Building Energy Simulation of Traditional Listed Dwellings in the UK: data sourcing for a base-case model

Michela Menconi[1*], Noel Painting[1] and Poorang Piroozfar[1,2]

[1] School of Environment and Technology, University of Brighton, Brighton, BN2 4GJ, UK
[2] Digital Construction Lab, University of Brighton, Brighton, BN2 4GJ, UK
*Corresponding author: m.menconi3@brighton.ac.uk

Abstract. The need for improving energy efficiency and reducing carbon emissions has made retrofitting existing homes a priority today. A research project has been designed with one of its aims to propose a framework to intervene in traditional listed dwellings (TLDs) to reduce their environmental impact in England, with a special focus on South East region. Selected case studies in the City of Brighton and Hove, have been modelled and simulated in their status quo using Dynamic Energy Simulation (DES). The models, calibrated using monitored energy and indoor conditions data, are then to be used to simulate the effect of permissible retrofit interventions.

DES requires accurate sourcing of multiple input data, to ensure that the models created, closely resemble the real case study dwellings in their energy performance and thermal behaviour. This process can be extremely challenging in the case of simulation of TLDs, where most of the envelope's construction is unknown and intrusive tests are not usually permitted. The data sourcing process is even more complex in the case of dwellings in use, because of the variability of occupancy profiles and patterns of use over time.

Providing a brief overview of the methodology adopted in this study, this paper describes, in detail, the approach devised to ensure that the most credible datasets are collected from different sources for generating models that accurately represent the real case study dwellings in their status-quo and can be used in the following stages of the analysis to asses potential retrofit interventions.

Keywords: Building Energy Simulation; Traditional Listed Dwellings; Base-Case Model; Dynamic Energy Modelling; Responsive Retrofit.

1 Introduction

1.1 Research background

The application of Building Energy Simulation (BES) for the analysis of buildings energy performance is an established strategy to assist in the design process of energy efficient buildings (Garber, 2009; Nguyen at al., 2014; Wang at al., 2005; Fesanghary et al., 2012) as well as in the choice of suitable retrofit interventions (Ascione at al., 2015; Kolaitis et al., 2013; Pernigotto et al., 2012; Stazi et al., 2013). Simulation has several advantages compared to physical modelling (including mock-up tests and field tests): it is less time consuming and more cost-effective; importantly, in the case of buildings in-use, it is non-intrusive (Yang et al., 2015); factors like outside weather can be controlled and changed in order to account for the effects of occupancy alone as well as those of one specific retrofit measure or of a combination of more than one (Wei et al., 2014). Simulation has been preferred to mathematical modelling (Diakaki et al., 2013) as well because it is a more developed method that allows for the testing of different retrofit scenarios with a more user-friendly approach requiring less coding skills. Nevertheless, when it comes to traditional buildings, there are still concerns with regards to the proper implementation of the models for BES (Barnham et al., 2008; Heath et al., 2010b; Ingram and Jenkins, 2013; STBA, 2012). Primary concerns are raised around deploying energy simulation for traditional buildings, because the processes and synergies that characterize this part of the stock are not always captured by models. The uncertainties around construction materials and thermal behaviours of the traditional stock require skilled modelers with tacit knowledge of local and indigenous building materials and construction methods. Furthermore, when BES is conducted on dwellings in use, the accuracy of the outcome is strictly linked to the “human factor” (Heath et al., 2010b): both the expertise of the modeler and, the occupants’ behaviour and the building’s pattern of use.

1.2 Aim of this paper

This paper describes, in detail, the process of creation of a base-case model for a pilot case study (CS) of a traditional listed dwelling (TLD). This work is part of an ongoing research that aims to devise effective and responsive retrofit strategies to improve the energy performance of TLDs in South-East England. The research project uses BES to assess the benefits of potential interventions on nine selected CSs representative of 19th C listed dwellings in Brighton, UK. This paper aims to provide a comprehensive report of all the data collected, their sources and the assumptions made to ensure that the datasets will help generate a model that closely resembles the actual energy performance and thermal behaviour of the real-world case.

1.3 Overview of the Research methodology

The research is articulated around successive stages of dynamic energy simulation. Once the model is created, the first dynamic energy simulation is run in building’s existing condition and the data output at this stage is used for calibration with actual monitored data. The calibrated models are then normalized to generate a baseline performance scenario to be used in the following stages of research to assess the benefits of potential interventions on the selected CSs. Figure 1 illustrates the methodology and methods utilized in this research for the creation of realistic dynamic energy models.

IES-VE has been chosen as a suitable energy simulation application for this research, because it is already validated against a number of global as well as regional standards (IES, 2018); it has been considered the most appropriate application for energy analysis in several precedent studies (e.g. Pomponi et al., 2015; Memon, 2014; McNally, 2014 to name but a few); it was also deemed suitable to evaluate the energy performance of traditionally constructed dwellings (Ingram, 2013; Flores, 2013; Moran, 2013); with its parametric capabilities, it allows for simulation of multiple case scenarios to be applied on the same model, hence the credibility of comparative analysis of the interventions is deemed to be high; it is an application developed in the UK and its use is widespread in the country as well as around the world; it offers a user friendly interface; and it does not require extensive coding skills.

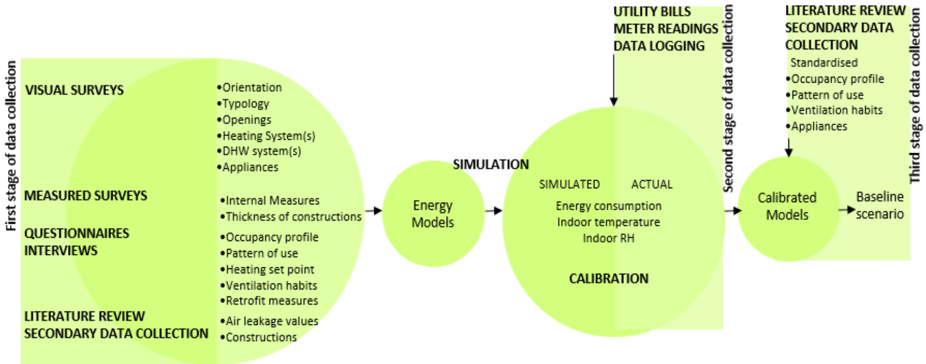

Fig. 1. The research design from the genesis of models to the production of a base-case performance scenario

In order to create accurate models of the selected CSs, a mixed methods approach was developed, for which multiple methods were used to gather, collate and analyze a wide range of input and monitored data. The pilot CS model, produced according to the procedure reported in this paper, was then calibrated using metered data for energy consumption and indoor conditions, in order to ensure that it accurately reproduces the real CS and represents its actual energy performance and thermal behaviour.

1.4 The paper structure

This paper starts with setting the scene for the study in an introduction section which includes the research background, the aim and an overview of the research methodology. It will then set out to explain the steps taken for developing the base-case model which will then be used as a basis for a parametric study of introduced permissible measures and interventions to improve the environmental impact of TLDs.

The model specifications include: geometry, orientation, site location and weather data, openings, construction materials, and carries on to heating and domestic hot water systems (DHWS), complemented by sources of heat gain and mechanical ventilation rates.

The paper concludes by providing some insight into the data sourcing process to ensure that models devised for BES closely resemble the actual energy performance and thermal behaviour of the real buildings they would represent in this study.

2 Model creation

2.1 Geometry

The pilot CS is a 1st floor converted flat located in Brunswick Place (City of Brighton and Hove) one of the earliest Regency developments in town. It was built during the 1st half of C19th and is a grade II listed dwelling as a part of the List Entry Number 1204771. Its layout is typical of similar converted flats in South-East England, with a living area containing kitchen and dining in the front, and a bedroom area in the rear of the flat; its total usable floor area is approximately 70 m^2. Its main elevation faces West, overlooking Brunswick Place, and is therefore exposed to the prevailing winds in this area, although partially sheltered by the offsetting buildings along the western side of the place.

In order to generate an energy model of the CS dwelling, first of all, a floor plan was generated in AutoCAD using the drawings and measures taken during the walk-in measured survey. The dxf drawing was then imported to IES and a 3D model was created in ModelIT (the model building component of IES). IES uses a relatively simple model geometry which does not necessarily comply with the architectural drawing protocols or technical design drawing conventions. The model produced in IES was therefore a simplified version of the drawings generated based on the surveys. This is crucial to reduce unnecessary model complexity and avoid potential simulation errors as a result of excessive level of details, which may confuse the application during simulation runs with very little to no impact on the outcomes of simulations. The adjacent volumes were also modelled, to take into account the thermal conditions at the boundaries and to include the shading effects in solar gain calculations. The temperature difference between the adjacent building volumes and the CS was assumed to be null or negligible (adiabatic conditions) as the surrounding flats are also occupied and heated (IES, 2015c; IES, 2016) throughout the year.

2.2 Orientation, site location and weather data

Activating the APlocate application within ModelIT, data related to the site location and weather was inputted. APlocate uses site data that contain values for latitude, longitude and altitude of different geographical locations throughout the world, taken from standard tables published by CIBSE and ASHRAE.

ASHRAE (2002) suggests the use of hourly weather data that corresponds to the same time period as the energy use data to which the model will be calibrated. However, if the savings are to be “normalized” to represent a typical year, the Guidance considers it also acceptable to use a typical year of local weather data or of data from a site that is near the building under investigation (usually an airport).

Brighton and Hove, UK, is a non-ASHRAE location. Therefore, initially the weather dataset relative to Shoreham Airport was used as the nearest geographical location included in the basic set of simulation weather files. During the following calibration phases, it was decided to adopt an average Brighton weather file provided by Meteo-

Norm to allow for a more accurate comparison between simulated and monitored energy consumption, temperature and relative humidity (RH) data and to aid this way in the calibration process.

A further stage of calibration was finally performed, using the specific Brighton weather file recorded for 2017 - to which most of the monitored data pertain - acquired from IES, to increase the level of confidence in the model created.

2.3 Openings, shading and insulation studies

When the geometry was completed, the types of openings, their exposure, and their use profiles were assigned using the IES module MacroFlo. Each window was modelled using an ad-hoc Opening-Type-Properties-Database (IES, 2015d; IES, 2015e) based on the data collected during the visual and measured survey. It stores information concerning the window's geometry, the leakage characteristics, the degree and timing of window opening and, when appropriate, its dependence on room temperature and/or RH. A profile has therefore been created for each window to define its pattern of use according to the information obtained from the interviewees.

It is worth noting that the coefficients that describe the air leakage characteristics, i.e. Crack Flow Coefficient (CFC) and Crack Length (CL), have been given a value of zero for all the external openings in the MacroFlo Database. The reason for this is that, calculating the infiltration rates using such values requires, beside data about the maximum openable area of each external opening (for which the values were extrapolated from the measured survey), the detailed information about cracks in the building envelope, as well as wind pressure coefficient data for the building surfaces; such data was not possible to acquire at this stage with the instruments available for this research. Although the use of ad-hoc accurate data for CFC and CL could potentially generate very accurate results, it also implies the risk of misleading outputs when detailed knowledge of such data is impracticable to gain. Air leakage rates were therefore considered null during the MacroFlo analysis that was only used to calculate natural ventilation rates, using the ad-hoc user-defined profiles for each opening. Infiltration rates were instead inputted as uniform values for each room Template in ApacheSim (see section 2.4, Windows). Values of CFC and CL have only been inputted in MacroFlo for the internal closed doors, to take into account air circulating inside the flats between those rooms whose doors are generally permanently closed. These values have been taken from those suggested by IES in the MacroFlo User Guides (IES, 2015d; IES, 2015e) in the measure of 1.3 l/smPa $^{0.6}$ for the CFC and of 100% for the CL around the opening perimeter.

When the Openings Database was completed, the right orientation was set for the geometry created and the module SunCast was run to perform shading and solar insolation studies. The impacts of air movement (as generated by MacroFlo) and solar shading calculations (as generated by SunCast) were then quantified in terms of heat gains and energy consumption to be used in ApacheSim, the thermal simulation engine in the IES.

2.4 Construction Templates

IES software calculates the envelope's U-value based on thickness, conductivity, density, heat capacity and resistance of each building element, (referred to as "construction" in the IES terminology). Using the Building Template Manager within ApacheSim (IES, 1015f; IES, 2017), Construction Templates were therefore created, to assign constructions and performance characteristics to each surface in the model. Each construction defines the thermal properties of a building element such as wall, ceiling/roof, floor/ground floor, window or door. It consists of layers of different materials, together with thermal properties of the materials, surface properties and other data used in the thermal analysis. Because of the private ownership of the dwelling, it was not possible to use any type of invasive technique, e.g. core sampling, to gain a clear understanding of the components of each construction. Therefore, specific building elements were created based on the assumptions made from the measured thickness of such elements (whenever this measure was possible to take), the visual and tactile inspection as well as the literature review, secondary data collection and conversations with experts about the typical and prevailing construction-methods and materials used in the area at that time.

Walls. The external walls in the pilot CS are made of rendered brickwork, as confirmed in the List Entry Summary, which talks of "stucco over bricks" (Historic England, 2018). The size of bricks varied slightly throughout the centuries in this area.

To make appropriate assumptions concerning constructions and materials of the envelope, the thickness of each wall was measured, and a tactile inspection of the inside was carried out, aimed at establishing the eventual presence of a traditional finish - such as plaster on lath and battens - or of modern dry-lining. Given its overall measure and the tactile inspection, the front wall was assumed to be made of imperial size bricks (227 mm x 115 mm), therefore the thickness of the brickwork was estimated to be 464 mm, hence a two-brick wall.

The external face of the main elevation is finished in traditional lime-based stucco as it originally was. The IES library does not include such a material. Therefore, for the modelling of this layer, a new lime-plaster material was created, for which the thermo-physical properties of traditional lime plaster were assigned, as suggested by the International Organization for Standardization -ISO- (BS EN ISO 104656, 2007) and CIBSE (2015). Such values are also in the range of those proposed by previous research (Cerny, R., et al., 2006; Theodoridou et al., 2016; Vejmelkova et al., 2012a) given the variability of thermal conductivity, heat capacity and vapour resistivity of this material, as a consequence of its moisture content.

The internal finishing of the front wall was assumed to be lath and plaster. This was a common method for interior finishing as it allowed for a smooth surface; it was frequently used on ornamental or unusual surfaces, like rounded walls, such as those found in the front elevation of the pilot CS. Therefore, the materials build-up of the front elevation has been modelled as: 20mm of stucco, brickwork, 40mm of cavity (the thickness of the vertical timber battens), 6mm of wood (oak essence for the lath) and 15mm of lime plaster (this thickness takes into account the increased thickness of the plaster forced into the gaps between the lath and the thickness of the layer on top of the lath).

Brick masonry was assumed to be the material used also in party walls (in adiabatic conditions with the adjacent dwellings) and the rear walls. Therefore, given the overall thickness of 250 mm and the tactile inspection (excluding the presence of plaster on lath or dry-lining), the rear elevation was estimated to be a single-brick wall (brickwork with 227 mm of thickness). The rear elevation was finished in lime-based render externally and in lime plaster internally.

The internal partitions were assumed to be made of brickwork (finished in lime plaster) as well, given their measure and tactile inspection: respectively one-and-a-half-brick walls for the main staircase and half-a-brick walls for the other partitions.

Internal floors- ceilings. The internal floor structures are made of timber joists as they were originally built; they were likely finished with floor-boards, but these have been replaced with chipboard flooring and carpets and they have been modelled accordingly. The ceilings instead, being generally less modified and still decorated in stucco, have been assumed to be finished in lath and plaster. The measured overall thickness has guided the definition of the composition of the layers of the construction, which were modelled, from inside to outside, as: carpet, chipboard flooring, cavity (220mm for the timber joists), oak (6mm for the lath), lime plaster (15mm for the plaster on lath).

Windows. Most of the windows are likely to be the original timber sash ones, as determined through visual inspections, and confirmed during the interviews. The frame materials, type and thickness of glazing as well as type of shading device used (and their profile of use) were modelled in the ApacheSim Constructions Database, with all their other characteristics, affecting the ventilation rates, having been detailed in MacroFlo (see section 2.3).

All the windows are single glazed (with a 6mm-thick glass) and some of them have shading systems (when present, they were added to the windows Constructions Database and given a pattern of use according to the information produced by the occupants). The values assigned, in the Apache Constructions Database, to the resistance of the shading devices, their shading coefficient and short-wave radiant fractions have been taken from previous research (IES, 2009), from CIBSE Guide A (2015), based on Wood et al. (2009) and from IES Apache-Tables (IES, 2015b).

Infiltration rates are certainly a variable to take into account when modelling old sash windows and their influence on energy consumption and indoor conditions has been thoroughly investigated by previous research (Baker, 2008; Pickles, 2016; Wood et al., 2009). The air leakage (resulted from windows and fabrics) was considered in this study as a uniform rate in each Room Template Database in ApacheSim. It was not possible to perform a blower door test to measure the actual air leakage rates of the CSs investigated because of the invasiveness of such test in private dwellings, which were all inhabited during the entire period of this study. Therefore, each room in the dwelling was assigned a specific air leakage value, according to the figures suggested by CIBSE (2015). The CIBSE Guide A (CIBSE, 2015: Table 4.24) provides in fact empirical values for air infiltration rates for rooms in flats (levels 1-5) on normally exposed sites in winter: they range from 1.40 Air Changes per Hour (ACH) for leaky buildings to 0.25 ACH for extremely air-tight buildings. For each room a value has been assigned within the range proposed by CIBSE, taking into account the results of the visual survey (where the windows were assessed in their state of conservation, observing the overall condition for all of them), the thermal imaging survey (that highlighted moderate rates of air leakage around the openings) and in accordance with existing literature concerning similar properties of the same period and area (IES, 2009; Porrit et al., 2013).

Therefore, although the air leakage value assigned to the model before the calibration was 1.4 ACH (as suggested by CIBSE for old leaky buildings), during the calibration, such value was fine-tuned (within the range suggested by CIBSE) to achieve acceptable differences between the simulated and monitored data. The process concluded assuming, for the pilot CS, a value of the air leakage in the area of 0.5 ACH, which allowed for a successful calibration of energy and indoor conditions data and is also in line with previous research on similar dwellings (IES, 2009; Porrit et al., 2011).

2.5 Heating and Domestic Hot Water Systems

Heating and DHWS were inputted in the Apache Systems Tab within the Thermal Template Tab. As part of the visual survey undertaken, data concerning the fuel(s) used, boiler and DHWS tank (wherever present) nameplate and size, as well as type and thickness of any insulation eventually found around the hot water tank, was collected. Then, data concerning the seasonal efficiency, and DHWS delivery efficiency was gathered online from the respective producers and inputted in the Apache Systems Tab for each system. The pilot CS, as most of the CS dwellings investigated, has central heating with a combi-boiler.

As the research is set in the UK, the UK National Calculation Methodology (NCM) System Data Wizard in IES was used to aid in the definition of the characteristics of the heating system, adopting some of the default values proposed given a certain boiler efficiency inputted. On the Apache Systems dialog box (IES, 2015g), a set of NCM system types are available for selection. This utility allows to describe the characteristics of the heating systems using the method implemented in the BRE Simplified Building Energy Model (SBEM). The system specifications entered here are interpreted into Apache Systems, where they are used for sizing central plant and calculating fuel consumption and carbon emissions. Therefore, in the Apache Systems Tab, only the Boiler Seasonal Efficiency (BSE) was manually inputted according to the value given by the producer. The UK NCM wizard then assigned, by default, a value to the Heating Delivery Efficiency (HDE) depending on the type of system (which, in the pilot CS, was set to: “Central heating using water – radiators”). The software finally calculated the value of the Seasonal Coefficient of Performance (SCoP) given these other two[1].

The pattern of use of the Heating system and temperature set point(s) were also set creating specific profiles in the Thermal Template for each room in the dwelling investigated, in accordance with the data acquired through questionnaires and interviews with the participants.

[1] SCoP is a parameter used in the Apache Systems tab to describe the efficiency of the heating system. This value is linked to the boiler seasonal efficiency (BSE) as per following formula: SCoP = BSE * HDE (IES, 2015g).

DHWS consumption was estimated based on the number of occupants, using the formula proposed by Energy Saving Trust (2008) for the average use (in l/day) of DHWS in UK dwellings, as follows:

$$DHW=40+28N\ l/day$$

where N is the number of occupants. The value obtained this way, was then divided by 24 to obtain the l/h consumed in the dwelling, as required by the software. The value finally found corresponds to the total estimated amount of hot water consumed in the dwelling each hour when the DHWS is in use. This total was then assigned to only one room Thermal Template (the main bathroom in this case), assuming that all the other room Templates have no DHWS when running the simulations.

Questions concerning the hot water usage were included in the questionnaires and interviews to help understand whether the pattern of use of the DHWS presented any variance that may lead to a use in excess (or much below) of the average use given by the formula, because of anomalies in the behavioural patterns (e.g. occupants that take showers somewhere else during the week or that make very little use of hot water). However, this was not the case for the pilot CS.

2.6 Heat Gains

Internal heat gains for each room Template (IES, 2015g) were also assigned, using the information acquired through the visual surveys (appliances, lighting fittings) and questionnaire surveys and interviews (occupancy profile, pattern of use) and adopting the values suggested for the heat gains by CIBSE Guide A (2015), as detailed below.

People. CIBSE Guide A (CIBSE, 2015: Table 6.3) provides average heat emission rates per person (male or average for mixture of men, women and children) depending on the activity and dry bulb temperature of the room. The Guide also suggests that the value of heat gain from a female body can be calculated multiplying by 0.85 the value given for the male body. In each room Template, the actual occupancy pattern, as evinced by the questionnaire survey and interviews, were taken into account to make a decision concerning the values of sensible and latent heat gains (assuming the rooms to be at 20°C), adapting them from Table 6.3 of the CIBSE Guide A (2015).

Lighting. The dwelling investigated mainly uses Fluorescent and Tungsten lamps (the occupants showing however a tendency to opt for more efficient lamps when in need of renovation).

CIBSE Guide A (2015) suggests considering the energy consumption of each lighting equipment as equal to the value of the sensible heat gain from it. Values suggested by CIBSE (CIBSE, 2015: Table 6.2) have been used for heat gain generated by lighting in the area of 8 to 12 W/m^2 based on fluorescent lamps. The Guide suggests the upper value for older installations and halved values for LED lighting. Therefore, the value used in each room Template for energy consumption and heat gain generated by lighting fittings was $12W/m^2$; the pattern of use of the lighting system was modelled according to the information produced by the occupants.

Appliances. The values suggested by CIBSE (2015) for energy consumption and heat gain of typical domestic and office equipment (CIBSE, 2015: Tables 6.6, 6.15 and 6.16) and of electric and gas cooking equipment (CIBSE, 2015: Tables 6.18 and 6.20) were taken into account, to make a decision about the appropriate data to input for heat gains from appliances. Such values, in CIBSE tables, depend on the appliance rating, the temperature of wash (for washing machines), the type of fuel and the presence or otherwise the lack of a hood (for cooking appliances). Therefore, heat gains and energy consumption for each appliance, were taken from the CIBSE Guide and inputted according to the information provided by the visual survey (type of appliances and their rating) and confirmed or complemented by the questionnaire survey and interviews. Profiles of use were also created for each appliance, according to the information provided by the participants with the questionnaire/interviews and concerning their occupancy profile as well as the frequency and length of use of the appliances.

2.7 Mechanical ventilation rates

Where extract fans were found, (in this case in the bathroom), the input value of 15l/s, as suggested by CIBSE Guide A for intermittent fans (CIBSE, 2015: Table 4.2a) was used in the Room Template Data in ApacheSim, in accordance with the occupation profile of the room, as deducted from the interviews with the occupants.

3 Conclusions

Performance gap is a growing area of research in BES. Its importance should by no means be understated, it is however very context specific and may vary from one study to another. It could have been argued, in the current research project, that as the interventions are introduced on a case by case basis and their impacts are measured accordingly, model calibration may have not been of such priority or significance in this study. This is correct but only to some extents. To be able to develop the scope and applicability of this research, and increase its validity and reliability through facilitation of cross-comparison internally (between the findings for different CSs in this research) and externally (between the findings of this research and those of other studies), it was crucial to ensure that models represent the real performance of the actual CSs as closely as possible, hence the paramount importance of this stage of the study.

The paper provides an insight into the data sourcing process used for the creation of realistic energy models of TLDs. It aims to address a gap frequently pointed out by previous research that considers BES of traditional dwellings extremely challenging because of the lack of detailed knowledge about their materials, constructions, and user behaviour. As a consequence, a wide number of assumptions were necessary to ensure that the created models are accurate representations of the real-world case.

The data sourcing process described was finally validated in the subsequent stage of calibration, when iterative simulations were run of the pilot CS model and their output was assessed against measured data concerning energy usage as well as indoor temperature and RH. The input data were checked and, when required, fine-tuned, to allow for a good correspondence between simulated and monitored data. When calibration achieved the expected outputs, the chosen input values were considered realistic for the specific CS. The same data collection and validation process was then repeated also for all the selected CSs investigated. To date, all the models are fully calibrated and ready to be used in the following stages of research, to assess the benefits of potential retrofit interventions on the selected dwellings, both as individual and combined measures.

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