in the dining rooms and data loggers (temperature and humidity) were installed in the main rooms avoiding humid rooms (such as the bathroom or the kitchen).

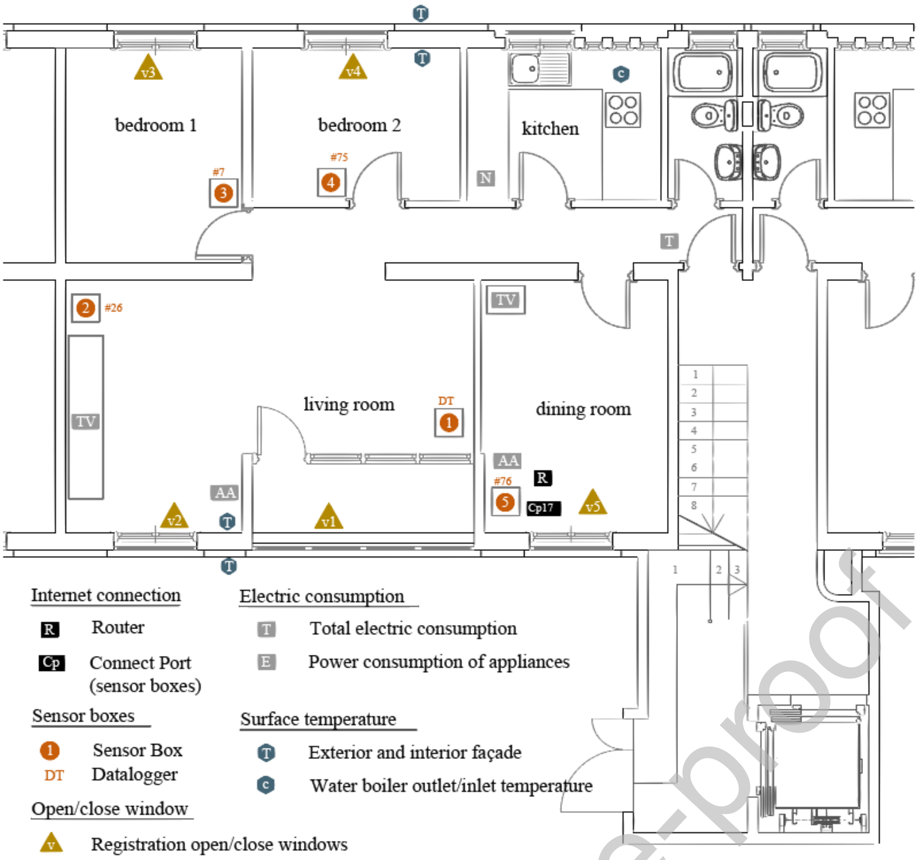


Figure 5 Measurement equipment location in CP17

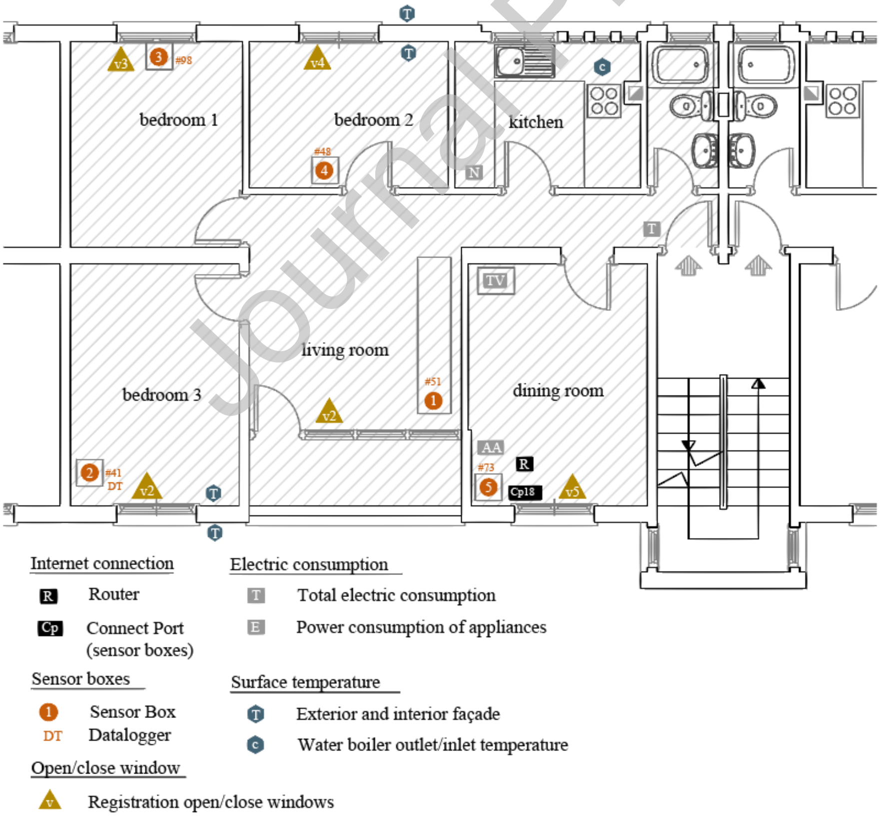


Figure 6 Measurement equipment location in CP18

Regarding the **envelope factors** the characterizations of the energy simulation model have been generated based on the real data. In situ U-value measurement and Blower Door tests were selected in order to measure the actual U-value and Air Tightness.

The U-value was measured with the Multifunction TESTO 435 instrument in the north facade in both the refurbished (CP17) and non-refurbished buildings (CP18). This equipment measures the thermal transmittance (and calculates the heat flux) of a building element by measuring a series of temperatures: the inner surface of the construction element considered, the indoor air temperature, and the outdoor temperature. The monitoring protocol can be found in Cuerda et al. [68] and the instrument characteristics are shown in Figure 4. The measurements were performed on the 28th (refurbished) and 30th (non-refurbished) of December 2014. The hourly schedule and the external conditions were mostly the same as can be seen in the graphs (Figure 7 and Figure 8). The value of the thermal transmittance is deduced from the graph when the curve is stabilized after several hours, obtaining values of 0.89 W/m^{2}K for the refurbished building (CP17) and 1.48W/m^{2}K for the non-refurbished building (CP18).

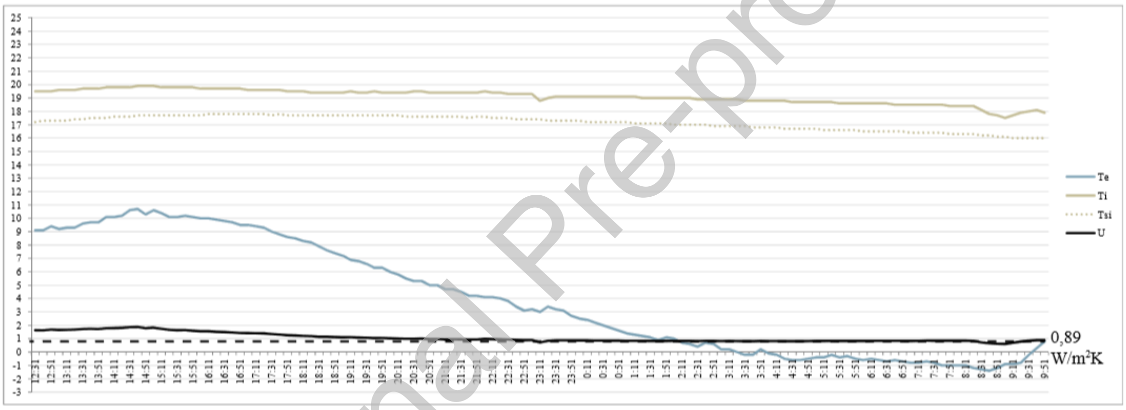


Figure 7 Actual U-value. CP17.

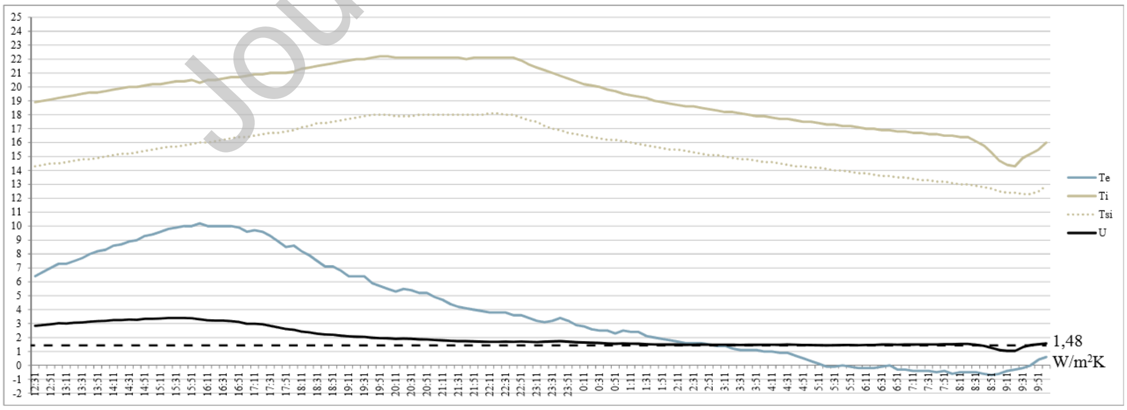


Figure 8 Actual U-value. CP18.

In order to obtain the Air Tightness value, the blower door test was carried out for 2 hours in both apartments on the 17th of March 2015 in compliance with UNE-EN 13829[69]. A power fan is mounted into the frame of the external door pulling air out of the house in order to generate a depressurization. This allows us to measure the airflow through the openings and all unsealed cracks.

The result of the Air Tightness measured value in the refurbished building at 50 Pa was 4.08 h-1. In order to use this value in the simulation model it was necessary to transform it at 1 Pa. The transformation of this value at 1 Pa was calculated using the Persily-Kronvall procedure [70] with a result of 0.204 h-1. In the case of the non-refurbished building the result of the Air Tightness measured value at 50 Pa was 6.21 h-1. The transformation of this value was calculated at 1 Pa with a result of 0.31 h-1. The results of the Blower Door test can be found in the appendix (Figure A3 and Figure A4).

Regarding **indoor factors** (such as the use of heating and cooling systems, opening/closing windows and data on electricity consumption) were measured during the monitoring campaign to determine the actual occupancy schedules and building operation in the dwellings. Each heating system was measured using a wall surface temperature probe (NTC) connected to a TESTO 175-T2 datalogger. The probe was located in the water inlet of the individual gas boiler. Thus, it was possible to identify the hours where the boiler was on and off. To meter electricity consumption and the use of the cooling system (split unit), a plug-in smart meter was used for each unit connected to a multiple-channel energy monitor that uses a wireless signal.

Demographic questionnaires and a contextualized interview were carried out in order to obtain information on users' practices and comfort level regarding heating and ventilation. The monitoring campaign included a period of sensor-based measurements followed by a period of sensor measurements and self-reporting. Each cycle ended with a contextualized interview.

Contextualized interviews were characterized for semi-structured interviews carried out in the user's home and showed us relevant practices related to energy and comfort while interacting with the actual systems in the buildings. These interviews were carried out four times during the year, before and after the summer period, as well as before and after the winter period. The post-monitoring interviews made it possible to visualize the data integration from the monitoring campaign, as the interview session was used to confirm or expand information about the assumptions extracted from the data analysis.

Mechanical ventilation was calculated following the Spanish Technical Building Code [71] which aims to maintain health conditions in the indoor environment by controlling the CO_2 level.

Natural ventilation was calculated following the equation (1) extracted from the Procedures for calculating Natural Ventilation Airflow Rates in Buildings [72] although the application of the mixed-method approach (Section 3.2) was necessary in order to complete it:

$$\boldsymbol{Q = C_d \,.\, A_{ef} \,.\, V_a \,.\, \sqrt{C_p}} \qquad (1)$$

Q = Flow rate (m3/s)
C_d = Discharge coefficient (a dimensional)
A_{ef} = Effective area (m2)
V_a = Air speed (m/s)
$\sqrt{C_p}$= Coefficient of building position with respect to wind direction

To determine the natural ventilation rate, information was collected about the opening and closing hours of windows over 15 days in the summer. Occupants were asked to fill in hourly schedules, attached to each window in the house, crossing off each hour that the windows were open.

In winter the questionnaire asked how often and how long the windows were left open. The answers from both occupants were very similar, "I clean the house for around 2 hours in the morning and open the windows for ventilation". However, further investigation into the topic showed that they only open the windows for half an hour, long enough to ventilate the dwelling, but not to cool it down. The post-monitoring interview, after the collected data regarding the evolution of the indoor temperature had already been analysed, allowing us to confirm that they opened the windows for a shorter period of time, under two hours. Due to the potential uncertainty resulting from this variable and its major influence on heating consumption, a sensitive analysis of the natural ventilation was performed. The results can be found in Section 3.3.3.

These parameters (related to indoor, outdoor and envelope factors) are used below in Section 3.2 to determine occupancy, heating, cooling and ventilation patterns to be used in the building energy simulations in Section 3.3.

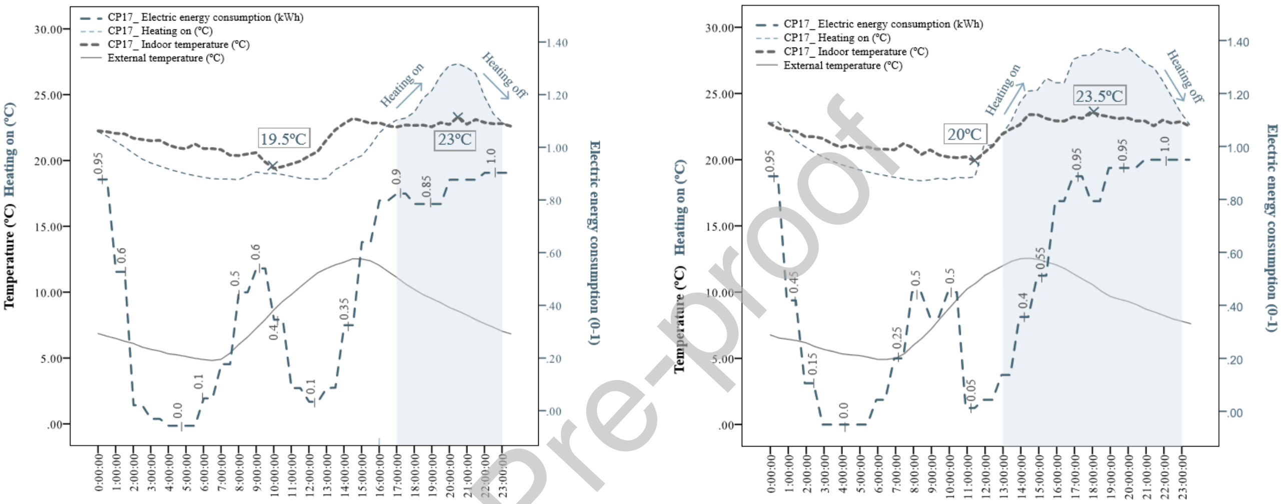
2.5. Occupancy schedules and building operation: mixed-method approach

The mixed-method approach is a methodology that integrates qualitative and quantitative data within a single investigation. In this study the application of this method aims to obtain adjusted simulation templates and occupancy patterns. For this, data extracted from the questionnaires (qualitative) completed by the users, with information on habits, customs, and daily routines, were combined with measured data (quantitative) extracted from the monitoring campaign with information relating to the performance of the building envelope, climate data and the use of air-conditioning and heating systems at home.

Actual occupancy presence data is compiled from the electric energy consumption timetable of electric devices which do not have continuous consumption (e.g. the fridge) from which we obtained the information to generate the occupancy presence schedules [59].

2.5.1. Definition of winter patterns

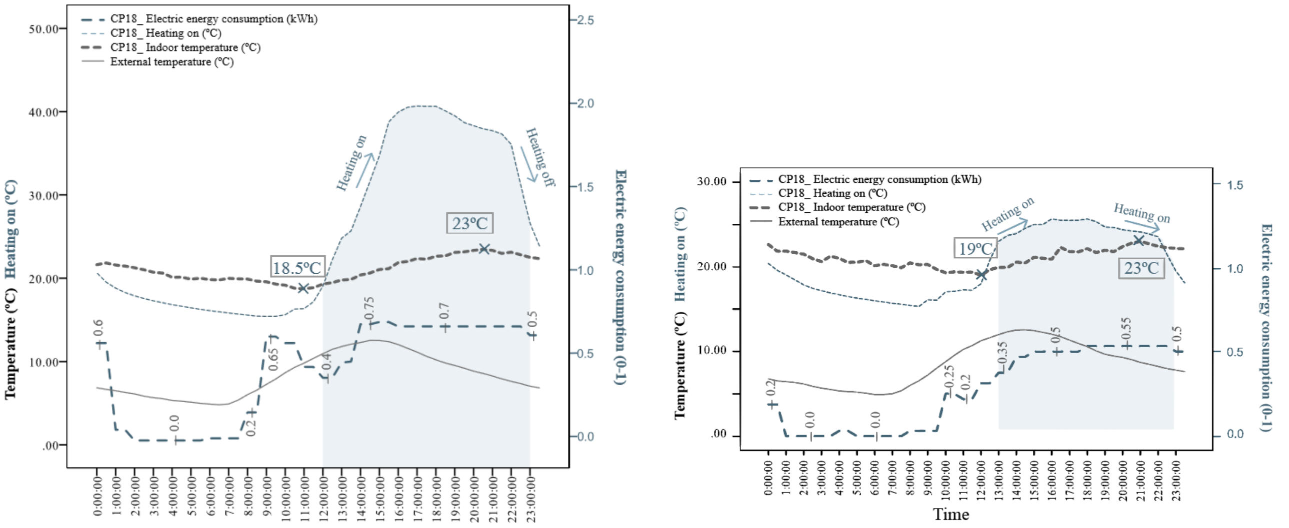
Figure 9 (refurbished) and Figure 10(non-refurbished) illustrate a mean day during the occupied period in the winter (vacation days are excluded). Mean days are elaborated for weekdays and weekends separately, given the major differences between these. The mean days are defined with the mean value per hour of the variable as follows: the use of heating systems based on the measurement of the boiler inlet temperature, the indoor temperature, the external temperature, and the electric energy consumption used to determine the occupant´s presence in the dwellings.



(a) (b)

Figure 9. Refurbished building (CP17). Mean weekday (left) and weekend (right) in winter.

As can been observed in Figure 9(a) the maximum indoor temperature of 23ºC is reached at 21:00 when heating is on and a minimum of 19ºC at 9:00 am when the user of the refurbished building (CP17) is at home and airing the house. Figure 9(b) shows that during the weekend, the user of CP17 turns the heating on between 13:00 and 23:00, more hours than during weekdays because she usually stays at home in the evening. The range of temperatures varies between 20ºC and 23.5ºC.

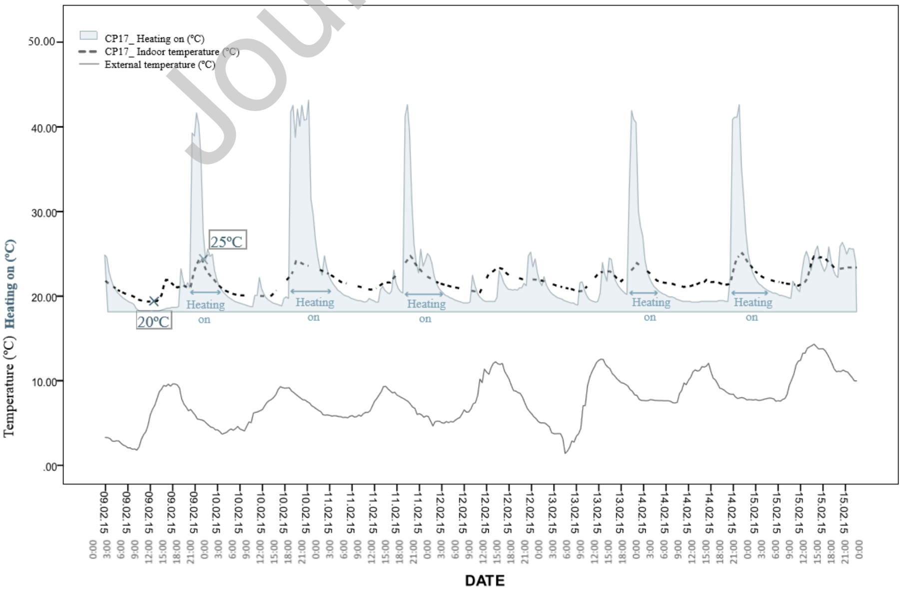


(a) *(b)*

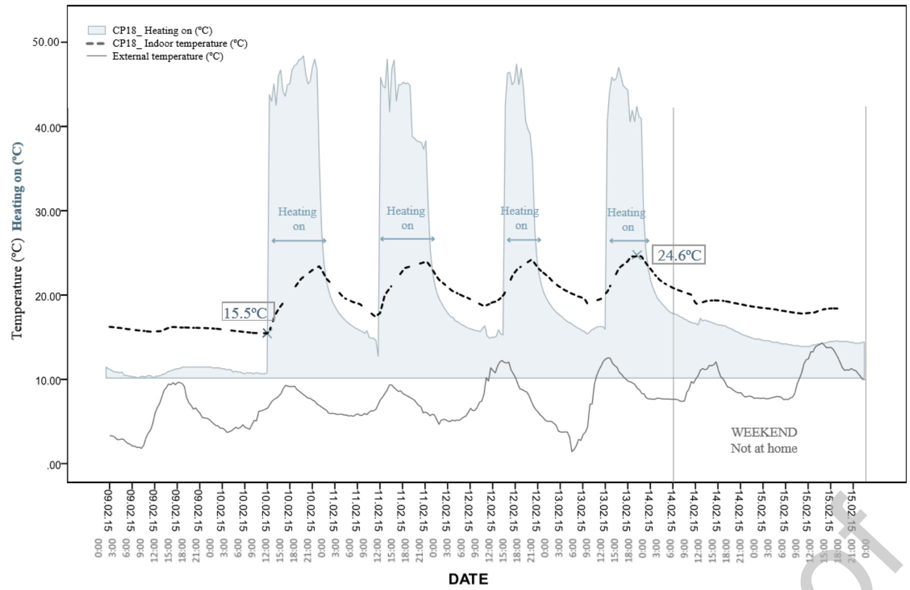
Figure 10 *Non-refurbished building (CP18). Mean weekday (left) and weekend (right) in winter.*

As shown in Figure 10(a) on weekdays the indoor temperature ranges from 18.5ºC to 23ºC. The heating system is on between 12:00 and 23:00. The use of electric devices shows how the user of CP18 is mostly at home when the heating is on. Figure 10b) illustrates that during weekends indoor temperature ranges from 19ºC to 23ºC. The maximum indoor temperature is reached at 21:00 when the heating is on. Electric energy consumption presents lower values during the weekends as the user is not at home on some of the weekends measured.

Figure 11 displays a selected week in the winter for CP17 (Fig.11(a)) and CP18 (Fig.11(b)). During this week the regular use of the heating system can be seen, as can the heating schedule and the periods where occupants are absent from home.



(a)



(b)

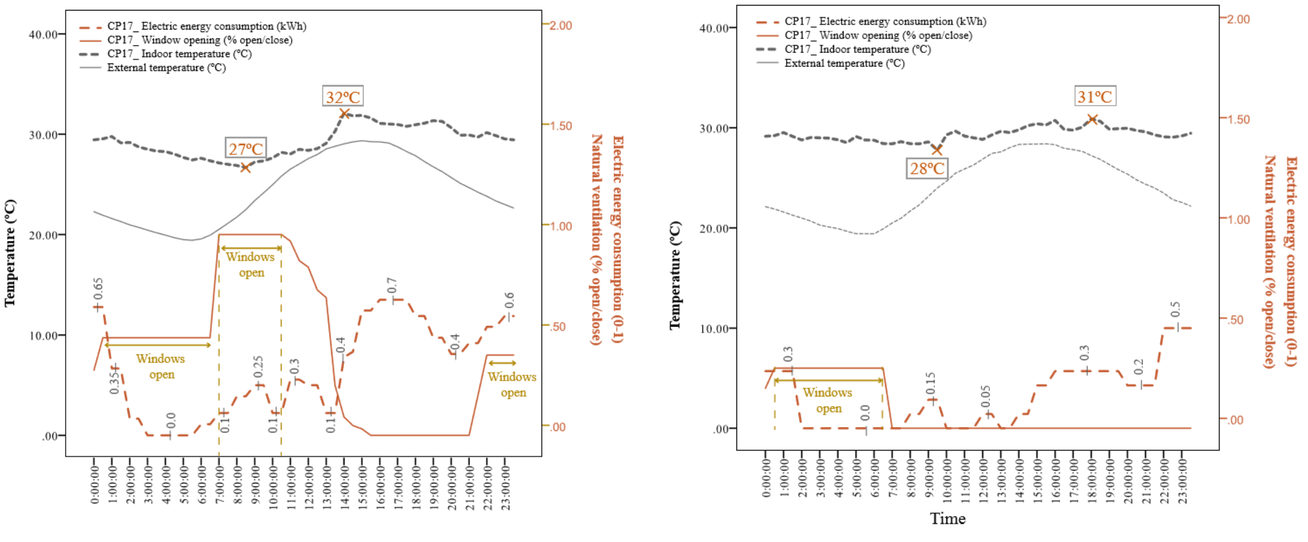
Figure 11 CP17 (above) and CP18 (below). A week in winter. Indoor and outdoor temperature and use of heating.

Figure 11(a) illustrates how the indoor temperature in this week ranges from 20ºC to 25ºC. The heating is on all but one of the 7 days of the week and the hours when the user of CP17 turns on the heating are similar every day, during the evening. In the case of CP18 (Figure 11(b)) the indoor temperature in this week ranges from 15.5ºC to 24.6ºC. The minimum temperature value is reached after the weekend when the user of CP18 is away from home. During the weekend the heating system is off and the weekday timetable for the use of heating is regular.

2.5.2. Definition of summer patterns

Figure 12 shows a mean day during the occupied period in the summer. Mean days are drawn up for weekdays and weekends, given the major differences between these. The range of indoor temperatures and when occupants open the windows can be seen.

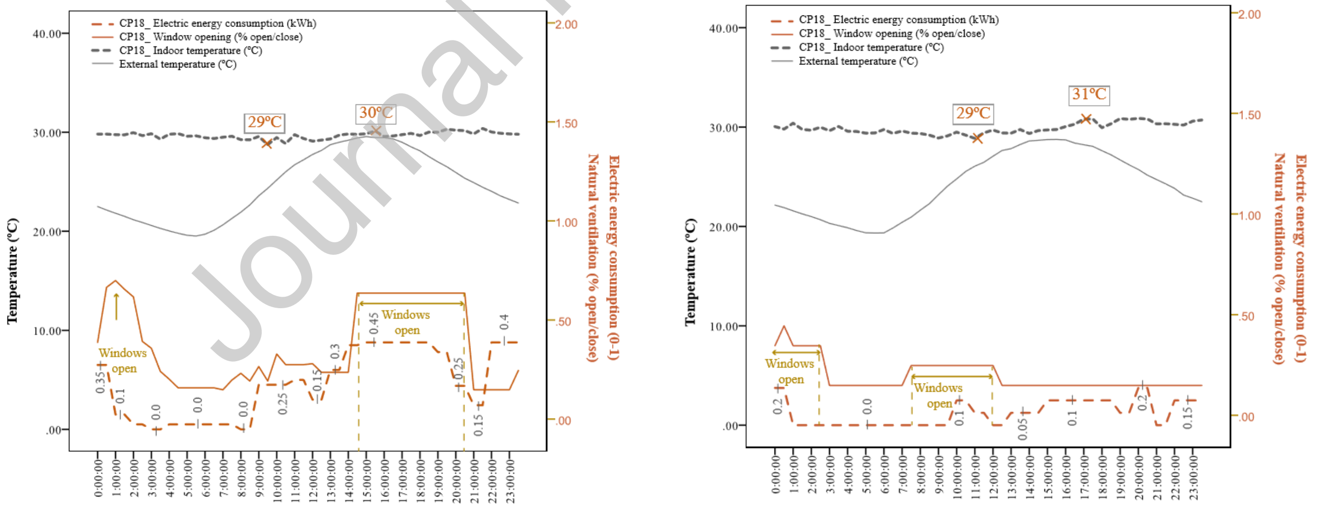
Figure 12(a) indicates that during weekdays the user opens the windows completely in the morning and partially during the night. The indoor temperature ranges from 27ºC to 32ºC, reaching the maximum value around midday. CP17 user is usually at home during the afternoon. Some weekends (Figure 12(b)) in the measured period, the user is not at home, as can be seen from the electric energy consumption, which is lower than during the weekdays. At weekends, the indoor temperature ranges from 28ºC to 31ºC.



(a) (b)

Figure 12. Refurbished building (CP17). Mean weekday (left) and weekend (right) in summer.

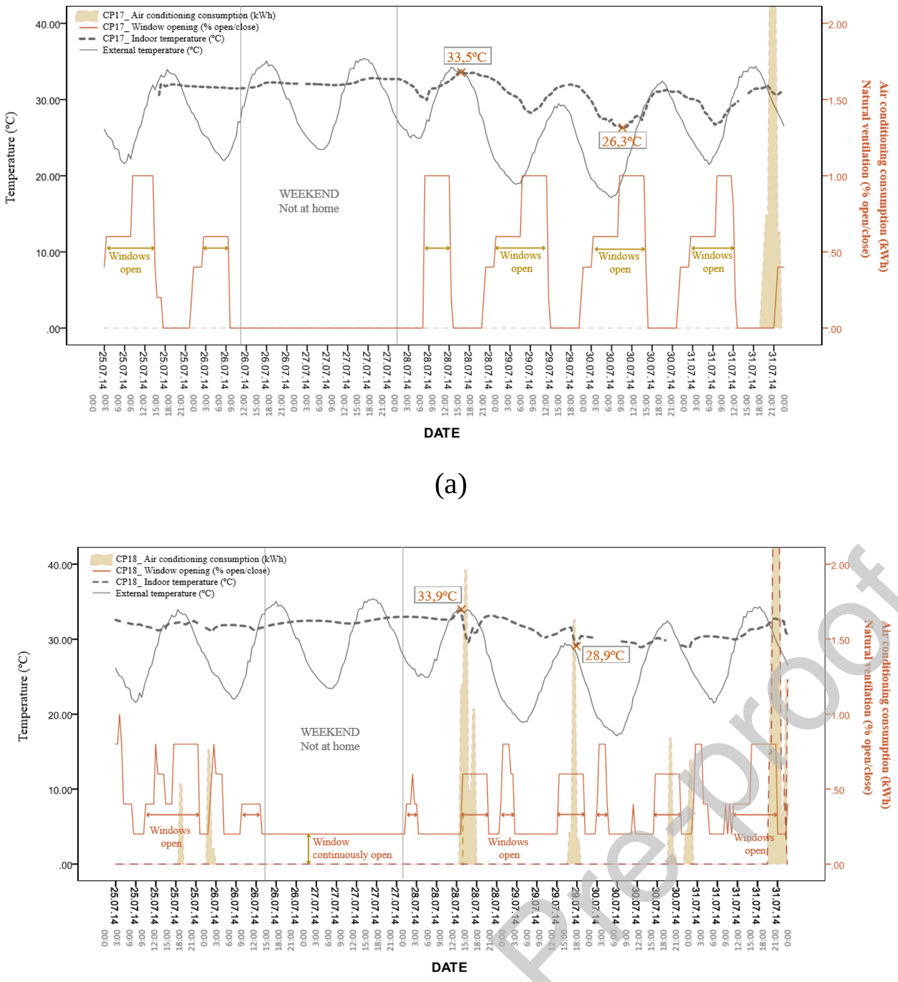
As shown in Figure 13(a) during weekdays, the range indoor temperature presents a low fluctuation from 29ºC to 30ºC. The occupant opens the windows in the afternoon and partially during the night. CP18 user is usually not at home during weekends, as can be seen from the very low mean value of the electric energy consumption (Figure 13(b)).



(a) (b)

Figure 13. Non-refurbished building (CP18). Mean weekday (left) and weekend (right) in summer.

Figure 14 shows a selected week in the summer when the dwelling is occupied. During a week the opening and closing of windows and the use of a cooling system can be observed.



(a)

(b)

Figure 14. CP17 (a) and CP18(b). A week in summer. Indoor and outdoor temperature and use of cooling

Figure 14(a) shows how the indoor temperature ranges from 26.3ºC to 33.5ºC. Windows are opened regularly, except during the weekend when CP17 user is not at home. The maximum temperature value is reached after the weekend. As can be observed in Figure 14(b) the indoor temperature ranges from 28.9ºC to 33.9ºC and the maximum value is reached after the weekend when the user has not been home. Some regularity can be observed in the opening of the windows: CP18 user opens the windows in the afternoon and at night. However, there is no evidence of regular use of the cooling system.

The irregularity of the use of the air-conditioning system in both apartments makes it difficult to establish a regular timetable for the actual use of this system. Therefore, the translation of AACC into simulation input was based on the analysis of the time series data collected for electricity consumption from the plug-in smart meter ubicated in the split unit during the summer occupied period. This analysis allow us to identify the hours during which the cooling system was on and off.

2.6. Building simulations

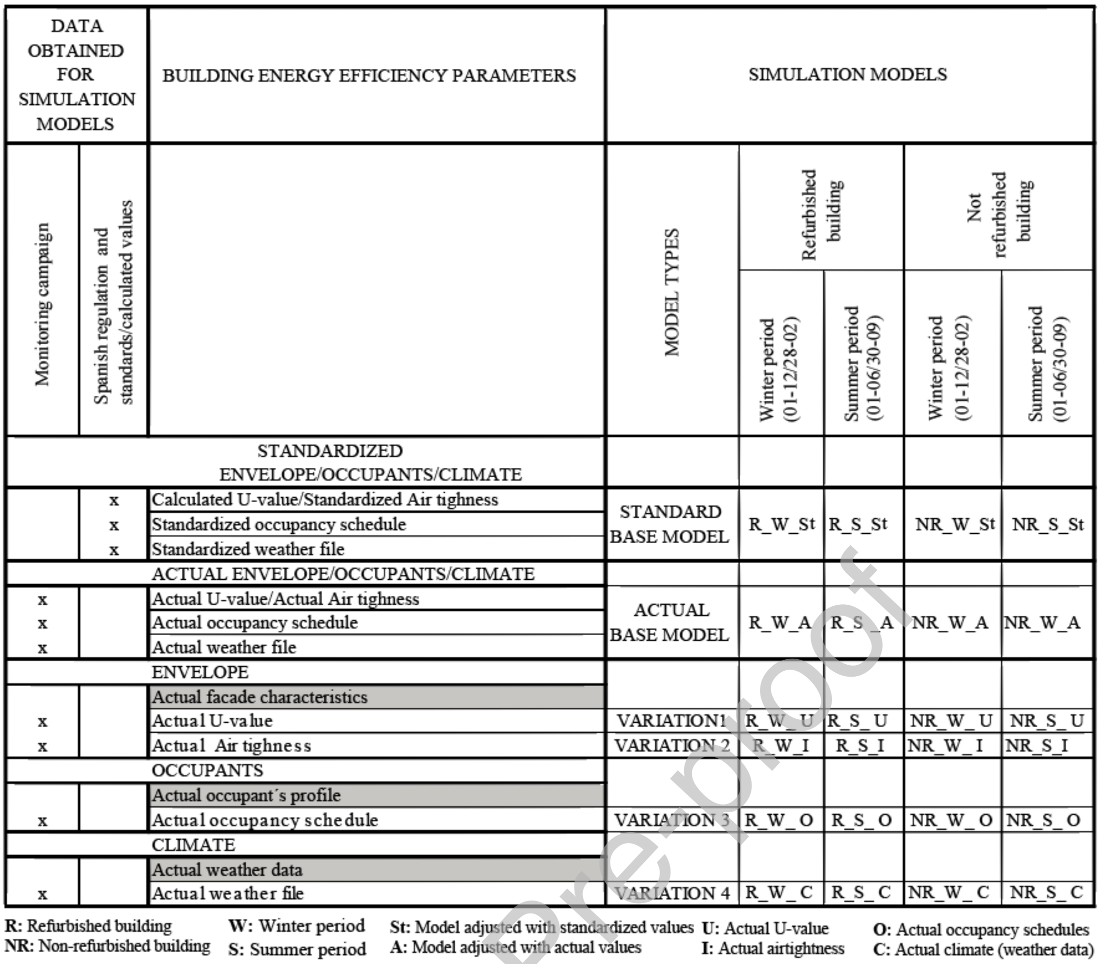
Building simulations allow us to study the influence of standard vs. actual factors (indoor, outdoor, and envelope factors) in the heating and cooling energy consumption. The actual values have been obtained from the monitoring campaign (Section 2.4) while standardized values have been collected from Spanish regulations (Spanish Building Technical Code) or recognised Spanish databases.

The building simulation software used was Design Builder [73], an EnergyPlus based software tool. The output studied was the energy consumption of the different models.

The case studies (refurbished and non-refurbished) were modelled. First, the case studies models were adjusted with all the parameters using standardized data. The case study models were then adjusted with all the parameters with actual data. This was followed by a parametric analysis, modelling 24 transient models, based on the standardized adjusted models with only one of the parameters modified on each model (U-value, Airtightness, occupancy schedules or weather data).

This parametric analysis allows us to ascertain the potential impact on the energy performance gap caused by using standardized or actual input data for building simulations.

Figure 15 shows the simulation models (types of model, simulation period, type of building) relating to the parameters studied and the type of data collected.



DATA OBTAINED FOR SIMULATION MODELS		BUILDING ENERGY EFFICIENCY PARAMETERS	SIMULATION MODELS				
				Refurbished building		Not refurbished building	
Monitoring campaign	Spanish regulation and standards/calculated values		MODEL TYPES	Winter period (01-12/28-02)	Summer period (01-06/30-09)	Winter period (01-12/28-02)	Summer period (01-06/30-09)
STANDARDIZED ENVELOPE/OCCUPANTS/CLIMATE							
	x	Calculated U-value/Standardized Air tighness	STANDARD BASE MODEL	R_W_St	R_S_St	NR_W_St	NR_S_St
	x	Standardized occupancy schedule					
	x	Standardized weather file					
		ACTUAL ENVELOPE/OCCUPANTS/CLIMATE					
x		Actual U-value/Actual Air tighness	ACTUAL BASE MODEL	R_W_A	R_S_A	NR_W_A	NR_W_A
x		Actual occupancy schedule					
x		Actual weather file					
		ENVELOPE					
		Actual facade characteristics					
x		Actual U-value	VARIATION1	R_W_U	R_S_U	NR_W_U	NR_S_U
x		Actual Air tighness	VARIATION 2	R_W_I	R_S_I	NR_W_I	NR_S_I
		OCCUPANTS					
		Actual occupant´s profile					
x		Actual occupancy schedule	VARIATION 3	R_W_O	R_S_O	NR_W_O	NR_S_O
		CLIMATE					
		Actual weather data					
x		Actual weather file	VARIATION 4	R_W_C	R_S_C	NR_W_C	NR_S_C

R: Refurbished building
NR: Non-refurbished building
W: Winter period
S: Summer period
St: Model adjusted with standardized values
A: Model adjusted with actual values
U: Actual U-value
I: Actual airtightness
O: Actual occupancy schedules
C: Actual climate (weather data)

Figure 15 Building simulation models.

2.6.1. Calibration models

In order to ascertain whether the models are adjusted to the actual building energy behaviour, simulation models have been calibrated following the statistic validation established in ASHRAE Guideline 14-2014[74] based on two error indicators: Normalized Mean Bias Error (NMBE), equation (2), and Coefficient of Variation of the Root-Mean-Square Error (CV (RMSE)), equation (3). ASHRAE Guideline 14 considers a building model to be calibrated with hourly data when monthly NMBE values fall within± 10% and monthly CV(RMSE) values fall below 30%.

Normalized Mean Bias Error (NMBE)

$$NMBE = \frac{1}{m} \times \frac{\sum_{i=1}^{N_i}(M_i - S_i)}{n-p} \times 100\ (\%) \qquad (2)$$

Coefficient of Variation of the Root-Mean-Square Error (CV (RMSE))

$$CV\ (RMSE) = \frac{1}{m} \times \sqrt{\frac{\Sigma_{i=1}^{N_i}(Mi - S_i)^2}{n-p}} \times 100\ (\%) \qquad (3)$$

where:

m: mean of measured values;

n: number of measured data;

p: number of adjustable model parameters. Use of 1 is recommended;

Mi: measured data at instance i;

Si: simulated data at instance i;

Ni: number of dates used in the calibration.

3. Results

The results are presented in three sections. The monitoring campaign results are presented in Section 3.1 to compare the actual values with the standardized ones. Section 3.2 analyses the mixed-method-approach results to generate the occupancy patterns and time-lines to adjust the simulation models. In Section 5.3 the energy consumption results are presented as Design Builder software is used to model the case studies.

3.1. Monitoring campaign results

This section presents the results on the actual data relating to users, building characteristics and weather data. Furthermore, the information collected from the monitoring campaign was compared with the standard data usually used as input data in the characterization of building simulation models to establish the extent of the differences between them.

3.1.1. Building envelope parameters (envelope factors)

In this section the actual U-value obtained from the monitoring campaign (Section 2.4) is compared with the standard global thermal transmittance value, which has been calculated following the method defined in the Spanish Technical Building Code [75] and it can be seen in Table 2.

Table 2 Calculated U-value (standardized value)

	CP17		**CP18**	
	Thermal resistance	U-value W/m^{2}K	Thermal resistance	U-value W/m^{2}K
Rse	0.04		0.04	
Thermal insulation	1.15		x	
Solid brick	0.28		0.28	
Coated with plaster	0.03		0.03	
Rsi	0.13		0.13	
	1.63	**0,61**	**0.48**	**2,07**

Rsi and Rse denote the internal surface resistance and external surface resistance respectively and the value depends of the direction of heat flow.

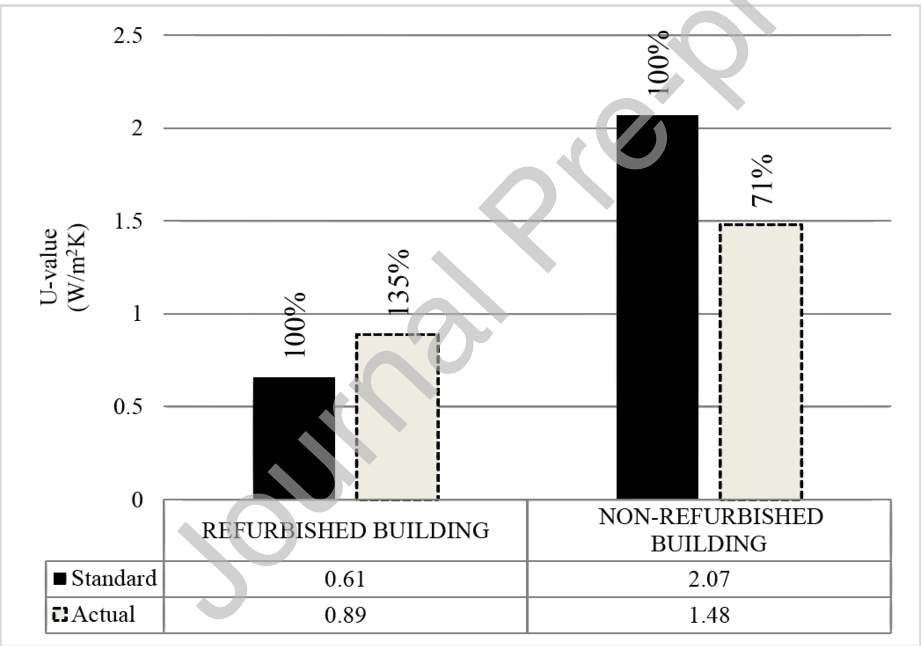
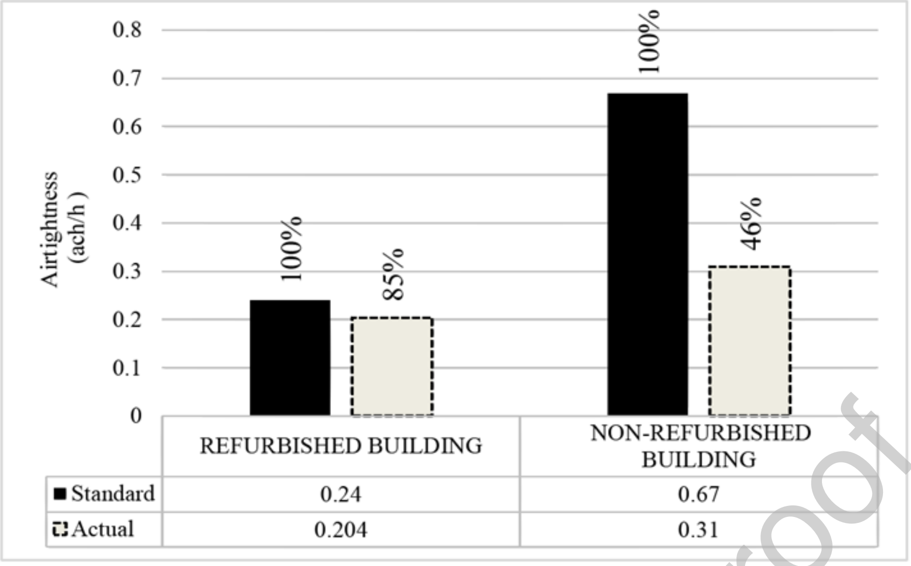


Figure 16 Comparison standardized and actual U-values

Figure 16 shows that, as expected, the U-value in the non-refurbished building is higher than in the refurbished one, both in standardized and measured values. However, a comparison of the actual (measured) parameters with the standardized parameters shows a discrepancy: the U-value is underestimated for the refurbished buildings (i.e. the actual U-value is higher than expected) and the U-value for the non-refurbished building is overestimated (i.e. the actual U-value is lower than expected).

The standard airtightness values used in simulation models for refurbished and non-refurbished buildings were 0.240 h-1 at 1Pa and 0.670 h-1 at 1Pa respectively. These values followed recommendations from officially recognised Spanish databases [76].



	REFURBISHED BUILDING	NON-REFURBISHED BUILDING
■ Standard	0.24	0.67
⬚ Actual	0.204	0.31

Figure 17 Comparison standardized and actual airtightness values

A comparison of the actual (measured) and the standard airtightness (Figure 17) shows a notable underestimation of the airtightness in the non-refurbished building (i.e. the actual airtightness is better than expected), while in the refurbished building there is a slight difference between the standard and actual values.

3.1.2. Climate parameters (outdoor factors)

The standard weather parameter values used as default for the city of Madrid in simulation models were obtained from the SWEC (Spanish Weather for Energy Calculations) weather file [77]. These weather files and were generated using Climed (Portuguese software developed by Ricardo Aguiar) from mean monthly data provided by the Spanish Meteorological National Institute and were converted from the DOE-2 binary to the EnergyPlus format [78]. These files are commonly used by modellers and designers for energy calculations.

Actual weather parameters were measured by a local weather station located on the rooftop of a building close to the case study buildings as explained in Section 2.4.

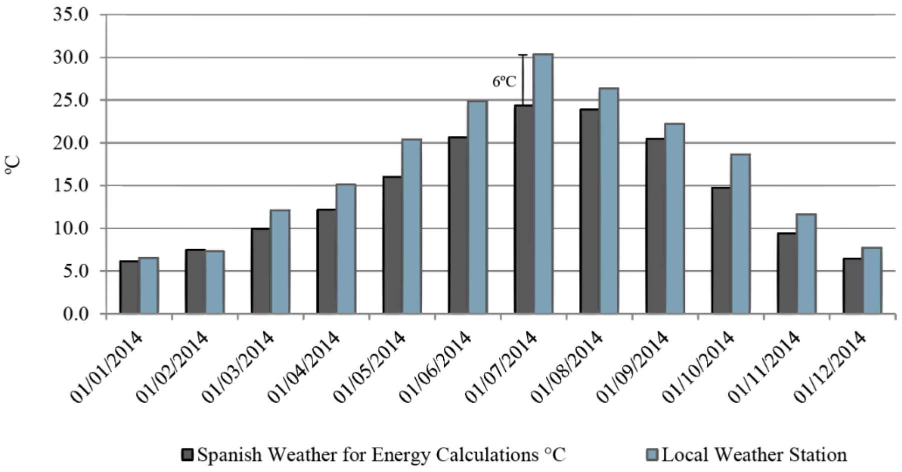


Figure 18 Outdoor dry-bulb temperature (ºC)

According to Figure 18, the temperature data from the local weather station were higher than standard temperature data throughout the year. This difference was heightened in the summer months (from May to August) increasing to 6ºC difference in July, the hottest month of the year.

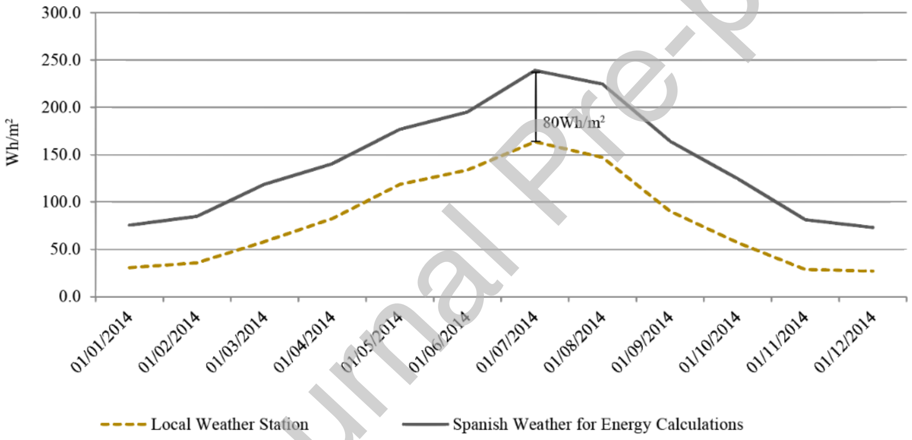


Figure 19 Normal Direct Solar Radiation (Wh/m^2)

Normal direct solar radiation presented a similar curve considering standard and actual data, but standard values were significantly higher (Figure 19) increasing by 80Wh/m^2 in July.

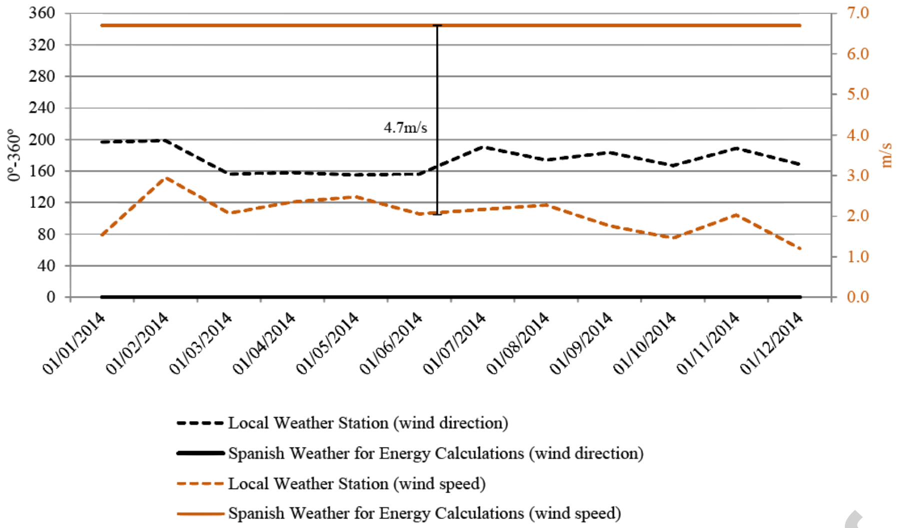


Figure 20 Wind Speed and Direction (m/s, º)

As shown in Figure 20 standard weather data included constant direction of 0º and constant wind speeds of 6.7 m/s. However, the actual climate data collected by a local weather station included real wind speed (lower than standard values) and direction.

Figure 18, Figure 19, and Figure 20 show significant differences between standard and actual data. The highest differences in outside dry-bulb temperature and normal direct solar radiation are found in the summer months, especially in July, and this may have a significant influence on the cooling consumption.

3.2. Mixed-method approach results

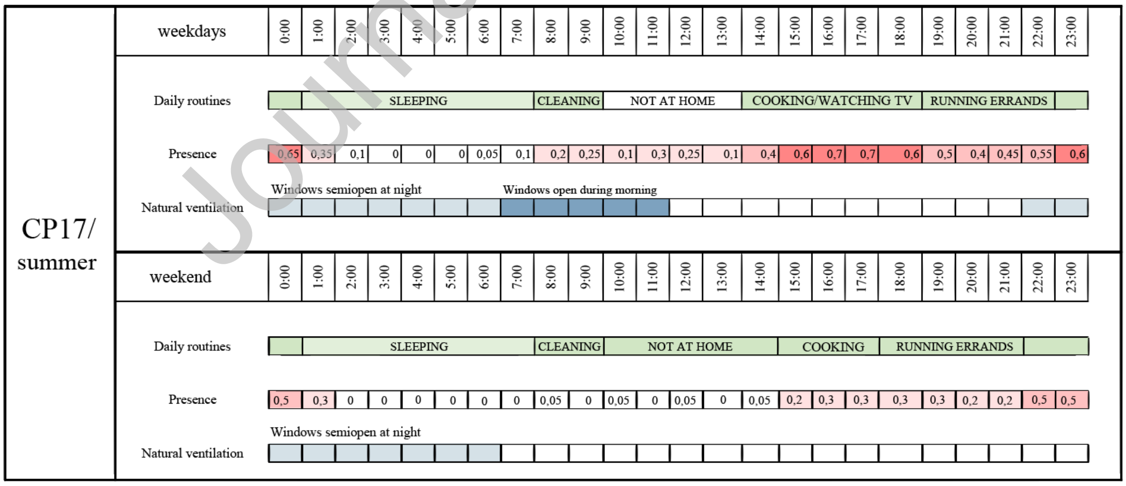
3.2.1.Daily routines: input for building simulation

Figure 21 to Figure 24 indicate the time-lines established after analysing the application of the Mixed-method approach (Section 2.5), combined with the information extracted from the questionnaires and diaries from the occupants, all of which are described below. These time-lines are explained in diary form and include relevant data that allow the simulation models to be adjusted in Section 3.2.2 below.

	weekdays	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
CP17/ winter	Daily routines		SLEEPING						CLEANING		NOT AT HOME (WORKING)							COOKING		WATCHING TV					
	Presence	0,95	0,6	0,1	0	0	0	0,1	0,25	0,5	0,6	0,4	0,15	0,1	0,15	0,35	0,7	0,85	0,9	0,85	0,85	0,95	0,95	1	1
	Heating on																	■	■	■	■ Heating on when cold	■	■	■	■
	Natural ventilation								■ Windows open while cleaning	■															
	weekend	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
	Daily routines		SLEEPING						CLEANING				RUNNING ERRANDS					COOKING		WATCHING TV					
	Presence	0,95	0,45	0,15	0	0	0	0,1	0,25	0,5	0,4	0,5	0,05	0,1	0,15	0,4	0,55	0,85	0,95	0,85	0,95	0,95	1	1	1
	Heating on														■	■	■	■ Heating on when she is visited by family	■	■	■	■	■	■	■
	Natural ventilation								■ Windows open while cleaning	■															

Figure 21 Time-lines. Refurbished building (CP17). Winter

CP17 user wakes up at 7 in the morning, she has breakfast, then takes a shower, gets dressed, and cleans the house while ventilating. She leaves the house and is out at work all morning. At noon she returns home for lunch and in the afternoons, she sometimes goes out to run errands. In the late evening, she cooks, has dinner, and watches the TV in the dining room until bedtime. She only puts the boiler on for heating manually when she feels cold, usually late in the evening. At weekends, she follows a routine similar to the weekday one, leaving home in the morning, but instead of working she runs errands or visits her family. She usually arrives home earlier than on weekdays and turns on the heating system at noon. At weekends, she is usually visited by her family, and also turns the heating on earlier for this reason.



	weekdays	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
CP17/ summer	Daily routines		SLEEPING							CLEANING		NOT AT HOME				COOKING/WATCHING TV					RUNNING ERRANDS				
	Presence	0,65	0,35	0,1	0	0	0	0,05	0,1	0,2	0,25	0,1	0,3	0,25	0,1	0,4	0,6	0,7	0,7	0,6	0,5	0,4	0,45	0,55	0,6
	Natural ventilation	▒ Windows semiopen at night	▒	▒	▒	▒	▒	▒	■ Windows open during morning	■	■	■	■											▒	▒
	weekend	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
	Daily routines		SLEEPING							CLEANING		NOT AT HOME					COOKING			RUNNING ERRANDS					
	Presence	0,5	0,3	0	0	0	0	0	0	0,05	0	0,05	0	0,05	0	0,05	0,2	0,3	0,3	0,3	0,3	0,2	0,2	0,5	0,5
	Natural ventilation	▒ Windows semiopen at night	▒	▒	▒	▒	▒	▒																	

Figure 22 Time-lines. Refurbished building (CP17). Summer

The summer routine of CP17 user is similar to the winter one, although she tends to spend more time away from home. While she is in Madrid, she continues to work part-time outside the home looking after an elderly man who lives in her neighbourhood. She gets up, has breakfast, takes a shower and gets dressed before leaving the house. In summer, the hours of ventilation are increased, and the windows are opened during the morning, for health purposes and in an attempt to remove the excess heat through ventilation. She usually leaves the house late in the afternoon to run errands. During the night she also opens the windows when the outside temperature starts to drop. She is not in Madrid most weekends.

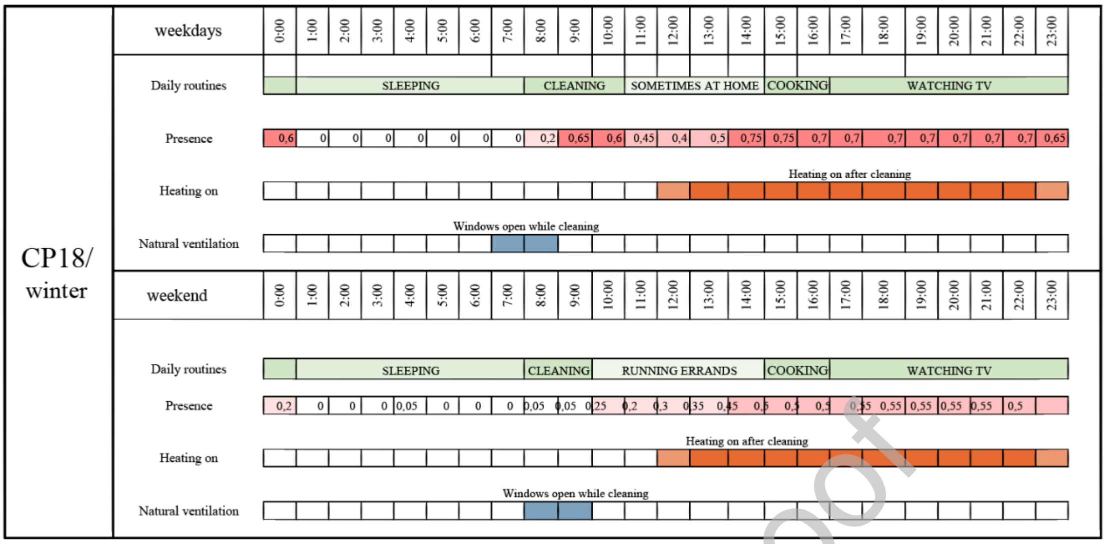


Figure 23 Time-lines. Non-refurbished building (CP18). Winter

CP18 user gets up around 7 in the morning, has breakfast, takes a shower, and gets dressed. She ventilates and cleans the house. When she closes the windows after ventilation, she turns on the heating system. During the morning she sometimes runs errands and returns home at noon to have lunch. She usually stays at home in the afternoon, but occasionally goes out for a walk with friends. She returns home for dinner and watches TV in the dining room until she goes to bed. At weekends, she is sometimes at home since she spends these days with her son. Occasionally, she stays at home at the weekends, and follows the same routine as during the week.

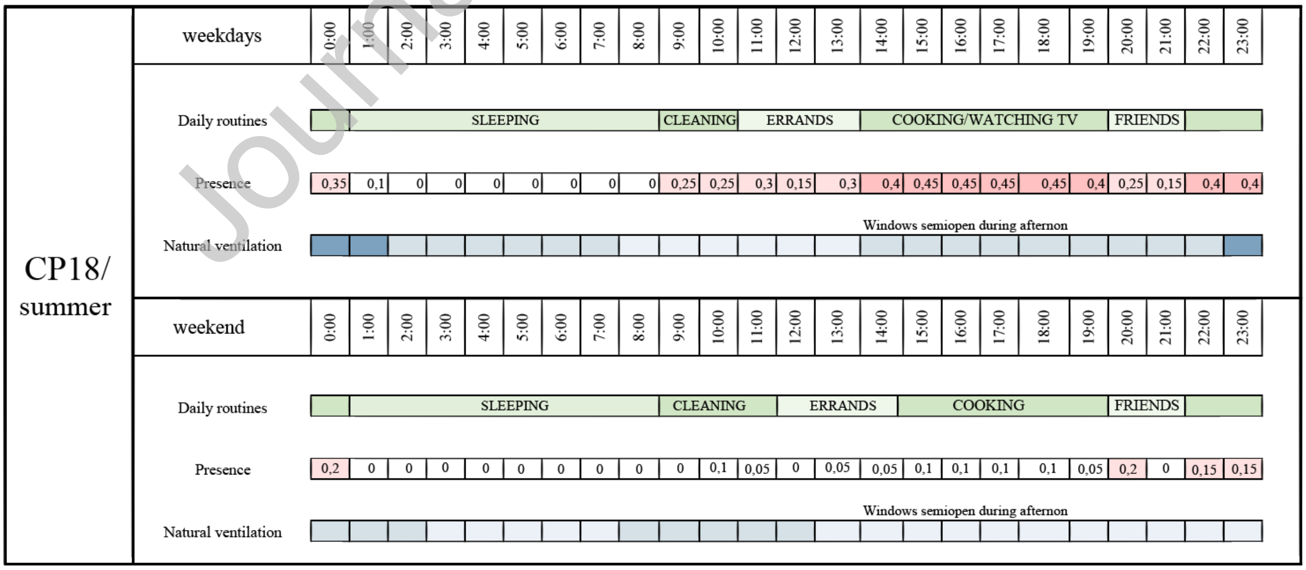
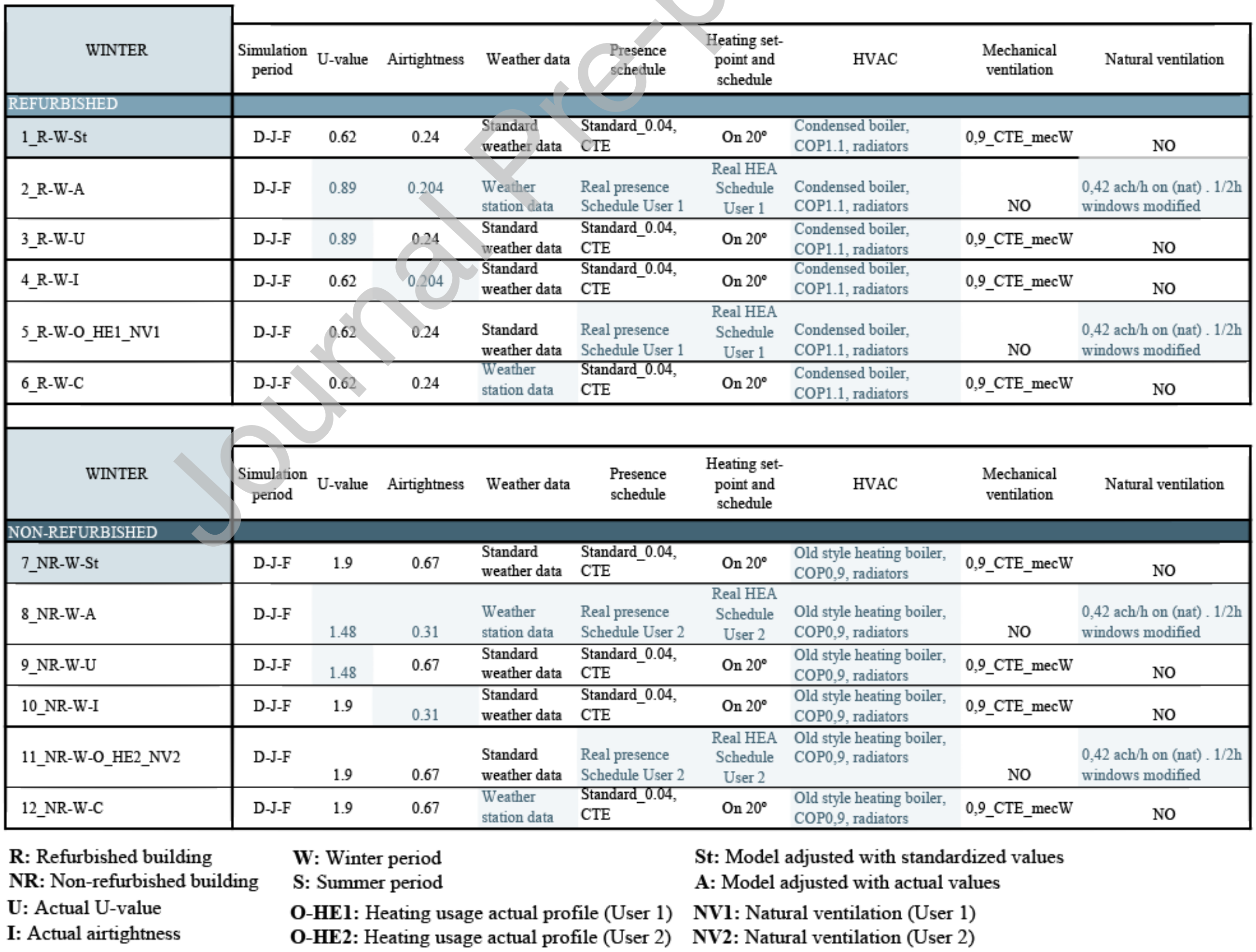


Figure 24 Time-lines. Non-refurbished building (CP18). Summer

In summer, CP18 user gets up around 7, just as in the winter. She has breakfast, takes a shower and gets dressed. Then, she usually goes out to run errands. She opens the windows slightly for ventilation in the morning but leaves the windows wide open in the afternoon hours. She returns home at noon for lunch and spends the afternoon watching TV until late afternoon. When the sun goes down, she usually goes out with her friends to take a walk. Just as in the winter, most weekends she is not at home.

3.2.2. Definition of energy simulation models

The monitoring campaign and the mixed-method approach yields results that allow the characterization of the energy simulation models. In this section, the simulation models are described by specifying the input data used for each model. In the first column Figure 25 and Figure 26 present the abbreviations used to name the models generated for winter and summer respectively, in order to evaluate heating and cooling consumption separately. Both figures show the input parameters used to adjust each model and highlight the actual data collected from the monitoring campaign in blue (Figure 25) and orange (Figure 26).

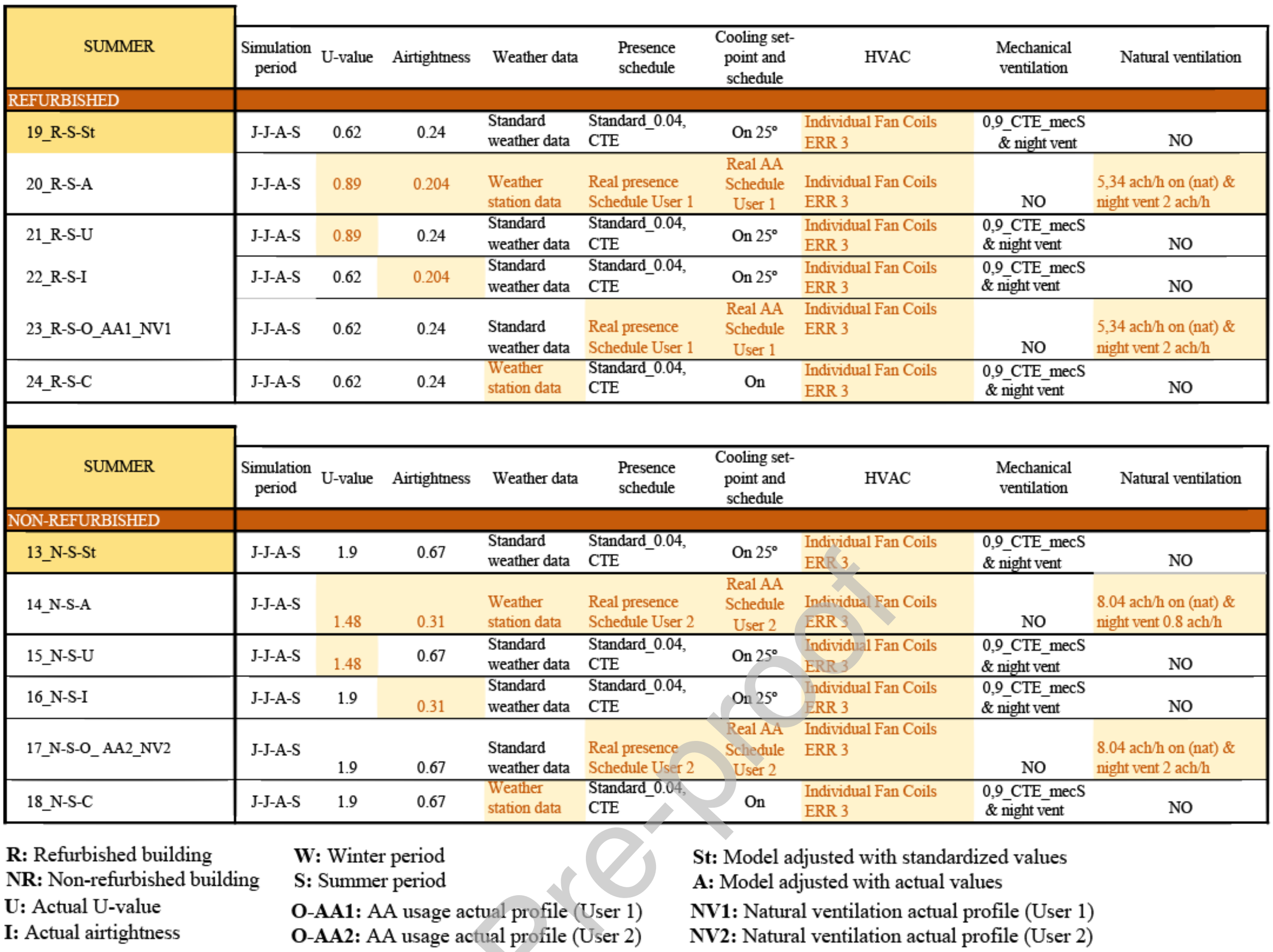


WINTER	Simulation period	U-value	Airtightness	Weather data	Presence schedule	Heating set-point and schedule	HVAC	Mechanical ventilation	Natural ventilation
REFURBISHED									
1_R-W-St	D-J-F	0.62	0.24	Standard weather data	Standard_0.04, CTE	On 20°	Condensed boiler, COP1.1, radiators	0,9_CTE_mecW	NO
2_R-W-A	D-J-F	0.89	0.204	Weather station data	Real presence Schedule User 1	Real HEA Schedule User 1	Condensed boiler, COP1.1, radiators	NO	0,42 ach/h on (nat) . 1/2h windows modified
3_R-W-U	D-J-F	0.89	0.24	Standard weather data	Standard_0.04, CTE	On 20°	Condensed boiler, COP1.1, radiators	0,9_CTE_mecW	NO
4_R-W-I	D-J-F	0.62	0.204	Standard weather data	Standard_0.04, CTE	On 20°	Condensed boiler, COP1.1, radiators	0,9_CTE_mecW	NO
5_R-W-O_HE1_NV1	D-J-F	0.62	0.24	Standard weather data	Real presence Schedule User 1	Real HEA Schedule User 1	Condensed boiler, COP1.1, radiators	NO	0,42 ach/h on (nat) . 1/2h windows modified
6_R-W-C	D-J-F	0.62	0.24	Weather station data	Standard_0.04, CTE	On 20°	Condensed boiler, COP1.1, radiators	0,9_CTE_mecW	NO

WINTER	Simulation period	U-value	Airtightness	Weather data	Presence schedule	Heating set-point and schedule	HVAC	Mechanical ventilation	Natural ventilation
NON-REFURBISHED									
7_NR-W-St	D-J-F	1.9	0.67	Standard weather data	Standard_0.04, CTE	On 20°	Old style heating boiler, COP0,9, radiators	0,9_CTE_mecW	NO
8_NR-W-A	D-J-F	1.48	0.31	Weather station data	Real presence Schedule User 2	Real HEA Schedule User 2	Old style heating boiler, COP0,9, radiators	NO	0,42 ach/h on (nat) . 1/2h windows modified
9_NR-W-U	D-J-F	1.48	0.67	Standard weather data	Standard_0.04, CTE	On 20°	Old style heating boiler, COP0,9, radiators	0,9_CTE_mecW	NO
10_NR-W-I	D-J-F	1.9	0.31	Standard weather data	Standard_0.04, CTE	On 20°	Old style heating boiler, COP0,9, radiators	0,9_CTE_mecW	NO
11_NR-W-O_HE2_NV2	D-J-F	1.9	0.67	Standard weather data	Real presence Schedule User 2	Real HEA Schedule User 2	Old style heating boiler, COP0,9, radiators	NO	0,42 ach/h on (nat) . 1/2h windows modified
12_NR-W-C	D-J-F	1.9	0.67	Weather station data	Standard_0.04, CTE	On 20°	Old style heating boiler, COP0,9, radiators	0,9_CTE_mecW	NO

R: Refurbished building
NR: Non-refurbished building
U: Actual U-value
I: Actual airtightness
W: Winter period
S: Summer period
O-HE1: Heating usage actual profile (User 1)
O-HE2: Heating usage actual profile (User 2)
St: Model adjusted with standardized values
A: Model adjusted with actual values
NV1: Natural ventilation (User 1)
NV2: Natural ventilation (User 2)

Figure 25 Data to adjust energy simulation models for winter



SUMMER	Simulation period	U-value	Airtightness	Weather data	Presence schedule	Cooling set-point and schedule	HVAC	Mechanical ventilation	Natural ventilation
REFURBISHED									
19_R-S-St	J-J-A-S	0.62	0.24	Standard weather data	Standard_0.04, CTE	On 25°	Individual Fan Coils ERR 3	0,9_CTE_mecS & night vent	NO
20_R-S-A	J-J-A-S	0.89	0.204	Weather station data	Real presence Schedule User 1	Real AA Schedule User 1	Individual Fan Coils ERR 3	NO	5,34 ach/h on (nat) & night vent 2 ach/h
21_R-S-U	J-J-A-S	0.89	0.24	Standard weather data	Standard_0.04, CTE	On 25°	Individual Fan Coils ERR 3	0,9_CTE_mecS & night vent	NO
22_R-S-I	J-J-A-S	0.62	0.204	Standard weather data	Standard_0.04, CTE	On 25°	Individual Fan Coils ERR 3	0,9_CTE_mecS & night vent	NO
23_R-S-O_AA1_NV1	J-J-A-S	0.62	0.24	Standard weather data	Real presence Schedule User 1	Real AA Schedule User 1	Individual Fan Coils ERR 3	NO	5,34 ach/h on (nat) & night vent 2 ach/h
24_R-S-C	J-J-A-S	0.62	0.24	Weather station data	Standard_0.04, CTE	On	Individual Fan Coils ERR 3	0,9_CTE_mecS & night vent	NO

SUMMER	Simulation period	U-value	Airtightness	Weather data	Presence schedule	Cooling set-point and schedule	HVAC	Mechanical ventilation	Natural ventilation
NON-REFURBISHED									
13_N-S-St	J-J-A-S	1.9	0.67	Standard weather data	Standard_0.04, CTE	On 25°	Individual Fan Coils ERR 3	0,9_CTE_mecS & night vent	NO
14_N-S-A	J-J-A-S	1.48	0.31	Weather station data	Real presence Schedule User 2	Real AA Schedule User 2	Individual Fan Coils ERR 3	NO	8.04 ach/h on (nat) & night vent 0.8 ach/h
15_N-S-U	J-J-A-S	1.48	0.67	Standard weather data	Standard_0.04, CTE	On 25°	Individual Fan Coils ERR 3	0,9_CTE_mecS & night vent	NO
16_N-S-I	J-J-A-S	1.9	0.31	Standard weather data	Standard_0.04, CTE	On 25°	Individual Fan Coils ERR 3	0,9_CTE_mecS & night vent	NO
17_N-S-O_ AA2_NV2	J-J-A-S	1.9	0.67	Standard weather data	Real presence Schedule User 2	Real AA Schedule User 2	Individual Fan Coils ERR 3	NO	8.04 ach/h on (nat) & night vent 2 ach/h
18_N-S-C	J-J-A-S	1.9	0.67	Weather station data	Standard_0.04, CTE	On	Individual Fan Coils ERR 3	0,9_CTE_mecS & night vent	NO

R: Refurbished building
NR: Non-refurbished building
U: Actual U-value
I: Actual airtightness
W: Winter period
S: Summer period
O-AA1: AA usage actual profile (User 1)
O-AA2: AA usage actual profile (User 2)
St: Model adjusted with standardized values
A: Model adjusted with actual values
NV1: Natural ventilation actual profile (User 1)
NV2: Natural ventilation actual profile (User 2)

Figure 26 Data to adjust energy simulation models for summer.

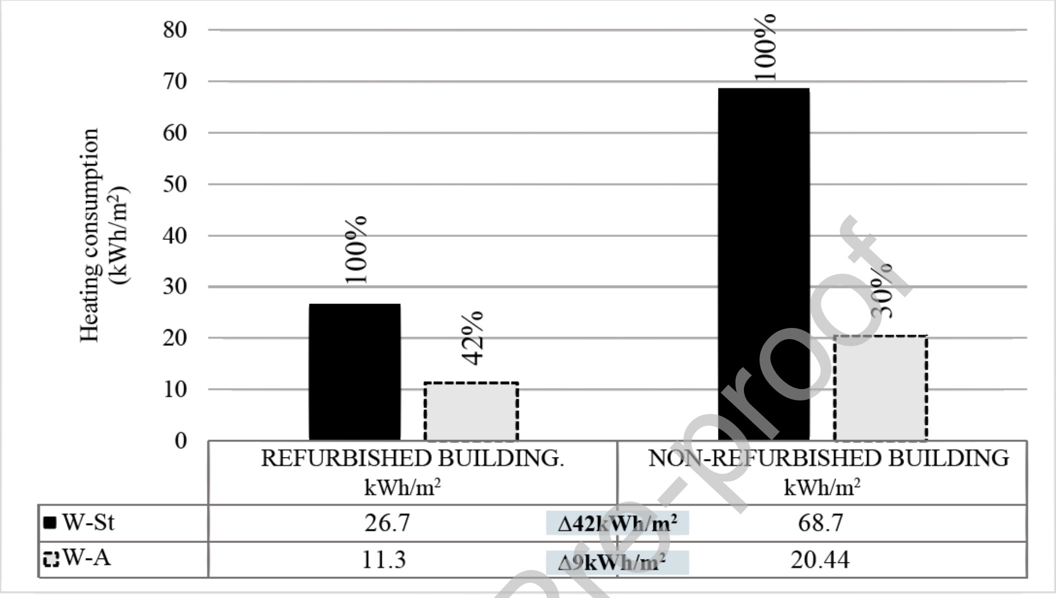
3.3. Energy simulation results

The simulation results for summer and winter are presented in this section.

The evaluation of the total heating and cooling consumption is performed in **two steps**. Firstly, **the total consumption for both the refurbished and non-refurbished conditions is analysed using two models**: the first using **all standard input data, plotted in black (St),** and the second using **all actual measured data, plotted in grey (A)** in relation to envelope parameters, occupancy patterns, and weather data. Secondly, in order to build on the previous findings, the energy consumption results obtained from the simulation models are shown as **standard, actual data, and a parametric study when only one parameter is changed**. These last models have been created based on the standard model and changing different parameters one by one: **U-value (U), Air tightness (I), occupancy variables (O), or weather data (CL)**. Figure 25 and Figure 26 list the input data used for each model.

From Figure 27 to Figure 30, graph bars are labelled with the percentage variation with respect to the model adjusted with standard data, which represents 100%. For the purposes of comparison each figure table shows the energy consumption difference between the refurbished and non-refurbished building highlighted.

3.3.1. Energy consumption for heating



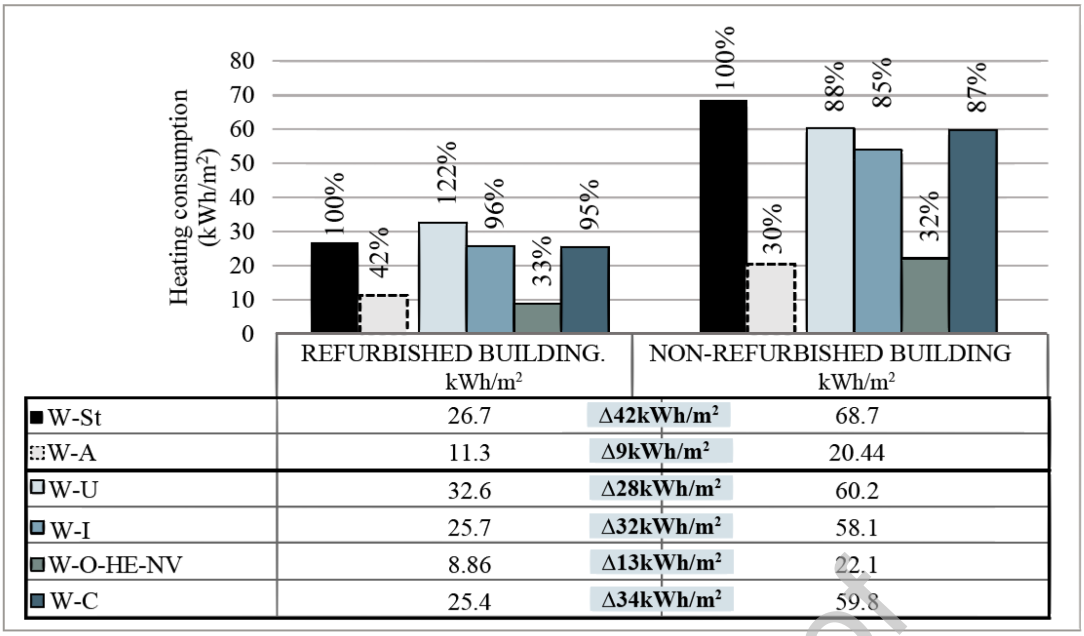
	REFURBISHED BUILDING. kWh/m²		NON-REFURBISHED BUILDING kWh/m²
■ W-St	26.7	Δ42kWh/m²	68.7
⬚ W-A	11.3	Δ9kWh/m²	20.44

W: Winter period **St:** Model adjusted with all standardized values
S: Summer period **A:** Model adjusted with all actual values

Figure 27 Total heating consumption

Figure 27 indicates that, for the **refurbished building**, the consumption in the model adjusted with standard data is more than double that of the model adjusted with actual data. However, in the **non-refurbished** case this difference is more than tripled.

Comparing the results between the refurbished and non-refurbished buildings, it can be seen that the simulations with standard data reveal a reduction in energy use of **42 kWh/m^2** per year, while the simulations with actual data provide a reduction of only **9.1 kWh/m^2** per year.



	REFURBISHED BUILDING. kWh/m^2		NON-REFURBISHED BUILDING kWh/m^2
■ W-St	26.7	Δ42kWh/m^2	68.7
⬚ W-A	11.3	Δ9kWh/m^2	20.44
□ W-U	32.6	Δ28kWh/m^2	60.2
■ W-I	25.7	Δ32kWh/m^2	58.1
■ W-O-HE-NV	8.86	Δ13kWh/m^2	22.1
■ W-C	25.4	Δ34kWh/m^2	59.8

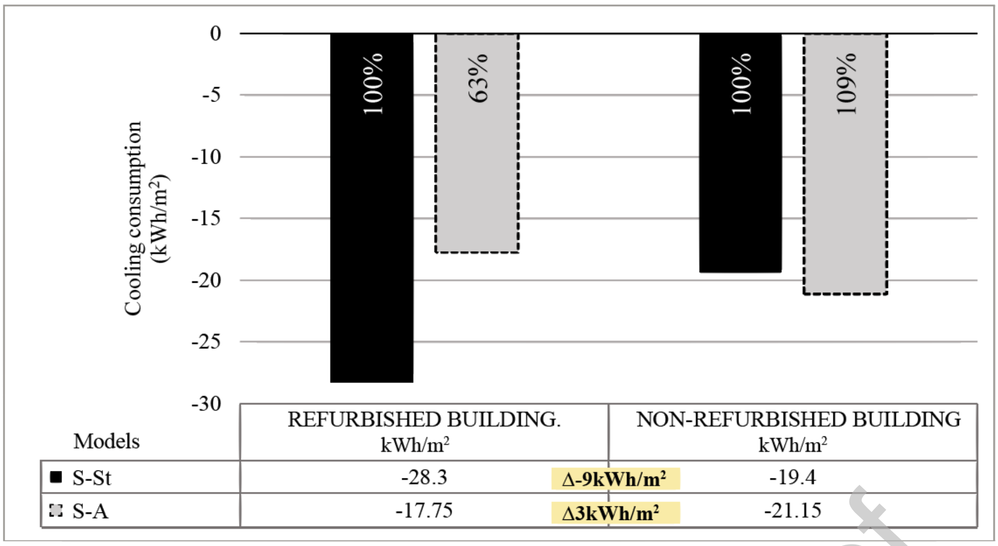
W: Winter period
S: Summer period
U: Actual U-value
I: Actual airtightness
St: Model adjusted with all standardized values
A: Model adjusted with all actual values
O-HE: Heating usage actual profile
NV: Natural ventilation actual profile

Figure 28 Parametric study of the total heating consumption

Figure 28 shows how in the **refurbished building**, the result of adjusting the **actual U-value** is the only parameter which generates an **increase in energy consumption** (i.e. 122%-100%=22%) in comparison to the model adjusted with standard values. However, the result of adjusting the actual airtightness and actual weather data indicates a reduction in consumption of 4% and 5% respectively, in comparison to the model adjusted with standard values. The adjustment of the **actual occupancy variables** reveals a **drastic reduction in energy consumption** (i.e. 100%-33%=67%) and **was the most influential factor in the gap between the model adjusted with standard or actual values**. **Therefore, the most important parameters are U-value and occupancy-related parameters, while air-tightness and climate do not show a significant difference.**

Regarding the **non-refurbished building**, **the adjustment with actual values of all parameters indicates a reduction in energy consumption**. There are similarities between the influence of the adjustment of actual U-value, actual airtightness and actual weather data (**differences between 11%-13%**) compared to the model adjusted with standard data. However, in the refurbished building, the adjustment of **actual occupancy variables in the simulation model also has a significant influence on the results, reducing energy consumption by 68%** compared to the model adjusted with standard values.

3.3.2. Energy consumption for cooling



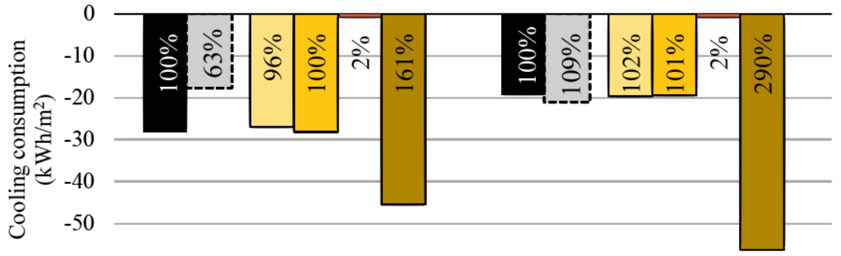
Models	REFURBISHED BUILDING. kWh/m^2		NON-REFURBISHED BUILDING kWh/m^2
■ S-St	-28.3	Δ-9kWh/m^2	-19.4
▨ S-A	-17.75	Δ3kWh/m^2	-21.15

W: Winter period **St:** Model adjusted with all standardized values
S: Summer period **A:** Model adjusted with all actual values

Figure 29 *Total cooling consumption*

Figure 29 reveals that for the **refurbished building case the cooling consumption in the standard data model is about 37% higher than in the model adjusted with actual data**. In contrast, interestingly, for the **non-refurbished building**, **the cooling consumption in the standard data model is about 9% lower than in the model adjusted with actual data.**

In **the results of the simulations with standard data,** the comparison before and after refurbished works **surprisingly** indicates **an increase in energy use of 9 kWh/m^2** per year, while **in the results of the simulations adjusted with actual data,** the comparison before and after retrofitting reveals **a reduction of 3 kWh/m^2** per year



	REFURBISHED BUILDING. kWh/m^2		NON-REFURBISHED BUILDING kWh/m^2
■ S-St	-28,3	**Δ-9kWh/m^2**	-19,4
▨ S-A	-17,75	**Δ3kWh/m^2**	-21,15
□ S-U	-27,04	**Δ–7kWh/m^2**	-19,7
🟨 S-I	-28,2	**Δ-9kWh/m^2**	-19,5
🟧 S-O-AA-NV	-0,5	**Δ0kWh/m^2**	-0,47
🟫 S-C	-45,5	**Δ11kWh/m^2**	-56,2

W: Winter period
S: Summer period
U: Actual U-value
I: Actual airtightness

St: Model adjusted with all standardized values
A: Model adjusted with all actual values
O-AA: Air-conditioning usage actual profile
NV: Natural ventilation actual profile

Figure 30 Parametric study of the total cooling consumption

As shown in Figure 30 the most influential parameters for the cooling consumption are **the climate and occupancy variables**. The adjustment of actual weather data causes an **increase of 61% and 190% respectively over the refurbished and non-refurbished standard models**. In contrast, the adjustment of occupancy variables with actual data causes a **reduction of the total cooling consumption reaching values close to zero**. This shows the importance of determining the relative impact of each of the parameters in the simulation. The adjustment of the **actual airtightness and actual U-values** in the model in comparison with the model adjusted with standard values has no relevant impact on the cooling results (**varying between 1% and 4%**).

The energy savings calculated with standard data would be **42 kWh/m^2** (68.7-26.7 kWh/m^2) per year for **heating**, and an increase of **8.9 kWh/m^2** (19.4-28.3 kWh/m^2) per year for **cooling.** Together this is a **33.1 kWh/m^2** reduction in a year. However, comparing this result with a simulation using actual occupancy patterns, building characteristics and weather data, the savings would be **9.14 kWh/m^2** (20.4-11.3 kWh/m^2) for **heating,** and 7.3 **kWh/m^2** (21.15-17.75 kWh/m^2) for **cooling**. Together this is only a **16.44 kW/m^2** reduction in a year, half of the **33.1 kWh/m^2** calculated with standard parameters.

3.3.3. Sensitivity analysis for heating: natural ventilation

In addition to the results presented in the sections above, a sensitivity analysis has been carried out on natural ventilation, studying the influence of the variation of this parameter on energy consumption.

This is based on a standard model although occupant parameters are adjusted with actual information regarding occupancy presence and schedule of use of heating system. Natural ventilation is the only variable modified for each model and its value is calculated applying the equation (1) explained in Section 2.4. The first model (W-A-O-HE-NVa) considers all the windows opened for two hours, resulting in 2.38 ACH (option a). The second model (W-A-O-HE-NVb) contemplates all the windows except two opened (two windows from the bedrooms that are not normally in use), effectively reducing the surface of window, resulting in 1.68 ACH (option b). The third model (W-A-O-HE-NVc) considers the reduced effective surface and reduces the time windows remain open to one hour, resulting in 0.84 ACH (option c). The final model (W-A-O-HE-NVd) considers the reduced effective surface of windows and only half an hour with windows open, resulting in 0.42 ACH (option d).

Table 3 Sensitivity analysis of heating consumption due to the variation of the natural ventilation rate.

	Natural ventilation values	**Refurbished building. Winter**		**Non-refurbished building. Winter**	
	Air Changes per hour ACH	**Heating consumption** kWh/m^2	%	**Heating consumption** kWh/m^2	%
W-St	**0.9 ACH**	**26.7**	**100%**	**68.7**	**100%**
W-A	**0.42 ACH**	**11.3**	**42%**	**20.4**	**30%**
W-A-O-HE-NVa	2.38 ACH	37.8	142%	74.1	108%
W-A-O-HE-NVb	1.68 ACH	28.6	107%	62.3	91%
W-A-O-HE-NVc	0.84 ACH	15.8	59%	41.2	60%
W-A-O-HE-NV3d	0.42 ACH	8.86	33%	22.1	32%

W: Winter period St: Model adjusted with all standardized values A: Model adjusted with all actual values
NVc: Natural ventilation option c NVd: Natural ventilation option d
NVa: Natural ventilation option a NVb: Natural ventilation option b
O-HE: Ocuppants and Heating usage actual profile

Table 3 shows the results of the sensitivity analysis. The first two rows show the models adjusted with all standard parameters and all actual parameters respectively in order to compare the results of the sensitivity analysis with them.

Table 3 reveals the great influence of the natural ventilation on heating consumption which varies between 8.9 kWh/m^2 and 37.8kW/m^2 (difference of 28.9kW/m^2) for the **refurbished building,** and between 22.1 kWh/m^2 and 74.1kW/m^2 (difference of 52kW/m^2) for the **non-refurbished building**. These values confirm the importance of the natural ventilation parameter for adjustment in simulation models with actual data and the utility of the use of mixed-methods combining quantitative and qualitative information to define them properly.

3.3.4. Calibration models

As can be seen in Table 4 the statistical validation of the energy model was verified hourly throughout one month in winter (from January to February) and summer (from July to August) periods, following the indicators established by ASHRAE Guideline 14. A good seasonal adjustment of the model with the real data was demonstrated, achieving lower values for NMBE and CV(RMSE) than the maximum values set by ASHRAE as ‘acceptable calibration tolerances’ (±10% and lower than 30%, respectively).

Table 4 Statistical validation of the energy model based on hourly values over a month: indoor air temperature measured vs simulated (DesignBuilder®).

	Refurbished building		**Non-refurbished building**	
	NMBE ±10%	CV(RMSE) <30%	NMBE ±10%	CV(RMSE) <30%
Winter period 16/01-15/01	7.28%	22.69%	6.26%	21.04%
Summer period 16/01-15/01	4.63%	19.14%	3.47%	19.20%

4. Discussion

This study was designed to determine the **effect of using actual rather than standardized data to adjust energy simulation models**. A **three-step methodology** (monitoring approach, mixed-method approach, and energy simulations) has been used to select and categorise influential parameters that affect the energy performance of buildings. This approach has been **validated through 2 case studies**, a refurbished and non-refurbished building in the city of Madrid. Accordingly, this discussion and conclusions are not intended to be generalized but are linked to the case studies and their climate context.

This **discussion concentrates on the relation between the methods used and the results of the simulations with actual data**.

4.1. Methods and application

Although the monitoring campaign provided very useful data for the simulation, it should be borne in mind that these campaigns can be expensive, time consuming and intrusive. A measurement campaign of at least one year is needed, the measuring equipment requires adjustments and many of the measurements have to be done in situ, continuously invading the users’ privacy. The **users´ willingness and availability** have been essential in developing this study.

In the case of the **U-value the level of measurement uncertainty** seems to be minimal due to the similarity between the boundary conditions in both cases. However even with some degree of uncertainty, measured U-values are higher in the case of the refurbished building and lower in the case of the non-refurbished building. This difference can be attributed to the source of the calculated U-value (called standard) estimated with data extracted from regulatory norms - considering different materials characterized under laboratory conditions rather than the global deterioration and energy behaviour of the building in real conditions.

This study reveals the importance of the use of **weather files** in simulations. This type of research has mostly been carried out in mild temperate climates with warm and cold summers [17, 29, 42, 48, 80], evaluating heating consumption. In this case, the research took place in the city of Madrid and when comparing the standard and actual weather files it is observed that **the summer temperature reaches higher values in the case of actual data**. Even so, in the case of the non-refurbished building adjusted with actual data, the cooling consumption is slightly higher than the model adjusted with standard data. Moreover, the influence of the users´ behaviour shows that **the residents rarely use air conditioning** (Figure 14), so that actual data regarding occupants produce almost 0 cooling consumption. This leads us to think that **it is necessary to further research thermal comfort in order to analyse the actual users' cooling needs and the socio-cultural or economic reasons leading them to use these cooling systems infrequently**.

The **application of the mixed-method approach** has **important implications for defining the occupancy presence schedules, heating and cooling set point, as well as schedules of natural ventilation and heating and cooling systems**.

It is worth noting that the figures of the daily averages during winter (Figure 9 and Figure *10*) **allow us to determine the presence patterns and the schedule of the heating system,** while in summer, the weekly study (Figure 14) shows the **irregular use of the cooling systems and consequent difficulty in defining a pattern**.

The **evolution of the indoor temperature can help to analyse the opening/closing of windows** and the use of the cooling and heating system, but **it is not enough to determine the patterns**. For this, it is essential to use the mixed-method approach which involves collecting, analysing and integrating quantitative and qualitative research. This approach **allows us to define the users´ timelines, making it possible to extract input data to adjust the simulation models and analyse the energy consumption of buildings**.

In this study, the adjustment of the actual use of heating and cooling systems, ventilation rates and schedules, as well as electricity consumption (to define the occupancy patterns) have been considered. However, there are numerous **factors relating to the occupants' behaviour** such as the control of the solar protections, the opening and closing of blinds, the use of lighting, and so on, which can lead to considerable savings and should be taken into account.

4.2. Energy simulations

Practitioners make use of standard parameters in building simulations, since actual data are not often available. In refurbishment cases where energy savings need to be calculated to determine the return of investments, simulations with standard data **may overestimate the energy savings, considerably increasing the payback periods**.

Although the buildings in the case studies are social housing, the users are not living in fuel poverty. However, **the results show a situation similar to fuel poverty** [81, 82] due to the occupants' use of the heating systems. The estimated heating consumption results, adjusting the models with actual data, are much lower than those calculated with the standard data (Figure 27), producing a pre-bound effect [22] which has a direct impact on the calculation of the payback periods of potential refurbishment. In the case of cooling consumption, the results are different. In the refurbished building the adjustment with real data produces a reduction in consumption, while in the non-refurbished building the adjustment produces an increase. If residents were less frugal with energy, **the energy consumption would be much higher when using actual values**.

The **parametric analysis** allows us to individualize each of the study variables in order to determine **their individual influence on the energy consumption** and to establish which variable leads to **more accurate simulation results**. **The adjustment with all the parameters modified with actual data in the same model could result in an average value** given that some values can produce and increase consumption while others reduce it (Figure 28and Figure 30).

In the case studies analysed, the **actual U-value adjustment generates a contrasting building energy performance in winter and summer**, increasing the heating consumption and reducing the cooling consumption (when the U-value is higher) and in the opposite case, decreasing the heating consumption and increasing the cooling consumption (when the U-value is lower). These results are in keeping with the findings of other studies [83-87], in which adding thermal insulation thickness (U-value decreases) could result in opposing performance in cooling and heating loads. The results also show that **the influence of adding thick insulation is higher on heating consumption than on cooling consumption** (Figure 28 and Figure 30). Building simulation studies have usually focused exclusively on heating consumption in central and northern climate zones [37, 88-92]. However, studying both seasons yields interesting results. Madrid has a continental climate with hot and dry summers, and cold winters, which involve a considerable use of energy input.

The reduction in heating consumption in both the refurbished and non-refurbished building is evident. However, this reduction is lower if the model is adjusted with actual data instead of standard data, since the **adjustment with actual data leads to a considerable underestimation of consumption**. This means that, if **standard values** were used to calculate heating energy savings (and retrofitting payback periods) **the possible energy savings** would be **overestimated**.

The relationship between the refurbished and non-refurbished models is interesting in the study of cooling consumption because, **using standard data**, the **total cooling consumption in the non-refurbished building is about 31% lower than in the refurbished one**. In contrast, **using actual data the total cooling consumption in the non-refurbished model is about 16% higher than in the refurbished one** (Figure *29*). That is, evaluating the expected effect of refurbishment work, adjusting models with standard data, **the refurbished model results in a higher cooling consumption instead of saving energy**. This also **agrees with our earlier observations, which showed that reducing the U-value adding thick thermal insulation can generate an opposite building performance in the building.**

5. Conclusions

This study presents a **simple and well-structured methodology** to collect **accurate information about building and users' characteristics which combined with adjusted simulation models allow the realistic evaluation of building energy consumption**. The increase in time and effort in obtaining current data, in comparison to the simulations based on standard characterization of buildings, is made up for by the **importance of these results in furthering knowledge of the real performance of users and buildings, and contribute with an approach which can serve as an example and be replicated in retrofitted projects.**

The **comprehensive definition of a monitoring campaign** in which **non-intrusive methods** are used, and the **high degree of commitment and availability of the users** made it possible to obtain actual data of both the characteristics of the building and the habits of the users.

The use of monitoring data can **reduce the uncertainties** during the **design phase because of the pre-bound effect** and during **the phase of use because of the rebound effect** due to the **acquisition of prior knowledge of the user's preferences and requirements**.

The results of this study reveal the **usefulness of the application of the mixed-method approach** to define **building simulation templates** and **occupants´ behaviour patterns** for designing simulation models. Thus, it can provide accurate energy simulation models in order to calculate energy consumption closer to the actual energy consumption, which can **facilitate the calculation of payback periods in a renovation investment**.

In the case of heating consumption, the potential savings estimated when using the standard values are four times higher than those using actual values for adjusting the simulation models. Surprisingly, when the models are adjusted with standard data, the cooling consumption of the refurbished building is higher than in the non-refurbished building. Coincidentally, **there is a four-fold difference in potential savings for both heating and cooling between models adjusted with standard and actual parameters.**

The **variables with the greatest impact** on the difference between the use of real or standard data when adjusting the simulation models are those related to **user behaviour**, both in **winter and summer**, and to **weather data**, in **summer**. It is interesting to note that the **U-value adjustment with actual data generates an opposite building energy performance in winter and summer**.

CRediT author statement

Elena Cuerda: Conceptualization, Methodology, Investigation, Data curation, Formal analysis and Writing- Original draft preparation.

Olivia Guerra-Santin: Conceptualization, Data curation, Formal analysis and Writing- Reviewing and editing.

Juan José Sendra: Formal analysis, supervision and Writing- Reviewing and editing.

Javier Neila: Conceptualization, Formal analysis and supervision.

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Appendix

The floor plans of both case studies (CP17 and CP18) are presented in Figure A1 and Figure A2 respectively.

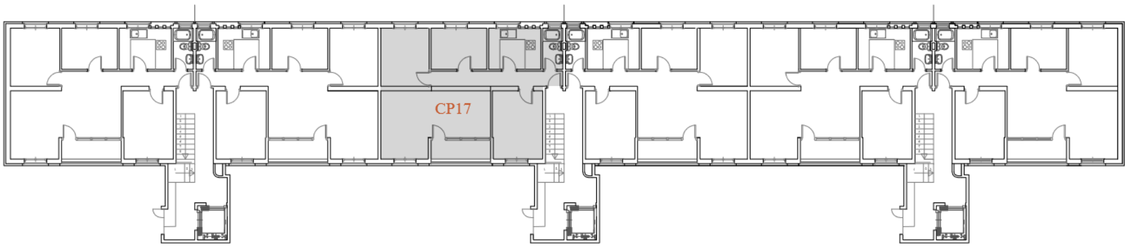


Figure A1. CP17 case study. Refurbished building.

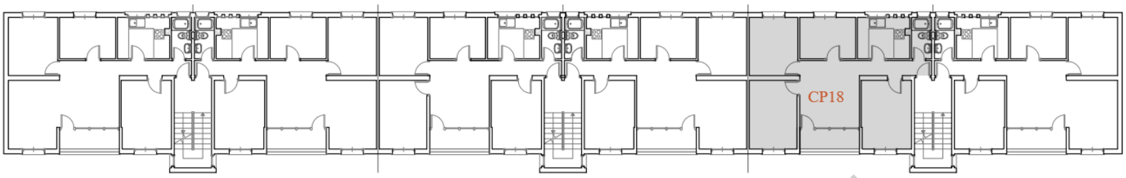
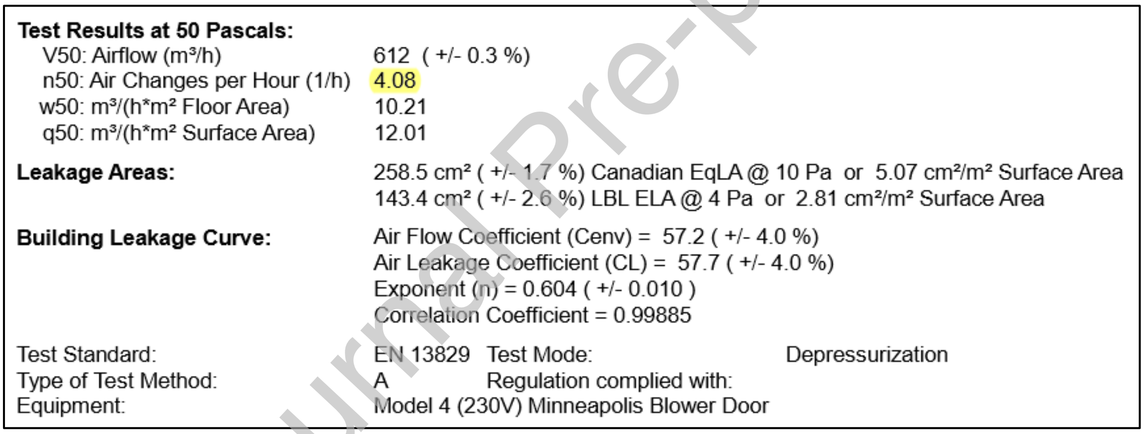


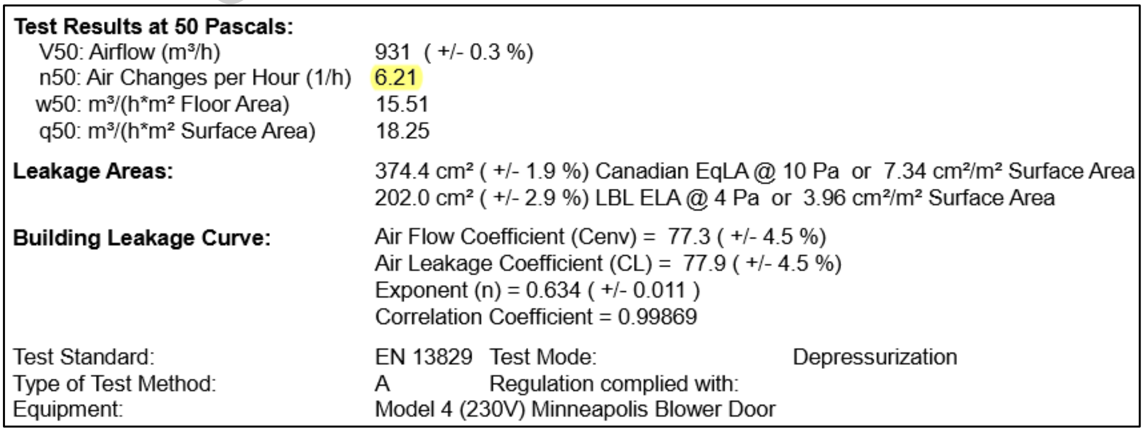
Figure A2. CP18 case study. Non-refurbished building.

Figure A3 and Figure A4 include the blower door test result for both case studies (CP17 and CP18) respectively. The airtightness value is highlighted in the figures.



Test Results at 50 Pascals:			
V50: Airflow (m³/h)	612 (+/- 0.3 %)		
n50: Air Changes per Hour (1/h)	4.08		
w50: m³/(h*m² Floor Area)	10.21		
q50: m³/(h*m² Surface Area)	12.01		
Leakage Areas:	258.5 cm² (+/- 1.7 %) Canadian EqLA @ 10 Pa or 5.07 cm²/m² Surface Area 143.4 cm² (+/- 2.6 %) LBL ELA @ 4 Pa or 2.81 cm²/m² Surface Area		
Building Leakage Curve:	Air Flow Coefficient (Cenv) = 57.2 (+/- 4.0 %) Air Leakage Coefficient (CL) = 57.7 (+/- 4.0 %) Exponent (n) = 0.604 (+/- 0.010) Correlation Coefficient = 0.99885		
Test Standard:	EN 13829	Test Mode:	Depressurization
Type of Test Method:	A	Regulation complied with:	
Equipment:	Model 4 (230V) Minneapolis Blower Door		

Figure A3 Blower door test result for the refurbished building.



Test Results at 50 Pascals:			
V50: Airflow (m³/h)	931 (+/- 0.3 %)		
n50: Air Changes per Hour (1/h)	6.21		
w50: m³/(h*m² Floor Area)	15.51		
q50: m³/(h*m² Surface Area)	18.25		
Leakage Areas:	374.4 cm² (+/- 1.9 %) Canadian EqLA @ 10 Pa or 7.34 cm²/m² Surface Area 202.0 cm² (+/- 2.9 %) LBL ELA @ 4 Pa or 3.96 cm²/m² Surface Area		
Building Leakage Curve:	Air Flow Coefficient (Cenv) = 77.3 (+/- 4.5 %) Air Leakage Coefficient (CL) = 77.9 (+/- 4.5 %) Exponent (n) = 0.634 (+/- 0.011) Correlation Coefficient = 0.99869		
Test Standard:	EN 13829	Test Mode:	Depressurization
Type of Test Method:	A	Regulation complied with:	
Equipment:	Model 4 (230V) Minneapolis Blower Door		

Figure A4 Blower door test result for the non-refurbished building.

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