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Abstract. The inclusion of heritage dwellings in the UK decarbonization policies can contribute to cut operational carbon emissions from the building stock; this needs to be made a priority if net zero carbon targets are to be achieved. However, the energy and carbon savings potential of suitable retrofit interventions on this part of the stock is extremely variable and strictly intertwined with the range of baseline conditions of such dwellings. This study aims to propose a framework for interventions in Traditional Listed Dwellings (TLDs) to improve their energy performance utilizing Dynamic Energy Simulation (DES) of selected case studies (CSs) in the city of Brighton and Hove (South-East England). To achieve this aim, the study established a baseline scenario which provides a basis for the assessment of energy performance and thermo-hygrometric behavior pre- and post-interventions and allows for comparison between different CSs under comparable conditions. Presenting a brief overview of the methodology adopted in this study, the paper describes the approach devised to generate such baseline scenario. The paper then compares the results obtained from simulation of normalized and baseline models with the status-quo energy consumption of the dwellings investigated (based on meter readings). This analysis finally allows to highlight some key physical determinants of the baseline HEC which, in the following stage of research, proved to have a considerable effect also on the amount of energy and carbon savings achievable post retrofit interventions.

Keywords: Normalization; Energy Baseline; Dynamic Energy Simulation; Energy Performance; Traditional Listed Dwellings; Building Envelopes.

1 Introduction

Dwellings operation contributes to 15% of the total greenhouse gas (GHG) emissions in the UK, the main source being the use of natural gas for heating (BEIS, 2021a; IEA, 2018). Therefore, the current decarbonization strategy (CCC, 2021) is unquestionably an urgent task for the residential building stock; however, it faces some key challenges. Approximately one quarter of dwellings in this country are traditional buildings; they were built before ~~1919 with~~1919 with breathable and solid walls, single glazed and leaky windows, uninsulated roofs and floors (STBA, 2012). The thermo-hygrometric balance of their constructions constitutes a first limitation to the range of retrofit interventions applicable for them, because any measure that may have an impact on such balance, could turn out to be detrimental to the health of their fabric and occupants (Suhr & Hunt, 2013). Therefore, the Building Regulations exempt this type of buildings from any energy improvement that may result in "long-term deterioration of the building's fabric or fittings" (HM Government, 2022: p.3). Most traditional dwellings also have high architectural and/or historic values (Historic England, 2012; Historic Scotland, 2013~~); hence~~); hence, many of them are listed. The listing adds further limitations to the suitable retrofit interventions, as it implies that any applicable measure must be carefully assessed with reference to its impact on the heritage value of the building. Therefore, the Building Regulations concede that heritage buildings do "not need to comply fully with the energy efficiency requirements where to do so would unacceptably alter the dwelling's character or appearance" (HM Government, 2022: p.3). Despite these limitations, if properly retrofitted, Traditional Listed Dwellings (TLDs) have been shown capable to play a pivotal role in the UK decarbonization policies (Grosvenor, 2021); furthermore, retrofit may ultimately contribute to the preservation of these heritage assets by allowing them to be comfortably and cost-effectively utilized by future generations. Yet, in the effort to improve the environmental impact of the UK buildings, the contribution of this part of the stock has long been underestimated.

Given this scenario, this study proposed and assessed suitable passive retrofit interventions for TLDs, aimed to reduce their operational CO_2 emissions. For this purpose, Dynamic Energy Simulation (DES) was utilized to model representative Case Studies (CSs) in South-East England and simulate their Heating Energy Consumption

(HEC) and thermo-hygrometric behavior, before and after a range of retrofit scenarios. This way, benefits and risks of carefully selected retrofit options[1] were appraised, to formulate optimal packages of interventions.

The body of literature generally considers a sequential approach the most appropriate to address energy efficiency improvements and management of change for heritage buildings (Changeworks, 2008; English Heritage, 2008; Flores, 2013; Historic England, 2012; Ingram, 2013; Moran, 2013; Sahin et al., 2015); such approach starts with establishing a baseline scenario for the evaluation of different retrofit solutions (Bell et al., 2010; Bothwell et al., 2011; Charles, 2012; Hong et al., 2006) and for heritage impact assessment (Blecich et al., 2016; ICOMOS, 2010; Morris et al., 2008). It is then possible to identify potential changes to be introduced to the baseline scenario and measure their impact against the baseline performance. Therefore, the research design utilized in this study, requires the setting of a baseline scenario of performance, to be compared, in the following stage of research, with multiple post-intervention scenarios, allowing to:

- measure and assess HEC savings, changes in the thermo-hygrometric balance of the constructions, and impact on the heritage features needing protection and
- perform cross-case analysis based on comparable conditions.

1.1 Background

Studies that utilized energy simulation to investigate the energy savings achievable through retrofit, commonly simulated first the models in their real status-quo condition, to calibrate the models with measured data, then in a baseline scenario and lastly in post-interventions scenarios to measure and compare the outcome of interventions amongst different CSs. This is the strategy applied by both Georgiou (2015) and Stazi (2017), utilizing DES to simulate multiple CS dwellings retrofit. In these studies, the energy models were first simulated using real profiles of use and then calibrated comparing the results from simulation to actual metered data. To generate a baseline scenario of performance, the calibrated models were normalized using: 1) a typical weather year (vs the specific one related to the same period of data collection used for calibration) and 2) standard profiles of use. The normalized models were finally used to simulate the intervention scenarios; the results concerning energy consumption post-interventions were compared with the baseline performance to devise combinations of effective interventions.

A normalization stage is not normally necessary for studies investigating the energy performance of one single building (IES, 2009; Mohammadpourkarbasi, 2015; Ascione et al., 2011; Sahin et al., 2015). These studies generally deployed the real occupancy profile, pattern of use and heating system of the specific CS investigated and compared the results of simulations of post-intervention scenarios to those relating to the building in its status-quo.

Few other studies, although working on the energy model of a single CS, used standardized input values - instead of real ones - for both the status-quo and post-retrofit models (Ben and Steemers, 2014; Franco et al., 2014; Blecich et al., 2016). The use of standardized inputs for the status-quo models was due to either the purpose

[1] The passive measures assessed, individually and in combination, in the following stage of research are draught-proofing, shading devices, secondary glazing, slim double-glazing, ground floor, roof and internal wall insulation.

of using the model as representative of the whole complex of similar dwellings on the same site (Ben and Steemers, 2014) or to the lack of real data because the building investigated was not in use (Franco et al., 2014 Blecich et al., 2016).

More rarely, when investigating multiple CS dwellings, only standardized input values were used for the status-quo models (Moran, 2013; Ingram 2013). This was meant to facilitate the cross-sectional analysis of results between different cases and was considered useful for energy advice, to account for potential future occupants (Ingram, 2013). These studies, however, acknowledged the limitations in such analysis, which gives little confidence in the accuracy of the models created as their results cannot be calibrated with metered data.

Instead of using real CSs, some studies developed models to be representative of certain typologies of dwellings, constructions, or periods; hence, they only adopted a standardized occupancy profile and pattern of use for obvious reasons (Marshall et al., 2016; Memon, 2014; Panayiotou, 2014; Porrit, 2012). Such studies, however, may fall short in precision in the models created as they have chiefly been developed without calibration, although some utilized other validation strategies.

Other studies, although modelling multiple dwellings, lacked a normalization strategy and used the real specific conditions of each CS for the simulation of both the status-quo and retrofit scenarios (Flores, 2013), aiming at improving accuracy in the calibration stage. When normalization is not carried out, however, the different models can only be compared to their own status-quo condition, while the comparison of the results of the same interventions on different CSs may be extremely challenging, if not impracticable. Furthermore, the isolation of physical determinants of HEC can be impracticable when the multiple CSs are characterized by different appliances, heating and domestic hot water (DHW) systems, as well as occupancy profiles and pattern of use.

Table 1 depicts a synthesis of the relevant literature reviewed for investigating the use of normalization in previous studies which deployed Building Energy Simulation (BES) for the analysis of potential retrofit interventions, using real CSs or prototypical buildings.

Table 1. Review of literature concerning BES for the analysis of potential retrofit interventions and type of approach deployed (real then standardized conditions, only standardized, or only real conditions).

Approach		Author(s), year	Location	Type of Model CS vs archetypal	Number of CSs	Pros	Cons
From real conditions to standardized conditions (normalization)		Georgiou, 2015	Cyprus	CS detached houses	7	1. Calibration is possible 2. The outcome of interventions can be easily compared amongst CSs	1. This approach requires a wide range of primary data, and many simulations runs
		Stazi, 2017	Italy	CS buildings	12		
Standardized Conditions	Models of prototypical buildings	Memon, 2014	UK	Prototypical 20th C dwelling	1	1. This approach requires a smaller number of simulations runs	1. This approach is based on secondary data 2. Calibration is not possible; hence the results may lack in accuracy
		Marshall et al., 2016	UK	Prototypical solid wall dwelling	1		
		Panayiotou, 2014	Cyprus	Prototypical dwellings	2		
		Porrit, 2012	UK	Prototypical 19th C dwelling	1		
	Models of real CS	Ben and Steemers, 2017	UK	CS heritage dwelling	1	1. The single model aims to be representative of a whole complex of dwellings	1. This approach is generally based on secondary data 2. Calibration is not possible; hence the results may lack in accuracy
		Blecich et al., 2017	Croatia	CS heritage public building	1	1. This was the most suitable approach as the building was not in use	
		Franco et al., 2014	Italy	CS heritage public building	1		
		Ingram, 2013	UK	CSs traditional dwellings	5	1. This approach facilitates the transversal analysis of results between different cases 2. Useful for energy advice, to account for potential future occupants	
		Moran, 2013	UK	CSs traditional dwellings	3		
Real conditions		Ascione et al., 2011	Italy	CS public heritage building	1	1. A normalization stage is not necessary when investigating one single building 2. Calibration is possible	1. Cannot account for potential future occupants
		IES, 2009	UK	CS mid-19th C villa	1		
		Mohammadpourkarbasi, 2015	UK	CS mid-19th C terraced house	1		
		Sahin et al., 2015	Turkey	CS public heritage building	1		
		Flores, 2013	Portugal	CSs traditional dwellings	10	1. Calibration is possible	1. Cross case analysis may be impracticable 2. The analysis of physical determinants of HEC can be challenging

1.2 Aim of this paper

A baseline scenario of energy performance and thermo-hygrometric behavior of the selected CSs was necessary in this research to assess the outcome of suitable retrofit interventions. For this purpose, the following scenarios were created, by simulation of subsequent stages of energy models:

1. Status-quo scenario, which shows the current total energy consumption of the dwellings investigated (including energy used for heating, hot water, lighting, and appliances);
2. Normalized scenario, which shows only the energy consumption for heating (HEC) in a standardized setting, where occupancy profile and pattern of use are the same for all CSs;
3. Baseline scenario, which shows the HEC of the CSs after a further level of standardization, when heating system have all been upgraded with the same high efficiency boiler.

The baseline scenario obtained this way, facilitates the assessment of the variations in HEC due mainly to changes in the materials build-up of the envelope, hence the outcome of passive retrofit measures, enabling a fair cross-case comparison.

Providing an overview of the data collection carried out to generate and calibrate the status-quo models, this paper describes in detail the strategy devised to generate the normalized and baseline models and the results of simulation of the three scenarios investigated.

2 Case studies material

Representative CSs of TLDs were selected using a non-probability sampling strategy (Bryman, 2008) obtained by carefully balancing convenience and purposive sampling techniques. A first filtering was made to find potential participants interested in this study and willing to participate, to be able to warrant an initial number of accessible, relevant, and suitable dwellings. For this purpose, a letter was circulated within the University of Brighton mailing list.

For the second search, it was decided to use invitation letters delivered door to door in two main areas of investigation: Kemp Town and Brunswick Town. These two areas, spread respectively to the East and West of the city's seafront, were built between the beginning and the end of the 19th C and represent the finest examples of Regency and early Victorian planning and architecture in Brighton and Hove. Such areas, being the earliest grand Regency developments in town, are also representative of materials and techniques used for all the rest of the 19th C throughout the city. This second search for participants, led to the final selection of eight CSs, well distributed geographically in the two areas of investigation; their position is shown in Figure 1, where numbers follow the chronological order of acquisition.

Figure 1. Map of Brighton seafront (source: Google Maps).
The two areas of investigation are indicated in the dashed lines; the numbers show the locations of the CSs selected.

The eight CSs selected and utilized cover all the overarching variables of this typology of dwellings (they occupy the lower-ground floor, ground floor, intermediate floor, or top floor - see Figure 2); therefore, they allow detailed exploration of a snapshot of the 19th C listed dwellings typology, typical of Brighton, as well as other seaside towns in the South-East of England.

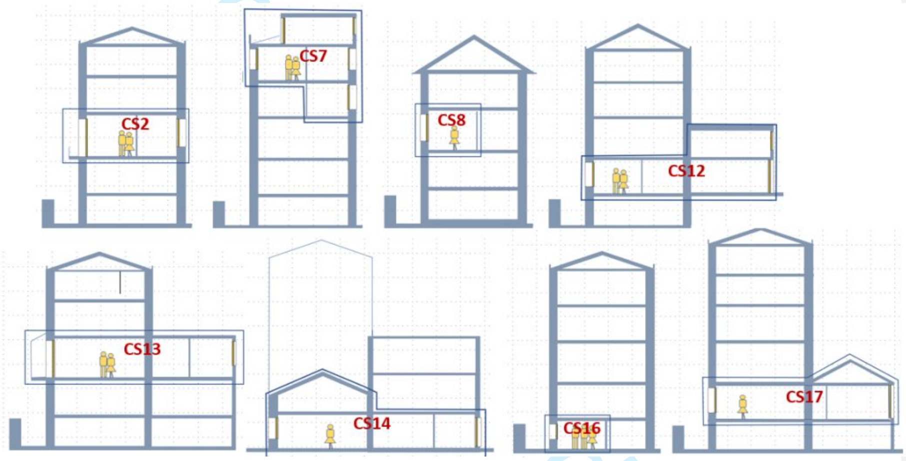

Figure 2. Schematic sections through the CSs showing the range of floor levels and number of occupants of the dwellings investigated.

Table 2 presents a synopsis of relevant physical data affecting the HEC of the CSs under investigation, which includes treated floor area[2] (TFA), thermal envelope area, thermal envelope-to-TFA ratio[3] (form-factor), windows-to-external walls area ratio[4] (WWR), orientation[5]. This data will be utilized for the analysis and discussion of results (section 5).

Table 2. Non-variable factors affecting HEC in the CSs ~~investigated~~investigated.

	TFA m^2	Thermal envelope m^2	Thermal envelope-to-TFA ratio	WWR %	Orientation
CS2	76.90	62.20	0.81	24	W
CS7	195.49	331.00	1.69	18	S
CS8	62.40	28.70	0.46	33	W
CS12	158.15	190.62	1.21	20	W
CS13	123.93	155.30	1.25	25	S
CS14	148.70	288.30	1.94	18	E
CS16	72.72	118.50	1.63	20	W
CS17	120.45	106.60	0.89	19	E

[2] Heated floor area of the dwellings.

[3] The thermal envelope-to-TFA ratio, or Heat-loss Form Factor is calculated as the ratio of the thermal envelope surface area to the treated floor area (TFA). This corresponds to the ratio of surface area that can lose heat (the envelope exposed to the external environment in this study) to the floor area that gets heated (TFA).

[4] The windows-to-walls ratio is calculated as the ratio of the total area of windows to the total area of external walls (those exposed to the external environment).

[5] Orientation is intended here the orientation of the main elevation.

3 Methodology

This study utilizes a mixed method approach on multiple CSs of 19th C listed dwellings (Figure 3), selected as representative of the majority of the TLD population in South-East England (for details on the CSs selection process please see section 2 and Menconi et al., 2018).

Figure 3. Brunswick Square, Hove, UK. One of the areas of analysis in this study (Brunswick town -Figure 1-, where CSs 2 and 8 are located -Figure2).

The approach used by conservation bodies for retrofitting TLDs recommends active measures (boiler upgrade) as the first interventions to be implemented in heritage buildings (Historic England, 2008), having minimum to no impact on their heritage significance (Rhee-Duverne and Baker, 2015). Passive measures should be implemented only following this stage because the envelope of these buildings holds the highest heritage value (Historic England, 2008; English Heritage, 2008). Hence, this research starts implementing boiler upgrade for all dwellings investigated, and then focuses on passive retrofit measures, therefore on buildings' physical determinants with a potential impact on HEC. It cannot be ignored that, alongside fabric and systems, users' behavior is an important determinant of dwellings energy consumption; however, occupants' behavior is an area of investigation on its own and a substantial volume of research exists in this field, which plays a fundamental role in explaining the gap between modelled and measured energy consumption in dwellings (Gilani et al., 2016). In this study, real occupancy profiles and patterns of use of the dwellings investigated were used to create reliable status-quo models; in the stages that followed, it was not within the scope of this research to investigate potential changes in the users' behavior and how they impact on HEC post interventions.

The study is articulated around successive stages of DES, following relevant stages of data collection. The first stage of data collection (data collection 1 in Figure 4) facilitated the creation of status-quo energy models (Model 1a in Figure 4; for details, please see Menconi et al., 2019a). The data output from their simulation was used for comparison with metered data (data collection 2 in Figure 4; for details on this stage please see Menconi et al., 2019b) to generate calibrated status-quo models (Model 1b in Figure 4).

Normalized models (Model 2 in Figure 4) were then made from the calibrated ones, standardizing some relevant variables (data collection 3 in Figure 4). Finally, baseline models (Model 3 in Figure 4) were created, which were aimed to isolate the physical determinants that play a role in the final HEC output of the simulations and to facilitate cross-case analysis.

In the following stage of research, a range of passive interventions applicable to the CSs were selected and simulated, individually and combined. The baseline scenario was used, in the final stage, to assess the output of the chosen measures, individually and in combination, by comparing the baseline HEC, associated CO_2 emissions, and indoor conditions and those post-intervention.

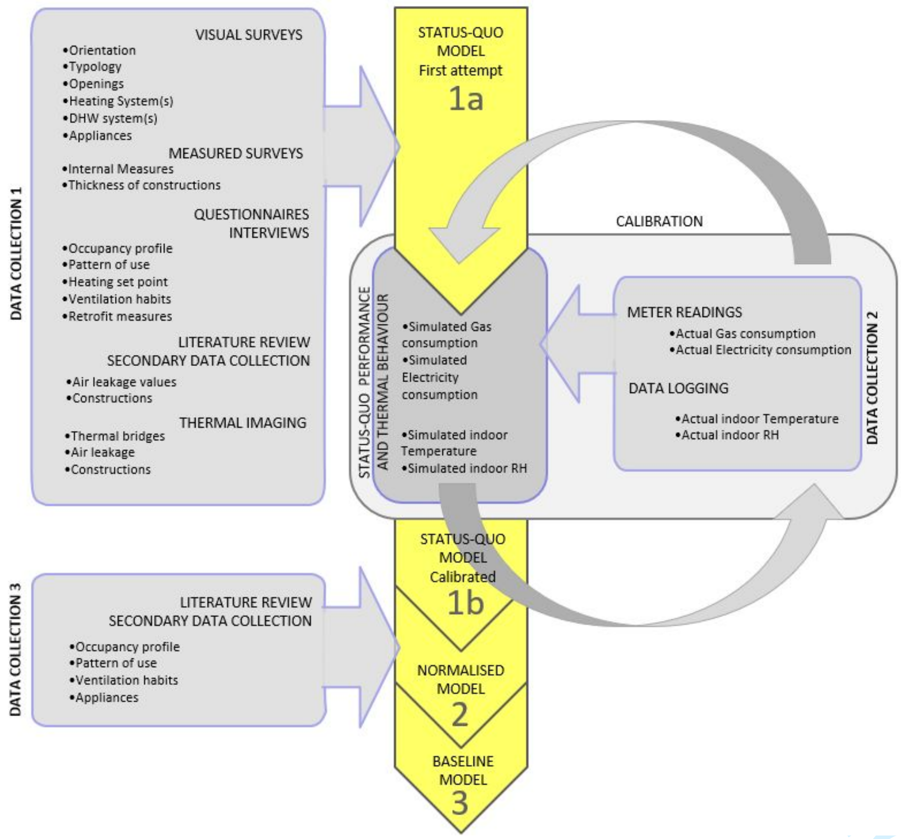

Figure 4. Research Design: stages to generate the Baseline Scenario.

4 The generation of a baseline scenario

The ISO50006 (2014, p.2) defines energy baseline as a "quantitative reference providing a basis for comparison of energy performance"; it states that "an energy baseline can be normalized using variables which affect energy use and/or consumption" and it "is also used for calculation of energy savings, as a reference before and after implementation of energy performance improvement actions" (ISO50006/2014, p.2).

To decide upon the process necessary in this study to generate a baseline scenario, firstly the type of energy consumption of interest was considered, then the typology of interventions. This study targets the reduction in space HEC (thereby in CO_2 emissions) of TLDs. It is focused on the envelope of selected representative CSs, hence on passive measures only and it is not within the scope of this research to investigate changes in user behavior and their impact on energy consumption. The process devised in this study is described in detail as follows.

4.1 Stage 1: Status-quo scenario

The dynamic thermal simulation operated for each CS, involved creating a 3D model of the dwelling and its adjacencies. Visual, measured, and thermal imaging surveys, alongside questionnaires and interviews with the occupants provided a range of primary data which were triangulated with secondary data from literature review and secondary data collection (Data collection 1 in Figure 4); these were used as input data for the generation of status-quo models (Model 1a in Figure 4). ~~).~~ Energy meter readings and indoor conditions data loggings added then further primary data (Data collection 2 in Figure 4), that, compared with the output from the first round of simulations, aided in the calibration process to obtain reliable status-quo models (Model 1b in Figure 4; see the Supplementary Documents, section 1 ~~–~~for an outline of the data collection process carried out for the creation of the status-quo energy models, ~~–~~ and section 2 ~~–~~for the detailed report of one of the ~~case studies~~CSs investigated). ~~).~~

4.2 Stage 2: Normalized scenario

The calibrated models were then modified to obtain normalized models (Model 2 in Figure 4). Normalization is defined by the standard as the process of modifying energy data "to compare energy performance under equivalent conditions" (ISO50006/2014, p.3).

For this purpose, elaborating on the approach taken by previous studies (Flores, 2013; Mansouri, 1996; Yao & Steemers, 2005), the determinants of energy consumption in dwellings were divided into (Figure 5, Stage1):

1. Contextual determinants
   - Linked to the physical characteristics (weather, size, envelope) or
   - Generated by long-term-choices (heating/DHW systems and appliances)
2. Behavioral determinants, linked to the pattern of use of the dwelling.

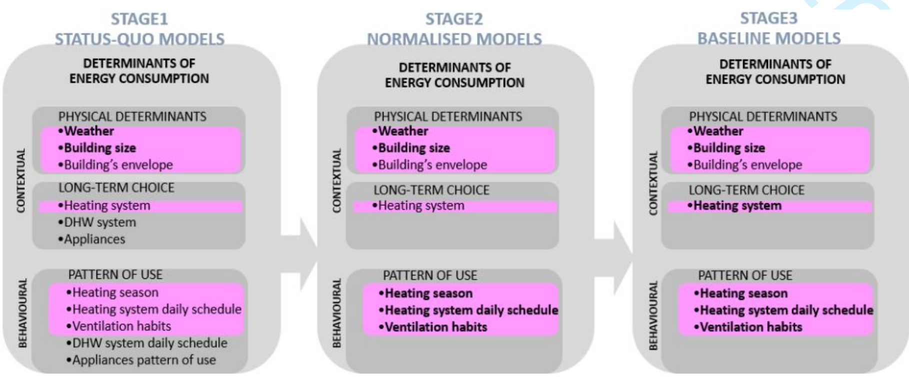

Figure 5. Determinants of energy consumption in the status-quo, normalized and baseline models. Highlighted in the pink boxes those that contribute to HEC. For each stage, ~~all~~ the standardized determinants are shown in bold.

Only some of the determinants of the whole energy consumption in dwellings contribute specifically to HEC (highlighted in pink in Figure 5). Weather and building size are amongst the most important determinants of residential HEC (Kavousian et al., 2013; Yao & Steemers 2005) but can be considered standardized from the first stage (hence in bold in Figure 5 for all models) because:

- all CSs investigated are in the same geographic location, hence subject to the same weather conditions
- the analysis of variation in HEC pre- and post-interventions is carried out dividing it by the heated floor area of the dwellings.

The normalized models (Figure 5, Stage2) must, firstly, allow for the isolation of variables affecting HEC by excluding all the determinants which are not directly pertaining to HEC. Hence, the models were assumed to be unoccupied but heated; this way, appliances, DHW systems, and their schedules of use, alongside heat gains due to various occupancy patterns, were all disregarded from the simulations because such determinants are not within the boundaries set in this study.

It cannot be ignored that, excluding occupancy heat gains in the retrofitted scenarios does not allow assessment of overheating risk. This was not within the scope of this ~~study,~~study; however, a test was carried out to assess whether the exclusion of occupancy heat gains could result in overlooking overheating risks in the post-retrofit scenarios. The test utilized CIBSE TM59 (2017) methodology in one CS (in its baseline scenario and after the application of the most effective combination of interventions) and did not show any risk of overheating.

Secondly, the normalized models must facilitate cross-case analysis by standardizing all the behavioral determinants of HEC; the normalization process therefore needed to include heating season, pattern of use of heating system(s) and ventilation habits (in bold in Figure 5 for the normalized model).

The decision concerning the standardized heating season to apply to all CS, was made based on the Energy Follow-Up Survey – EFUS – (BRE, 2013), aimed to collect data on patterns of energy use in the English housing stock to update the assumptions for current models. The report states that most households in England heat their homes daily for an average period of 5.6 months, from October to March-April. Therefore, the heating period for the normalized models was set to 15th October to 20th April, which also matches the average heating season as stated by the interviewees.

The EFUS also highlighted that most households in the UK heat their homes according to a fixed weekly pattern where, usually, weekdays have a different time-schedule from weekends (BRE, 2013). To determine the heating schedule and set point(s) to assign to all the dwellings, data from CIBSE Guide A (2015) and BRE (2018) was used. CIBSE (2015) provides winter thermal comfort temperatures for different rooms in dwellings (with living rooms, bedrooms, and bathrooms in the range of 22-23°C, 17-19°C and 20-22°C respectively). Most studies that deployed standard pattern of use for the BES of dwellings in the UK (Ingram, 2013; Moran, 2013; Porrit, 2012) referred to SAP 2009 (BRE, 2018), which provides heating set-point temperatures for use in calculating dwellings' energy consumption. In accordance with previous research and following SAP 2009 indications, the normalized temperature set-point used in this research in the living areas is 21°C, whereas the set-point for all the other areas is 18°C. The hours of heating were set according to SAP and Rd SAP calculations (based on EFUS and in accordance with CIBSE, 2015) as detailed in Table 3 (BRE, 2018).

Table 3. Temperature set-point and hours of heating as set in the normalized ~~models~~models.

Rooms	Temperature set-point	Hours of heating	
		Weekday	Weekend
Living room	21	7am-9am and 4pm-11pm	7am-11pm
Other rooms	18		

Ventilation rates also needed to be standardized for all the CSs. Considering the windows always shut, because of no occupancy, would lead to excluding heat-losses due to ventilation, therefore to unrealistic values of space HEC. Nonetheless, pre- and post-intervention heat-losses would be the same, which means this will hardly have any impact on the results because what the research aimed to assess is the change in HEC between the pre- and post-retrofit scenarios. However, it was finally decided to generate profiles concerning natural ventilation, to allow for a more realistic scenario, to better assess the thermal behavior of the dwellings pre- and post-interventions and to investigate the risk of condensation due to changes in the fabric. Indoor temperatures and relative humidity (RH) are main determinants that trigger natural ventilation in dwellings. Therefore, a profile was needed in Macro-Flow for all windows, to avoid overheating and excessive indoor RH. SAP (BRE, 2018: Table P2) provides values of the threshold temperature around 22° C, corresponding to the likelihood of high internal temperatures. Similarly, Memon (2014) used a standardized profile for ventilation based on the condition that if the indoor temperature exceeds 24°C and the building is occupied then the windows will get opened. A similar approach was also taken by Porrit (2012) in his study of a typical 19th C dwelling in the South-East of England, where windows were considered opened by up to 25% of their openable area. The same value for the opening percentage was used in this study. According to CIBSE (2015), RH in the range of 40-70% is considered acceptable in dwellings. Therefore, a formula profile was set and applied to the whole year, that ensures that the windows are open when the indoor temperature exceeds 22° C and/or the indoor RH exceeds 70%.

Apart from temperature stimulus, another important determinant in the profile of windows opening in dwellings is the indoor air quality; most occupants operate the windows to refresh the indoor air (Andersen et al. 2009; Drakou et al., 2011; Drakou & Tsangrassoulis, 2012). Assuming the dwellings to be unoccupied during the whole period of investigation, high percentages of CO_2 can be excluded from the determinants of windows opening in this study. Nevertheless, a check was done of the values given for air-leakage in each habitable room to assess if they already provide the air exchange rates suggested by CIBSE Guide A (2015) and Building Regulations (HM Government, 2022). In all the CSs, the status-quo ACH was higher than that prescribed by Building Regulations due to infiltration. This finding is in accordance with what has already been evinced by the literature (EST, 2006): most of the times, the air-leakage values of dwellings in England, exceed the values of 0.5ACH, considered necessary to provide a healthy and comfortable environment for the occupants (EST, 2006; BRE, 2009).

Lastly, to normalize the models, it was necessary to equalize the pattern of use of the shading devices. Two patterns were used, as shown in Table 4, for the heating and non-heating periods respectively, as they are characterized by different hours of daylight.

Table 4. Pattern of use of the internal shading devices as set in the normalized ~~models~~models.

Period	Time of shading device closed
1st Jan - 20th April	12midnight-7am; 8pm - 12midnight
21thApril - 15thOctober	12midnight-7am; 11pm – 12 midnight
16th October – 31st December	12midnight-7am; 8pm - 12midnight

The normalized models obtained this way are characterized by:

- DHW and appliances not in use
- Standardized heating schedule, temperature set-points, ventilation profile, and shading devices profile
- energy consumption output exclusively due to space-heating.

4.3 Stage 3: Baseline scenario

The normalized models were finally used to create baseline models and generate a baseline scenario of energy consumption and carbon emissions. According to ASHRAE (2002), the baseline model must represent the dwelling as it would have existed in the absence of the energy conservation measures; the retrofitted models, on the other hand, represent the building after the energy conservation measures are applied. The differences between the baseline and post-retrofit models must be limited to the retrofit measures only; all other factors, must be uniform between the two models.

A baseline scenario is necessary in this study, to:

- allow for cross-case comparison
- facilitate the analysis of:
  - energy consumption exclusively due to space heating
  - the impact of changes in the envelope's construction on HEC.

Therefore, all the normalized models were finally upgraded with the same high-efficiency gas boiler (in bold in Figure 5 for the baseline model), to generate a baseline scenario where only their physical determinants can play a role in the output concerning HEC. Table 5 shows the Seasonal Efficiency (BSE) and Seasonal Coefficient of Performance (SCOP) of the status-quo and baseline heating systems applied to the models.

Table 5. Heating system(s) in the status-quo, normalized and baseline scenario (post boiler upgrade).

CS	Status-quo and normalized scenario			Baseline scenario		
	Heating system(s)	BSE[6]	SCoP[7]	Heating system	BSE	SCoP
2	Gas Combi boiler	0.81	0.7228	Gas Combi boiler	0.90	0.8031
7	Gas Regular boiler	0.78	0.696	Gas Combi boiler	0.90	0.8031
	Electric underfloor heating	-	1.067			
8	LPG gas burner	0.70	0.5600	Gas Combi boiler	0.90	0.8031
	Electric heater	0.80	0.7467			
12	Gas System boiler	0.81	0.7228	Gas Combi boiler	0.90	0.8031
13	Gas Combi boiler	0.81	0.7228	Gas Combi boiler	0.90	0.8031
14	Gas Combi boiler	0.78	0.696	Gas Combi boiler	0.90	0.8031
	Gas Combi boiler	0.90	0.8031			
16	Gas Combi boiler	0.85	0.7585	Gas Combi boiler	0.90	0.8031
17	Gas Combi boiler	0.85	0.7585	Gas Combi boiler	0.90	0.8031

[6] Boiler Seasonal Efficiency. It is the ratio of the total seasonal heat output to the total seasonal fuel input.

[7] Seasonal Coefficient of Performance of the Heating System. IES automatically calculates the value of the SCoP for each system created, given the Boiler Seasonal Efficiency (manually inputted) and the Heating Delivery Efficiency (HDE), assigned to each system by default.

The generation of baseline models was meant to conclude the process of setting same conditions for all CSs. The results achieved from baseline models simulation, constituted the benchmark to refer to, in the following stage of this study, when assessing realistic energy savings and carbon reduction potentials due to retrofit interventions.

5 Results and discussion

This section presents the results of this stage of the study. It is organized in the following stages of analysis:

First, the status-quo energy consumption of the CS dwellings investigated (obtained as explained in section 4.1) is presented. Then, this status-quo energy consumption is compared to:

a. HEC of the normalized models (as explained in section 4.2)

b. HEC of the baseline models (as explained in section 4.3).

Figure 6 presents the status-quo total energy consumption (in kWh/year) of the dwellings investigated. It was obtained from spot measurements carried out for the duration of one year (data collection 2 in Figure 4) and used for the calibration of the energy models. It varies significantly amongst the selected CSs. This is mainly due to differences in size, floor level, occupancy, heating systems and pattern of use between the dwellings (Figure 2, Tables 2 and 5).

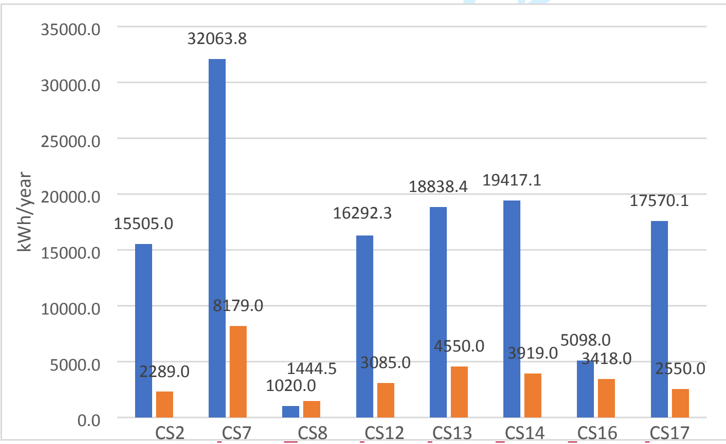

Figure 6. Status-quo energy consumption in kWh/year: gas (or LPG, for CS8) in blue and electricity in orange.

The measured data portrays a status-quo scenario of energy consumption significantly higher than that presented in the summary statistics for domestic buildings using the National Energy Efficiency Data-Framework (NEED) (BEIS, 2021b). The NEED summary shows a median value of annual gas consumption just below 14000kWh for domestic properties built before 1919, and just below 10000kWh for converted flats (built before or after 1919). The findings of this study however, showed a mean value of annual gas consumption for the cases studied close to 16000KWh and even higher.

Figure 7 utilizes box-and-whisker plots to compare the status-quo measured energy (gas and electricity) consumption to the normalized and baseline consumption of the CSs investigated. The first two boxplots (highlighted in red) show the status-quo measured energy (gas and electricity) consumption for the CSs investigated.

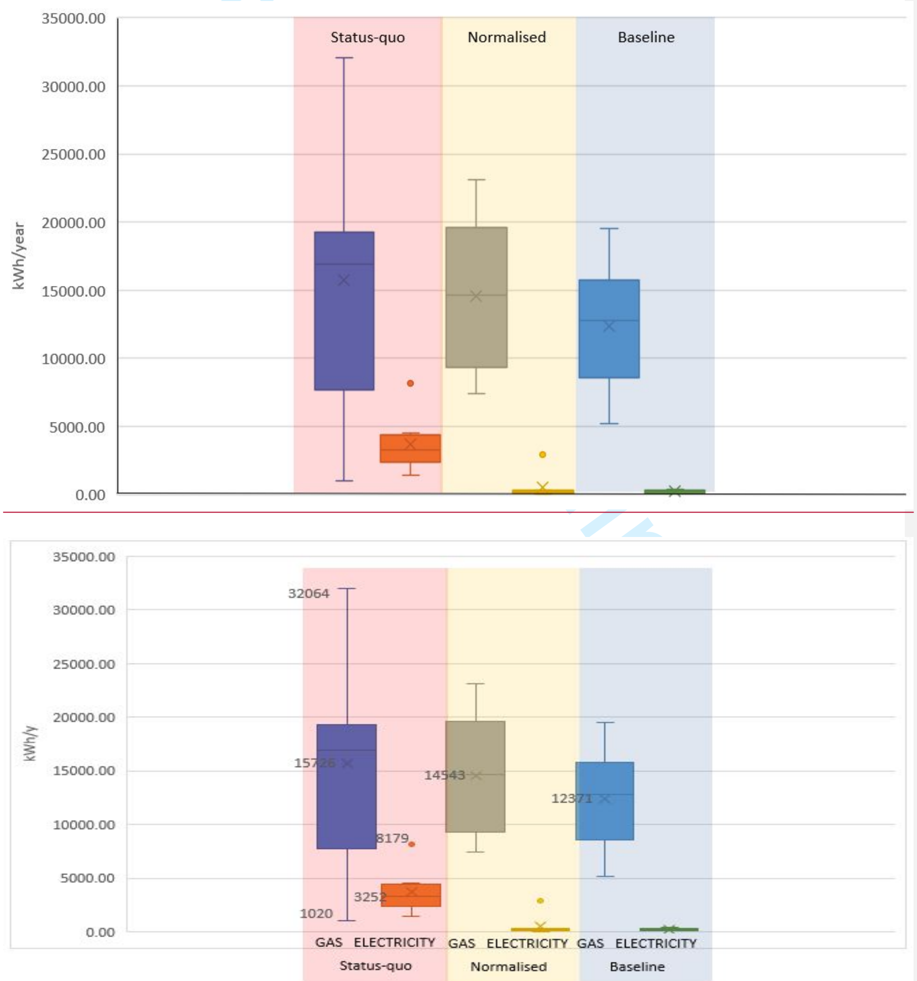

Figure 7. Status-quo, Normalized and Baseline annual energy consumption (kWh/year)

The wide range of gas consumption values in existing condition (first boxplot in Figure 7) is reflected in the long shape of the boxplot in this graph. The mean value is 15726 kWh/year; the long whiskers show the maximum and minimum value. The maximum gas consumption (32064 kWh/year) refers to CS7 and is due to multiple reasons, certainly the most relevant being:

- CS7 is the largest dwelling, with a TFA of 195m^2 (Table 2)

- it has the largest thermal envelope area (331m^2, Table 2) and one of the highest form factors (1.69)
- the heating system is used for more hours/day (the occupants here are both retired).

The minimum gas (or LPG for CS8) consumption value is 1020 kWh/year pertaining to CS8, with the smallest TFA (62 m^2, Table 2), thermal envelope area (29m^2, Table 2) and form factor (0.46, Table 2) and occupied only in the evenings.

The boxplot of the status-quo electricity consumption (the second in Figure 7) is much more compact, around the median value of 3252 kWh/year. There is one outlier (more than 1.5 times the box-length from the median in the graph). This value refers to CS7, with 8179 kWh/year, due to the electric underfloor heating system used in the kitchen and in the main bathroom (while all the other CSs have gas or LPG powered heating systems – as seen in Table 5).

The boxplots highlighted in yellow in Figure 7 show the results from simulation of the normalized scenario, that refers exclusively to HEC and has standardized pattern of use for all CSs. In the normalized scenario the median values are centered. However, the boxplot for gas consumption (third one in Figure 7) is only slightly shorter than the status-quo and this could be explained by:

- the variations of TFAs, alongside other non-variable factors, i.e., thermal envelope-to-TFA ratio, WWR, and orientation (as seen in Table 2)
- the variations of individual heating systems (in the normalized scenario only behavioral determinants of HEC were standardized; heating systems, on the other hand, are still characterized by different energy efficiencies in this stage of simulation - see Table 5 - although running according to the same heating schedule and temperature set-points).

The mean normalized gas consumption is 14543 kWh/year, not much lower than the status-quo mean value. However, the whiskers are much shorter in the normalized scenario, where the two extreme outputs (CSs 7 and 8) are much closer to the median once the pattern of use has been normalized.

The range of electricity consumption results is extremely narrow for the normalized scenario (fourth boxplot in Figure 7) as the simulations only consider HEC, having excluded all the electrically operated appliances. The only exception is again CS7, which shows an extreme value (at approximately three times the box-length from the median). This result was expected, as the normalized scenario maintains the individual status-quo heating system, which is partially electric in CS7 (Table 5).

Finally, the boxplots highlighted in blue in Figure 8 show the baseline scenario for HEC, computed from simulation of the normalized models with the same heating system (energy efficient gas boiler, Table 5) being applied to all. The baseline scenario shows a more compact gas consumption boxplot (fifth one in Figure 7 – mean value of 12371 kWh/year). Here, whiskers are much shorter than in the status-quo and normalized scenario because both pattern of use and heating systems have been standardized. In the baseline scenario the whiskers length is mainly due to the variations of TFAs between baseline models (alongside other non-variable factors, as seen in Table 2). The electricity consumption (last boxplot in Figure 7) is nearly[8] zero for all the CSs as the same gas boiler was applied for all of them (Table 5). The baseline models created this way, permitted to exclusively account for the changes in HEC due to the application of passive measures in the subsequent simulation runs.

The CSs investigated are all located in the same geographical area, therefore are not subject to differences in weather. They are also all distributed along the seafront area, hence are not different in altitude. Therefore, a further cross-case comparison was made between the energy performance of the different CSs, by simply dividing the annual energy consumption by the TFA of each dwelling. This stage was aimed to compare the dwellings under investigation, excluding the impact of their diverse size (floor area), on HEC. In this stage the main determinants considered are, therefore, the buildings envelopes alongside occupancy profiles, pattern of use, systems, and appliances.

Figure 8 shows the status-quo, normalized and baseline annual scenario of total energy consumption per m^2 of TFA. Therefore, it excludes the differences due to the range of sizes of the dwellings investigated from the analysis of the determinants of energy consumption. The shape of the status-quo boxplot is still long, mainly due to the range of patterns of use and heating systems. The normalized scenario shows a much more compacted size of box and whiskers. In fact, the determinants of energy consumption were reduced to material build-ups and heating systems (alongside the non-variable factors – form factor, windows-to-walls ratio, and orientation, as seen in Table 2). Finally, the baseline scenario shows a further reduction in the length of whiskers, having excluded the range of heating systems from the determinants of energy consumption. The mean value for the baseline scenario is 105.7 kWh/m^2year vs 124.6 kWh/m^2year for the normalized models, showing that the addition of new highly efficient gas boilers brings on average 19.3 kWh/m^2year energy savings.

[8] The electricity consumption calculated by the software at this stage refers only to certain basic functions of the boiler, i.e.: 1. central heating pump (used to push the water through the radiators) and 2. boiler fan (used to extract the flue gases to the outside).

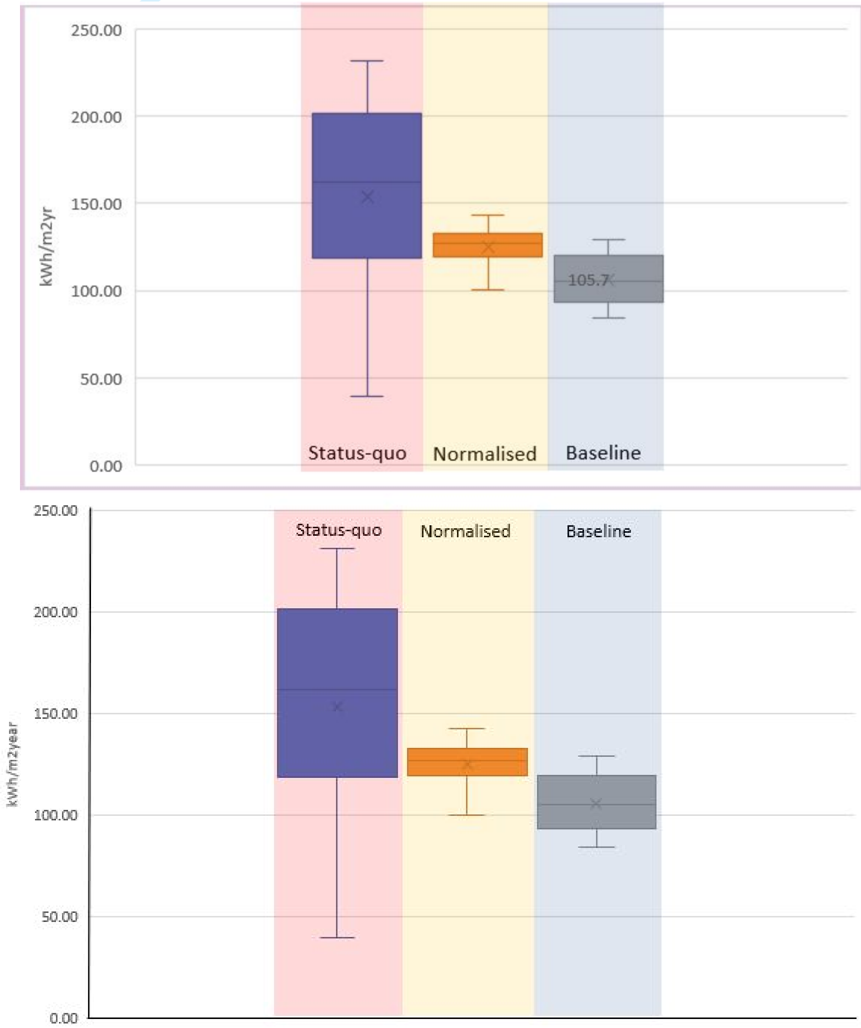

Figure 8. Status-quo, Normalized and Baseline annual energy consumption (kWh/m²year)

Figure 9 shows the baseline scenario of annual HEC per m² of TFA of each CS. It was used to assess the differences in results exclusively due to envelope material build-ups, alongside some non-variable factors shown in Table 2. The largest difference in the baseline HEC per m² is found between CSs 8 and 13. The thermal envelope constructions are similar and uninsulated in both these baseline models. Hence the different HEC is likely due to variances in thermal envelope area (29 m² for CS8 vs 155m² for CS13, see Table 2 and Figure 10) and form factor (0.46 vs 1.25, Table 2) which make of CS8 the best performing in its baseline scenario despite having the highest WWR of all CSs (33%, Table 2) - possibly also due to the heat gain taking place through the large west-facing single-glazed windows. –The thermal envelope areas of CSs 7 (331m²), 12 (191m²) and 14 (288m²), are larger than that of CS13, however their baseline HEC results lower than that of CS13. This is likely due to the baseline models envelope material build-ups, which have been partially insulated in CSs 7, 12 and 14.

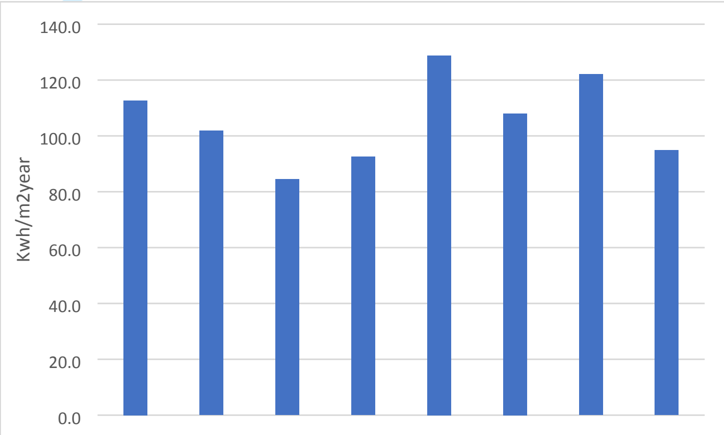

Figure 9. Annual HEC per m² TFA (in kWh/m²year) of the CS in their Baseline scenario.

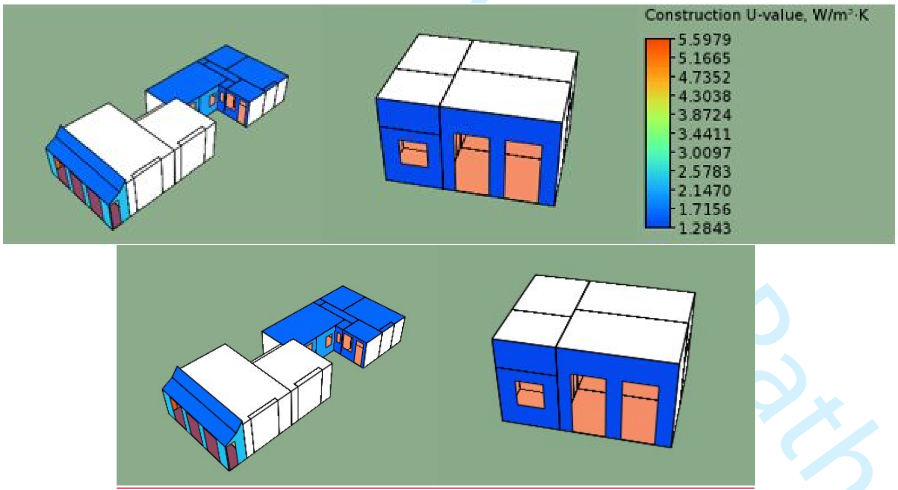

Figure 10. CS13 (left) and CS8 (middle), where the highest difference in the baseline scenario of HEC/m²year was found – the external envelope is shown in color.

6. Conclusion

The novelty of this paper consists in the ~~described~~ description of the process devised in this study to generate a baseline scenario for heating energy consumption (HEC) of selected representative case studies (CSs) of traditional listed dwellings (TLDs). This is a fundamental stage in any study that aims to compare the energy performance pre- and post-interventions, and to allow for comparison between different CSs under equivalent conditions ~~(ISO 50006/2014)~~. Nevertheless, few and far between are the studies that detailed the actual process and the variables involved in it, and this paper aims to address this gap, to facilitate the application of a sequential approach as such in similar studies~~. –~~ on traditional buildings in the UK or in other EU countries.

The following steps were necessary to obtain baseline models from the status-quo calibrated ones (Figure 4):

- normalization of the calibrated status-quo models by means of exclusion of all the determinants of energy consumption which have not an impact on space heating and standardization of all the behavioral determinants of HEC
- application of same high-efficiency gas heating system to all CSs.

The baseline scenario aims to focus the analysis only on physical determinants of HEC, namely the envelope of the dwellings investigated (to assess the benefits of applicable passive retrofit interventions on it) and some non-variable factors. These were presented in this paper and their influences were assessed on the final HEC.

The paper discussed the results obtained from meter readings and simulation of the CSs under investigation, in their status-quo, normalized and baseline scenarios. The The findings of this stage of the study measured data portrayssshow that a status-quo scenario of energy consumption significantly higher than that presented in the summary statistics for domestic buildings using the National Energy Efficiency Data-Framework (NEED) (BEIS, 2021b). The NEED summary shows a median value of annual gas consumption just below 14000kWh for domestic properties built before 1919, and just below 10000kWh for converted flats (built before or after 1919). The findings of this study however, showed a mean value of annual gas consumption for the cases studied close to 16000KWh and even a higher median (as presented in Figure 7, first boxplot). This suggests that converted heritage flats are among the worst performing properties in the category of traditional dwellings.

Commented [MM1]: This part has been moved to section 5 to comply with the reviewers' comments.

All the CSs show considerable to significant improvements achievable by their heating systems upgrade, resulting in an average 15% HEC savings potential across the CSs investigated in this study. This finding further confirms the advice of conservation bodies, which stresses the importance of this intervention prior to any passive retrofit measure as these can pose higher risks to the heritage value of the dwelling and to the thermo-hygrometric balance of its constructions (English Heritage, 2008; Historic England, 2012; Suhr & Hunt, 2013; The Prince's Regeneration Trust, 2010, to cite but a few).

This paper also contributed intoto the discussion of the influence of some non-variable factors (treated floor area, thermal envelope area, form factor and window-to-wall ratio (non-variable factors) on the final HEC of TLDs. From this stage of the study, form factor was shown to have the highest impact on the energy performance of the CSs investigated in their baseline scenario, far outweighing their window-to-wall ratio.

The further stage of this study,In the following stage, of this study, deployed the baseline models have been deployed and modified their external envelopes materials build-ups have been modified to simulate the retrofit interventions applicable to them, individually and in combination, and to assess the potential energy savings achievable through those interventions. The baseline scenario generated using this the methodology presented, provides provided a basis for comparison of energy performance and thermo-hygrometric behavior pre- and post-passive retrofit interventions, facilitating cross-case comparison.

The analysis of the findings of this study highlightede results of the following stage of study showed how the range of baseline conditions described in this paper are strictly intertwined with the range of energy and carbon saving potentials of the investigated interventions investigated. This paper also discussed the non-variable factors affecting the final HEC of TLDs, in their status-quo, normalized and baseline scenario. The following stage of research showed how the same factors also played an important role in determining the amount of energy and carbon savings achievable as a result of retrofitting TLDs in South-East England.

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An energy performance baseline scenario for 19thC Listed Dwellings in the UK

Supplementary documents

1. Data collection for models creation in IES-VE

1.1 Construction Templates

Walls

Masonry

Most of the external walls in the dwellings selected are made of rendered brickwork. This is confirmed in the listed entry summaries which report the main characteristics of the sequence of terraced houses to which each CS belongs (Historic England, 2018b). By the Regency period in fact, brick making was common in England and widely used in areas where clay was available more than other materials, like Brighton (RTH, 2018a). The thin layer of clay that could be found on the surface of the city's soil (called "brick earth"), was used during the Regency period as raw material for the brick making process. The bricks were mostly used for the 'framing' of buildings as they were still a relatively expensive construction material. Also, to avoid unnecessary costs, it was the convention that the bricks required for a building project would be sourced from brick earth dug up immediately adjacent to the building site and then fabricated and fired in situ. This is exactly what happened in Brunswick Town (RTH, 2018a; Nick Tyson curator of RTH, personal communication, 11th of June 2017).

The size of bricks varied slightly throughout the centuries in this area, constantly being twice as long, as they were broad for ease of handling them. Throughout the 19th C, in Brighton, bricks of imperial size (227mmx115mm) were still used; metric size bricks however soon became the favourite choice (215mmx102.5mm). Both these sizes of bricks were found In the Regency Town House in Brunswick Square (Nick Tyson curator of RTH, personal communication, 11th of June 2017).

During the survey, the overall thickness of each wall was measured in the dwellings under investigation. A tactile inspection of the wall then guided the assumptions concerning the presence or not of plaster on lath and battens or plasterboard on the inside. Hence, the layer of brickwork in the material build-ups was assumed to be made of imperial size bricks or of metric size bricks, given the outcome of the measured survey and depending on the presence or not of plaster on lath (or plasterboard) internally. The thickness of the layer of imperial brickwork in the constructions was estimated to be:

- 115mm for a half-brick wall
- 227mm for a one-brick wall
- 352mm= 227mm+10mm (mortar)+115mm for a one-and-half-brick wall
- 464= 227mm+10mm (mortar)+227mm for a two- bricks-wall and so on

When the bricks were assumed to be of metric size, the thickness of the layer of brickwork was estimated to be:

- 102mm for a half-brick wall
- 215mm for a one-brick wall
- 327= 215mm+10mm (mortar)+102mm for a one-and-half-brick wall
- 440= 215mm+10mm (mortar)+215mm for a two-bricks-wall and so on.

Brick masonry was assumed to be the material used also for rear and party walls, although frequently these in Brighton were made of Bungaroush. This is a typical compound used in the area of Brighton; the Regency Society describes it as "made principally of lime, gravel, coarse sands and flints, often with some brick fragments or other rubble added. The combination forms a type of mortar, or reinforced concrete" (RTH, 2018b). This compound was not modelled as the software only allows the creation of construction templates made of homogeneous layers, eventually including one composite layer (which can be made of two materials in different percentages), which would not be yet a good approximation of the real material. However, to assume the party walls made of bricks even when they may not be, did not interfere with the simulations results due to the fact that the software assumes all the walls adjacent to other buildings to be in adiabatic condition with the neighbouring dwellings (all occupied and heated). Therefore, the difference, if any, between the U-value of a bungaroush and that of a brick wall can be ignored in the simulation.

The rear walls were considered made of bricks, as no evidence was found on site, of the actual presence of bungaroush in the constructions investigated.

The internal partitions were modelled as:

- brick walls when their measures, visual and tactile inspection confirmed it
- stud walls partitions when the measured, visual, and tactile surveys gave good reasons to believe so or when the interviews confirmed that the internal layout of the dwellings had been modified over time.

Finishes

During the regency period, lime-based plasters were largely used in Brighton, as a uniform exterior finish for the main elevations of large terraces of houses and as internal finish applied on timber lath or directly on brick walls constructions (RTH, 2018b). Despite the distinction, the requirements for lime-based products used internally (plasters) or externally (renders) were essentially the same in most cases (Nogueira et al., 2018).

The use of lime was widespread during the early 19th C, before the introduction of modern cements. The main advantages in the use of lime plaster compared to more impermeable cement-plasters, are that:

- the microporous structure of lime plaster, allows the walls to absorb and release moisture (the characteristic “breathability” of traditional buildings)
- lime plaster also allows for some structural movement to take place avoiding the risk of cracking, which is higher with cement-based render (RTH, 2018b).

The listed entry summary of the dwellings investigated frequently describes their front elevation as covered in stucco. A variety of materials were used to produce traditional stucco; in England, the most common was an exterior render prepared from hydraulic lime, sand and hair (to reduce shrinkage during setting) (Constantinides & Humphries, 2018; Nogueira at al., 2018). The main reason for the widespread use of this type of stucco was its affordability compared to stone; this was mainly true in England and Wales and in many seaside resorts in these regions, where it also provided defence against the salt spray. It was generally used to cover the whole façade but not the sides and back (Constantinides & Humphries, 2018). The stucco that covers most of the regency terraces in Brighton and Hove is a type of render made from lime mortar. To be used in construction, lime was taken from chalk and heated in a kiln at approximately 1,000° C, to produce ‘quicklime’; the quicklime was then mixed with water to form ‘lime putty’; after a period of maturation, this was mixed with sand and other fine aggregates, to create a range of plasters and renders (Minerva Stone Conservation, 2018; RTH, 2018b).

During the Regency period many attempts were made to produce harder, smoother and more durable plasters, adding ingredients to the lime putty, such as white marble dust, or milk, cheese and egg white (all rich in protein), to improve the binding and waterproofing qualities of stucco; pozzolanic materials were also used to improve strength and resistance to water penetration (Nogueira, R. et al., 2018).

Most stucco was painted, and in the Regency period, it was often much darker than it is today (RTH, 2018b). The main characteristic of stuccoed terraces, however, was their unified entity, obtained with the use of a uniform colour for all the row of houses.

In all the dwellings investigated, 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. To generate realistic building constructions, the new material had to resembles the thermo-physical characteristics of the lime-based plasters and renders generally used in the traditional buildings investigated. Materials are defined in IES using the following parameters: density, thermal conductivity, heat capacity, water vapour resistivity.

Therefore, a review of the existing literature concerning lime plasters was carried out, taking into account the values reported by the different authors for such parameters. Table 0.1 reports a synthesis of the literature reviewed.

TABLE 0.1 REVIEW OF LIME PLASTERS THERMO-PHYSICAL DATA FROM THE LITERATURE

Author	Location of the study	Thermal conductivity W/mK	Density kg/m³	Specific heat capacity J/KgK	Vapour resistivity GNs/Kgm	Water vapor diffusion resistance factor (μ)	Permeance (equivalent thickness of air) (m)
Čachova, M. et al., 2016	Czech Republic	-	-	-	50 (wet) 185 (dry)	10 (wet) 37 (dry)	-
Cerny, R., et al., 2006	Czech Republic	0.73 (dry)	1660	970 (dry)	75	15	-
Konakova et al., 2017	Czech Republic	-	1630	-	62.5	12.5	-
Nogueira et al., 2018	Portugal	-	-	-	<75	<15	
Pavlikova et al., 2016a; 2016b	Czech Republic	0.674	1650		24.5 (wet) 51 (dry)	4.9 (wet) 10.2 (dry)	--
Stefanidou et al., 2010	Greece						
Theodoridou et al., 2016	Cyprus	0.69 (dry) 0.94 (wet)		812 (dry) 887 (wet)			
Tesarek et al., 2017	Czech Republic	-			75	15	
Veiga et al., 2001		-	-	-	-	-	< 0.08 (renders) < 0.10 (plasters)
Vejmelkova et al., 2012a	Czech Republic	0.65 (dry) 0.83 (wet)	1745	-	29 (wet) 61 (dry)	5.8 (wet) 12.2 (dry)	-
Walker & Pavía, 2015	Ireland	0.8	1820	863.9	-	-	-

A wide range of values were found by different authors for the range of samples of lime-based plasters investigated. Most of the studies (Fort et al., 2014; Pavlikova et al., 2016a and b; Vejmelkova et al., 2012a) agreed that the thermal performance of lime plasters is strictly related to the total pore volume, distribution and cross connections of pores and changes considerably when the same material is analysed in a wet or dry condition. The thermal conductivity of water in fact is more than 20 times higher than of that of air (Fort, J. et al., 2014). Therefore, also the thermal conductivity of the lime increases with the increase of moisture content at a ratio that depends on the porosity of the material. The literature reviewed suggests different values for the thermal conductivity of lime-based plasters, which range from 0.65 W/mK (Vejmelkova et al., 2012a) in dry conditions, to 0,94 W/mK (Theodoridou, 2016) in wet conditions, also reporting values higher than 1,0 W/mK (Fort, J. et al., 2014) when the volumetric moisture content increases above 0.1m³/m³.

The behaviour of the material with water vapour is assessed using three different parameters in the studies investigated: vapour resistivity, water vapour resistance factor and permeance (μ-value). They provide a measure of the material's reluctance to let water vapour pass through it. These parameters are linked by following relationships illustrated in Figure 0.1, where:

- T is thickness of the material (m)
- A is the vapour permeability of still air (0.2gm/MNs).

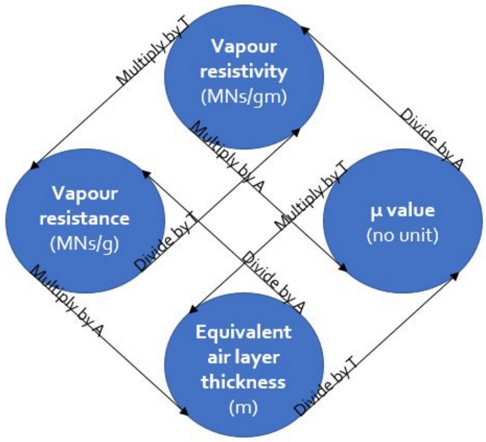


FIGURE 0.1 RELATIONSHIP BETWEEN: VAPOUR RESISTIVITY, WATER VAPOUR RESISTANCE FACTOR AND PERMEANCE (μ-VALUE)

The vapour resistance values proposed by different studies for different tested lime plasters are not homogeneous and range from 25.4 MNs/gm (Pavlikova et al., 2016a) for wet material, to 185 MNs/gm (Čachova, M. et al., 2016) for dry material. The studies reviewed agree that the capacity of the lime-based plasters to let water vapour pass through them, decreases with increasing moisture content; therefore, the vapour resistivity follows an inverse pattern, increasing with diminishing moisture content.

It was finally decided to follow the indications given by the International Standard Organization (BS EN ISO 10456, 2007) and CIBSE (2015) for the definition of the characteristics of the lime-plasters to be used in the simulation. These are as follows:

- Thermal conductivity: 0.8 W/mK
- Density: 1600 kg/m^3
- Specific heat capacity: 1000 J/KgK
- Water vapour resistance factor (μ): 6 (wet material); 10 (dry material).

The values of the vapour resistivity calculated using ISO μ-values range from 30 MNs/gm for a wet material to 50 MNs/gm for a dry material. 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 material database window in IES only allows for the input of one value for each of the parameters. Therefore, the value of 45 MNs/gm (within the limits suggested by ISO) was assigned to the water vapour resistivity of the lime-based plaster used internally, which is also within the range of values proposed by previous research and corresponds to the value that the software gives to the lightweight plaster. It was considered whether to use a higher value for the lime plaster used externally (stucco), that was certainly meant to be more water resistant because exposed to the environment. However, stucco is also frequently wet in the climatic area investigated, therefore its resistivity could be lessened, potentially reaching values much lower than 45 according to previous research. Therefore, the same value of 45 MNs/gm was given to the lime plaster used internally and externally.

The internal face of exterior walls, mainly in the most important rooms and where the walls, like in Brunswick square, are curved, was originally often finished in lime plaster over lath. This was a common method for interior finishing as it allowed smooth finish for ornamental or unusual shapes like rounded walls. Plaster on lath has been mostly replaced with plasterboard, whenever works were carried out on the interior surfaces, as this construction is faster and less expensive to install. However, in most of the CSs, where curved walls are present (in CS2), and the tactile inspection confirmed it and/or the participants were aware of the existence of such construction in the internal face of the walls (for most CSs in the front walls), a material build-up that resembles lath and plaster was modelled. In those CSs the materials build-up accounted for:

- 30 to 50mm of cavity (the thickness of the vertical timber battens)
- 6mm of wood (oak essence for the lath) and
- 15mm of lime plaster (this thickness aiming to take into account the plaster forced into the gaps between the lath as well as the plaster on top of the lath and any further layer of plaster frequently added during the time when the lath has not been replaced by plasterboard).

The rear elevations were mostly finished in lime plaster externally and internally; when the walls were made of bricks they were usually directly coated in plaster with no need for the additional cavity and lath.

Internal floors - ceilings

The intermediate floors are made of timber as they were originally. The original ones were finished with floorboards, but these were frequently replaced with chipboard flooring and carpets and they have been modelled to reflect this. The ceilings, instead, as generally less modified, have been mostly assumed to be still the historic one finished in lath and plaster.

Ground floors

CSs 12, 14 and 16 contain floors in direct contact with the ground. In none of these CSs were the occupants aware of the materials build-up of the ground floor, but they confirmed that no insulation had been added over time to them. The floorings in such dwellings are made of wood, carpet, laminate, vinyl, clay tiles or stone. To model them, the default constructions contained in the software database for uninsulated suspended timber floors and uninsulated solid ground floors were used and modified in line with previous similar research (IES-VE, 2009; Memon, 2014; Neroutsou & Croxford, 2016).

The soil-ground floor interface temperature is of paramount importance for the accuracy of the output of hygro-thermal simulations (Coelho et al.,2018). The soil behaves as a temperature buffer; however, the actual interface temperature is not easily monitored and in heritage buildings this can be even more challenging because of the impossibility of carrying out invasive tests. According to IES, the ground temperature at a depth of about 1m, can be generally assumed to be 13°C in the UK (IES-VE, 2018a). Therefore, for each floor in contact with the ground, a constant temperature boundary condition of 13°C was set utilising an ad-hoc temperature profile applied to the whole year.

Roofs

CSs 7, 12, 13, 14, and 17 contain roofs, although only CS7 is a top floor dwelling. It spans over the top two floors of two terrace houses and half of its roof was converted to generate an added floor covered by a flat roof. All the other roofs are traditional timber constructions. In CS7 it was possible to inspect the roof space (in the older part of the dwelling, where the loft space had not been converted). The typical construction found here, made of timber rafters, timber boards and slate tiles (Figure 0.2), was assumed to be also used in the pitched roofs of the other CSs, with the addition of layer of gypsum plasterboard in the internal face when the roof covered a habitable space. The ceiling below the sloping roof (Figure 0.3), was already insulated with sheep-wool in CSs 7, hence the construction was created accordingly in IES.

Only in CS14 the pitched roof had been recently renovated, hence a layer of insulation was added to the materials build-up.

FIGURE 0.2 THE TIMBER ROOF IN CS7 -INSIDE AND OUTSIDE- SHOWING THE TIMBER CONSTRUCTION AND THE SLATE TILES CLADDING

FIGURE 0.3 THE TIMBER ROOF IN CS7, SHOWING THE TIMBER CONSTRUCTION AND THE SHEEP-WOOL LOFT INSULATION IN PLACE

The flat roofs, where present, are all made of timber; a few of them are insulated (as evinced from the interviews with the occupants, or where the construction is fairly recent). The external layer is made of felt bitumen. The assumptions concerning the status-quo material build-ups for flat roof constructions, were made based on their overall thickness. In CS12 overall thickness of the flat roof construction was measured through the skylight (Figure 0.4, left). In CS13, only the distance from lintel to gutter was possible to measure, hence the overall thickness of the flat roof construction had to be deducted from that measure (Figure 04, right).

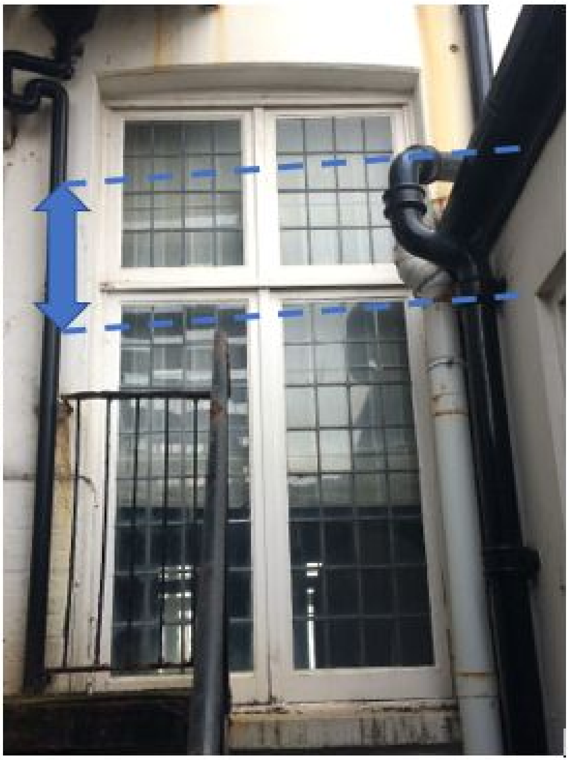


Figure 0.4 The flat roofs in CSs 12 (left) and in 13 (right)

Glazing

Most of the windows are the original timber sash ones in the main elevations, while those on the back elevations or on the loft were sometimes modernized. The models take this into account in the Apache-Sim module and reproduce each external opening with its size, materials and type of shading device eventually used (all the other characteristics, affecting the ventilation rates, having been detailed in Macro-Flo).

The status-quo scenario, for most CSs, was therefore modelled as a single glazed construction. In IES, the clear float glass modelled for this construction, is 6mm thick, which is actually the case only for some of the windows investigated (e.g. for the high front windows in CSs 2 and 13, as shown in Figure 0.5), most of the others likely being thinner than 6mm.

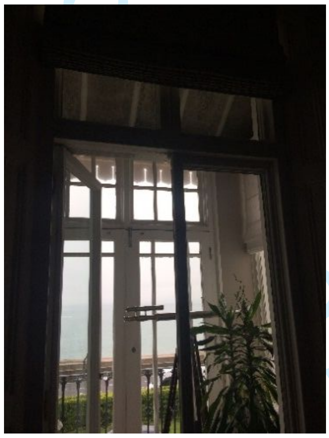


Figure 0.5 CSs 2 and 13: front windows

A clear float pane of 6mm was used in the status-quo constructions because, when modelling a glazing system, IES recommends to account for the main performance parameters (IES-VE, 2018c). The interventions assessed in this study are aimed to reduce heating energy consumption (HEC), hence the most relevant parameter when modelling the building envelope, is the thermal transmittance (U-value) of the status-quo and retrofitted constructions. When it comes to glazed constructions, two values are calculated:

- the centre of pane U-value, which refers exclusively to the glass and is the reciprocal of the sum of the internal and external thermal resistance and total thermal resistance of the glazing [1].
- the whole window U-value, which includes the effects of frame and glazed edge area.

In this study, the thickness of 6mm for the status-quo glazed constructions, was considered appropriate to achieve a centre of pane U-value of the construction as close as possible to the reference U-value taken from the literature. The whole window U-value of the constructions created varies for each window, depending on the parameters related to the frame (material -softwood for most of them- and frame % -window frame area/whole opening area). In the Project Construction Tab, for all the other input (Thermal Conductivity, Angular dependence[2], Resistance, Transmittance[3], Outside and Inside Reflectance[4],Refractive Index[5], Outside and Inside Emissivity[6]) the default value associated with the given material was used for this construction, as suggested by IES when such values are not given by the manufacturer (IES-VE, 2018e).

The values assigned in the Apache Constructions database to the resistance of the shading devices, their shading coefficient and short-wave radiant fractions were taken from previous research (Fitton et al., 2017; IES-VE, 2009), from CIBSE Guide A (2015), based on Wood et al. (2009) and from IES-VE Apache-Tables (IES-VE, 2018b), that elaborated data from BRE and ETSU. Table 0.2 presents the relevant input values concerning shading devices, as found in the literature reviewed. To make a decision concerning the right input to use for each shading device, assumptions were made for each model, based on the visual survey and on the values suggested by the literature. Such values ware applied using a profile specifically made for each shading device, that reflects its actual pattern of use as given by the interviewees.

TABLE 0.2 SHADING DEVICES AND THEIR SHADING COEFFICIENT, SHORT WAVE RADIANT FRACTION AND THERMAL RESISTANCE

Shading device	Shading coefficient	Short wave radiant fraction	Resistance m^2K/W
Conventional roller blinds, curtains, venetian blinds (CIBSE, 2015)	-	-	0.05

[1] In the case of a double or triple glazing, the sum of the thermal resistances of the layers of glass and the thermal resistance of the cavity.

[2] Specifies the angular dependence of the pane's optical properties, as explained in: https://help.iesve.com/ve2019/glazed_construction___construction_layers.htm. The option 'Fresnel', used by default by the software, calculates the angular dependence using the Fresnel equations and the specified refractive index.

[3] The transmittance of the pane for solar radiation at normal incidence, as explained in: https://help.iesve.com/ve2019/glazed_construction___construction_layers.htm.

[4] The reflectance of the outside or inside surface of the pane for solar radiation at normal incidence.

[5] The refractive index of the material composing the pane.

[6] The emissivity of the outside and inside surface of the pane. These are used to calculate the thermal resistance of the adjacent surface or cavity (unless this resistance has been otherwise specified).

Closely fitted curtains (CIBSE, 2015)	-	-	0.07
Fully sealed blinds (CIBSE, 2015)	-	-	0.18
Low-emissivity fully sealed blinds (CIBSE, 2015)	-	-	0.44
Blinds (IES-VE, 2009)	0.61	0.3	0.05
Wooden Shutters (IES-VE, 2009)	0.28	0.4	0.29
Curtains (IES-VE, 2009)	0.49	0.3	0.07
Venetian Blinds (IES-VE, 2018c)	0.61	0.3	-
White cotton curtains (IES-VE, 2018c)	0.54	0.3	-
Cream linen blinds (IES-VE, 2018c)	0.40	0.3	-
Curtains (fine) (IES-VE, 2018c)	0.76	-	-
Blinds (Fitton et al., 2017)	-	-	0.14
Heavy curtains (Fitton et al., 2017)	-	-	0.16
Low-emissivity roller blinds (Fitton et al., 2017)	-	-	0.30
Well-fitting shutters (Fitton et al., 2017)	-	-	0.33

Heating and DHW Systems

Table 0.3 reports the status-quo heating and DHW system(s) in each CS. Combi boilers are shown in green in the Table as they are the most energy efficient.

TABLE 0.3 HEATING AND DHW SYSTEM(S) FOR EACH CASE STUDY

CS number	heating system1	heating system2	heating system3	DHW1	DHW2
2	combi boiler ALPHA in tech 26 XE	-	-	from combi boiler	-
7	regular boiler POTTERTON "Prima" n8	-	electric underfloor heating n.8	HW tank 40*70cm n.7 from regular boiler n.8	HW tank 30*140 cm n.8 from regular boiler n.8
8	Calor Super Heat butane gas heater (LPG)	electric heater	-	hot water tank with electric immersion heater	-
12	system boiler VAILLANT ecoTEC Plus 630	-	-	HW tank 450x1150mm from system boiler	-
13	combi boiler WORCHESTER GREENSTAR Cdi	electric heater De Longhi "RADIA"		from combi boiler	-
14	combi boiler 1 WORCHESTER living area	combi boiler 2 VOKERA Easi-heat Plus	electric underfloor heating	from Combi boiler 1 kitchen and shower	from Combi boiler 2 bathroom
15	combi boiler VAILLANT ecoTEC Plus 831	-	-	from combi boiler for back of house	from THERMtec off peak immersion heater for front of house
16	combi boiler Main	-	-	from combi boiler	-
17	combi boiler Greenstar 28i	-	-	from combi boiler	-

1.2 Heat gains

People

CIBSE Guide A (2015) 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 questionnaires/interviews, was taken into account to make a decision concerning the values of sensible and latent heat gains to use (assuming the rooms to be at 20°C).

The values used in the status-quo models are reported in Table 0.4 respectively for a male (m), female (w) or an average of male-female-child (a) occupant. In the Table, to each type of activity corresponds a value of the heat gains as prescribed by CIBSE and a typology of room to which such activity was related in this study.

Table 0.4 Values of sensible and latent heat gains used in the simulations

Activity	Room templates	Sensible Heat Gain	Latent Heat Gain
Seated, inactive	Bedroom	90(m); 76(w); 78(a)	25(m); 21(w); 22(a)
Seated, light work	Bath, Kitchen, Study	100(m); 85(w); 90(a)	40(m); 34(w); 36(a)
Standing, light work	Living room, Kitchen	110(m); 94(w); 97(a)	50(m); 42(w); 44(a)

Lighting

The dwellings investigated mainly use Fluorescent lamps and Tungsten lamps (showing also a propension to opt for more efficient lamps when in need of renovation); some of the flats have LED lights in some rooms.

CIBSE Guide A (2015) explains that all the electrical energy used by a lamp is released as heat, therefore the value given to the energy consumption of each appliance corresponds in this case to the value of the sensible heat gain from it. Values suggested by CIBSE (2015) were used for heat gain generated by lighting in the measure 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 values used in each room template for energy consumption and heat gain generated by lighting fittings are:

- 12W/ m^2 for room templates where lighting was mostly Tungsten
- 8W/ m^2 for room templates where lighting was mostly Fluorescent
- 4W/ m^2 for room templates where lighting was mostly LED.

Appliances

The values suggested by CIBSE (2015) for energy consumption and heat gain of typical domestic and office equipment and of electric and gas hooded cooking equipment were used in this study. Such values depend on the appliance rating, the type of wash (for washing appliances), the type of fuel and the presence or not of a hood (for cooking appliances). Therefore, heat gains and energy consumption for each appliance in each dwelling were taken from CIBSE Guide and inputted in each model according to the information provided by the visual survey (type of appliances present in each CS and their rating) and confirmed or complemented by the questionnaires and interviews. Table 0.5 reports the input values concerning energy consumption and heat gain used for each appliance, when present. A profile of use was also created according to the information provided by the occupants with the questionnaire/interviews and concerning the frequency and length of use of each appliance.

TABLE 0.5 VALUES OF ENERGY CONSUMPTION AND HEAT GAIN FOR DOMESTIC APPLIANCES USED IN THE SIMULATIONS ACCORDING TO CIBSE (2015)

Equipment		**Energy consumed (1 hour)**	**Heat gain**
Washing machines	A-rated (60ºC wash)	940W	-[7]
	A-rated (40ºC wash)	560W	-
	C-rated (60ºC wash)	1230W	-
	C-rated (40ºC wash)	740W	-
Tumble driers	A-rated	1840W	-
	C-rated	2450W	-
Dishwashers	A-rated (65ºC wash)	1000W	-
	A-rated (55ºC wash)	700W	-
	C-rated (65ºC wash)	1320W	-
	C-rated (55ºC wash)	920W	-
Ovens (electric or gas)	A-rated	970W	147W[8]
	C-rated	1370W	
Microwave oven		1390W	-
Microwave oven standby		4W	-
Hobs	Electric	725W	147W[9]
	Gas	1000W	293W[10]
Televisions	LCD	50W	50W
Tv standby	-	1W	1W
DvD standby	-	4W	4W
Fridge-freezers	A-rated	36W	-
	C-rated	60W	-
Refrigerators	A-rated	16W	-
	C-rated	31W	-
Freezers	A-rated	24W	-
	C-rated	36W	-
Desktop Computer		73W	73W[11]
Flat panel monitor		90W	90W
Laptop Computer		36W	36W

[7] CIBSE (2015) suggests ignoring the casual heat gains produced by washing machines, dishwashers and tumble driers as they are considered negligible.
[8] Recommended rates of radiant heat gains from hooded electric and gas appliances during idle (ready-to-cook) condition (CIBSE, 2015) for a convection oven (half size being these values for restaurant equipment).
[9] Recommended rate of radiant heat gains from hooded electric appliances during idle (ready-to-cook) condition (CIBSE, 2015) for a range top (half size being these values for restaurant equipment).
[10] Recommended rate of radiant heat gains from hooded gas appliances during idle (ready-to-cook) condition (CIBSE, 2015) for a range top (half size being these values for restaurant equipment).
[11] According to CIBSE (2015) heat gains from office equipment is equal to the total power input.

2. Case Study 2

2.1 Notes

[A1] 115mm for a half-brick wall (imperial size).

[A2] 227mm for a one-brick wall (imperial size).

[A3] 352mm= 227mm+10mm (mortar)+115mm for a one-and-half brick wall (imperial size).

[A4] 464mm= 227mm+10mm (mortar)+227mm for a two-bricks wall (imperial size).

[B1] 102.5 mm for a half-brick wall (metric size).

[B2] 215 mm for a one-brick wall (metric size).

[B3] 327.5 mm= 215mm+10mm (mortar)+102.5mm for a one-and-half brick wall (metric size).

[B4] 440mm= 215mm+10mm (mortar)+215mm for a two-bricks wall (metric size).

[B5] 552.5mm= 215mm+10mm (mortar)+215mm+10mm (mortar)+102.5mm for a two-and-half bricks wall (metric size).

[B6] 665mm= 215mm+10mm (mortar)+215mm+10mm (mortar)+215mm for a three-bricks wall (metric size).

[C] 30 to 50mm of cavity (depending on the overall thickness of the construction) for the vertical timber battens needed in the lath and plaster construction.

[D] 6 to 8 mm of wood, oak essence, for the lath on plaster construction. It has been decided to replace the default value (1025 MNs/gm) for the vapour resistivity of the oak layer in IES with the same vapour resistivity value (45 MNs/gm) of lime plaster. This was done to account for the overall permeability of the construction, given by the spacing of the lath, and for the contribution of the oak layer in the overall U-value of the construction.

[E1] A new material (lime plaster) was created and added to the materials library of the project, to simulate the lime-based plaster typically used in the regency buildings in Brighton.

[E2] 15mm of lime plaster was used to model the traditional plaster on lath construction.

[F] For these input values data from previous research have been used (IES, 2009; IES, 2015b; CIBSE, 2015).

[G] To calculate wind pressure, Macro-Flo uses coefficients provided for a range of exposure types.

[H] The Crack Flow Coefficient (CFC, a coefficient characterising the leakage properties of the crack) and the Crack Length (CL, the length of the crack around the opening, expressed as a percentage of the opening's perimeter length) have been given a value of zero for all the openings. For the internal doors generally closed it has been assigned a value for the CFC given by IES Tables (IES, 2015).

[I1] The opening threshold refers to the temperature in the room adjacent to the opening which, when exceeded, will trigger the opening of the window or door. Once open, it will remain so until the Degree of Opening profile is zero, regardless of subsequent values of the adjacent room air temperature. In this research it has always been given a value of 0°C to ensure that the pattern of opening simply follows the Degree of Opening percentage profile.

[I2] The Degree of Opening is a Profile which determines when and to what degree the opening type is considered open.

[J] SCoP is the Seasonal Coefficient of Performance of the Heating System. The software automatically calculates the value of the SCoP for each system created, given the Boiler Seasonal Efficiency (manually inputted) and the Heating Delivery Efficiency (HDE), assigned to each system by default when using the UKNCM wizard.

[K] For the Heating Plant Radiant Fraction, the default value given by the software for the corresponding UK NCM Type was used, and namely 0.2 for the UK NCM type Central heating using water (radiators).

[L] DHW consumption was calculated using the formula: DHW=40+28N l/day (Energy Saving Trust, 2008) where N=number of people in the dwelling.

[M1] Values of heat gains from people were taken from CIBSE Guide A (CIBSE, 2015: Table 6.3) for male, female, or mixture of occupants.

[M2] Values of heat gains from lighting equipment were taken from CIBSE Guide A (CIBSE, 2015: Table 6.2).

[M3] Values of heat gains from typical domestic equipment were taken from CIBSE Guide A (CIBSE, 2015: Tables 6.15 and 6.16).

~~[M4] Values of heat gains from hooded cooking equipment were taken and adapted from CIBSE Guide A (CIBSE, 2015: Tables 6.18 and 6.20).~~

~~[N1] Values for the auxiliary ventilation were taken from CIBSE Guide A (CIBSE, 2015: Table 4.2(a)).~~

~~[N2] Values for the infiltration were taken from CIBSE Guide A (CIBSE, 2015: Table 4.24) and modulated based on the outcome of visual survey, interview, and thermographic survey.~~

Location and listing

Location: Brunswick Place
Typology: 1st floor converted flat
Date of construction: 1st half 19C
Listing: Part of List Entry Number 1204771

NOS 9-69 AND ATTACHED WALLS AND RAILINGS
Grade: II

Location: NOS 9-69 AND ATTACHED WALLS AND RAILINGS, 9-69, BRUNSWICK PLACE, Non-Civil Parish, HOVE, The City of Brighton and Hove
Brunswick Town Conservation Area

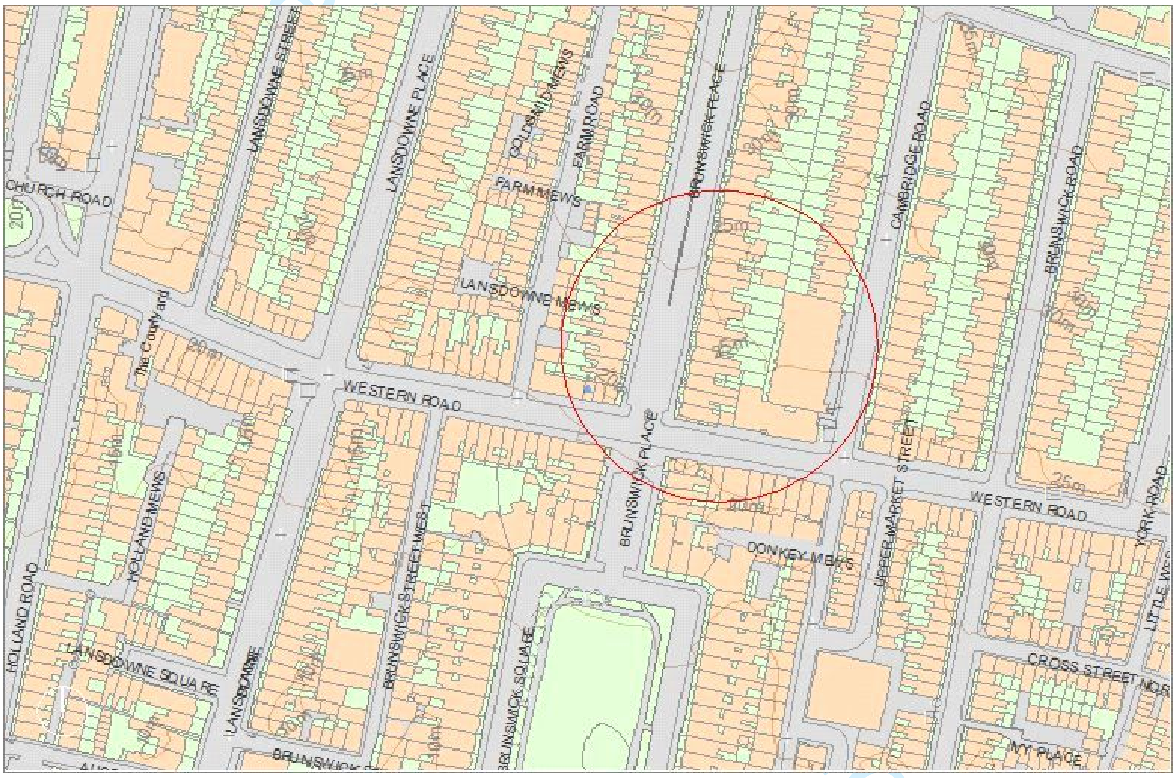


Figure 0.5 Map showing the listed buildings included in the entry, adapted from Historic England (2018). Evidenced in the red circle the location of CS2

Extract from the List Entry Summary:
"*Terrace of dwellings. c1840-1855, some mid C20 alterations to attics. Stucco over brick, slate roofs. Terrace on hillside. 4 storeys plus attic over basement; Nos 9-13 have deep bow-fronts, otherwise 3-window frontage to each shallow curved full-height bay; sash windows with some glazing bars missing, some attic windows inserted between pilasters in parapet, others with baluster parapets, moulded cornice, moulded surrounds to square-headed window openings, individual cast-iron balustrade to first floor of each dwelling, rusticated ground floors, pilaster doorcases, variety of doors (mostly half-glazed with leaded lights), approached by short flight of steps, some with tessellated pavements. Cast-iron railings and bottle balustrading returned from entrances along street frontage*" (Historic England, 2018).

2.2 Status-quo

Constructions and building materials

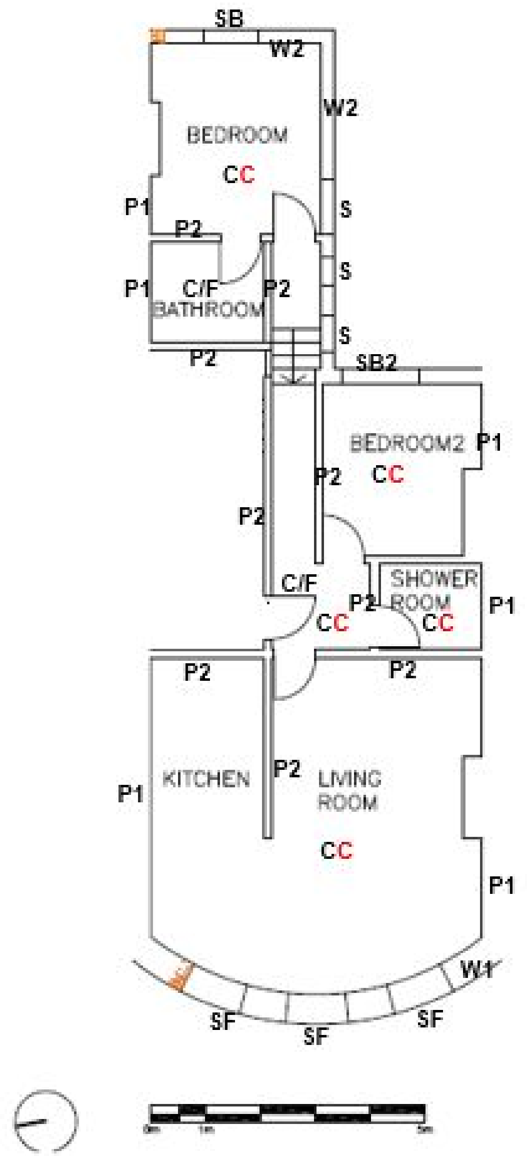


FIGURE 0.6 CS2: FLOOR PLAN WITH ANNOTATED REFERENCE ID FOR EACH CONSTRUCTION (IN BLACK: FLOORS; IN RED: CEILINGS/ROOFS)

Internal Ceiling/Floor - Reference ID: C
Overall U-value: 1.2669 $W/ m^2·K$

Layer Description (from outside to inside)	Thickness mm	Conductivity W/mK	Density Kg/m^3	Specific Heat Capacity J/kgK	Resistance m^2K/W	Vapour Resistivity MNs/gm
Wilton Carpet	10	0.06	186.3	1360	0.1667	13
Chipboard Flooring	25	0.13	500	1600	0.1923	-
Cavity	220	-	-	-	0.1800	-
Oak [D]	6	0.19	700	700	0.0316	45
Lime plaster [E1]	15	0.8	1600	1600	0.0187	45
Total Construction	276					

External Wall 550 - Reference ID: W1
Overall U-value: 1.0163 $W/ m^2·K$

Layer Description (from outside to inside)	Thickness mm	Conductivity W/mK	Density Kg/m^3	Specific Heat Capacity J/kgK	Resistance m^2K/W	Vapour Resistivity MNs/gm
Lime plaster [E1]	25	0.8	1600	1000	0.0313	45
Brickwork [A4]	464	0.84	1700	800	0.5524	58
Cavity [C]	40	-	-	-	0.1800	-
Oak [D]	6	0.19	700	2390	0.0316	45
Lime plaster [E1]	15	0.8	1600	1000	0.0187	45
Total Construction	550					

External Wall 250 - Reference ID: W2
Overall U-value: 2.1323 $W/ m^2·K$

Layer Description (from outside to inside)	Thickness mm	Conductivity W/mK	Density Kg/m^3	Specific Heat Capacity J/kgK	Resistance m^2K/W	Vapour Resistivity MNs/gm
Lime plaster [E1]	13	0.8	1600	1000	0.0313	45
Brickwork [A2]	227	0.84	1700	800	0.2702	58
Lime plaster [E1]	10	0.8	1600	1000	0.0125	45
Total Construction	250					

Internal Partition 382 - Reference ID: P1
Overall U-value: 1.3952 $W/ m^2·K$

Layer Description (from outside to inside)	Thickness mm	Conductivity W/mK	Density Kg/m^3	Specific Heat Capacity J/kgK	Resistance m^2K/W	Vapour Resistivity MNs/gm
Lime plaster [E1]	15	0.8	1600	1000	0.0187	45
Brickwork [A3]	352	0.84	1700	800	0.4190	58
Lime plaster [E1]	15	0.8	1600	1000	0.0187	45
Total Construction	382					

Internal Partition 382 - Reference ID: P1
Overall U-value: 1.3952 $W/ m^2·K$

Layer Description (from outside to inside)	Thickness mm	Conductivity W/mK	Density Kg/m^3	Specific Heat Capacity J/kgK	Resistance m^2K/W	Vapour Resistivity MNs/gm
Lime plaster [E1]	17.5	0.8	1600	1000	0.0219	45
Brickwork [A1]	115	0.84	1700	800	0.1369	58
Lime plaster [E1]	17.5	0.8	1600	1000	0.0219	45
Total Construction	150					

Wooden Door
Overall U-value: 2.1944 $W/ m^2·K$

Layer Description (from outside to inside)	Thickness mm	Conductivity W/mK	Density Kg/m^3	Specific Heat Capacity J/kgK	Resistance m^2K/W	Vapour Resistivity MNs/gm
Pine	40	0.14	419	2720	0.2857	200
Total Construction	40					

External Window sash front - Frame: Softwood (15%) - Reference ID: SF
Overall U-value (including frame): 5.5505 W/ m²·K

Layer Description (from outside to inside)	Thickness mm	Conductivity W/mK	Gas	Resistance m²K/W
Clear Float 6mm	6	1.06	-	0.0057
	Internal Device	Resistance	Shading Coefficient	Short wave radiant fraction
Shading Device information [F]	Blinds	0.14	0.49	0.3

External Window bedroom - Frame: Softwood (15%) - Reference ID: SB
Overall U-value (including frame): 5.5505 W/ m²·K

Layer Description (from outside to inside)	Thickness mm	Conductivity W/mK	Gas	Resistance m²K/W
Clear Float 6mm	6	1.06	-	0.0057
	Internal Device	Resistance	Shading Coefficient	Short wave radiant fraction
Shading Device information [F]	Curtains	0.16	0.49	0.3

External Window sash back - Frame: Softwood (15%) - Reference ID: S
Overall U-value (including frame): 5.5505 W/ m²·K

Layer Description (from outside to inside)	Thickness mm	Conductivity W/mK	Gas	Resistance m²K/W
Clear Float 6mm	6	1.06	-	0.0057
	Internal Device	Resistance	Shading Coefficient	Short wave radiant fraction
Shading Device information [F]	None	-	-	-

External Window bedroom2 - Frame: Softwood (15%) - Reference ID: SB2
Overall U-value (including frame): 5.5505 W/ m²·K

Layer Description (from outside to inside)	Thickness mm	Conductivity W/mK	Gas	Resistance m²K/W
Clear Float 6mm	6	1.06	-	0.0057
	Internal Device	Resistance	Shading Coefficient	Short wave radiant fraction
Shading Device information [F]	Curtains	0.16	0.49	0.3

Internal Window - Frame: Softwood (30%)
Overall U-value (including frame): 3.7888 W/ m²·K

Layer Description (from outside to inside)	Thickness mm	Conductivity W/mK	Gas	Resistance m²K/W
Clear Float 6mm	6	1.06	-	0.0057

Openings database

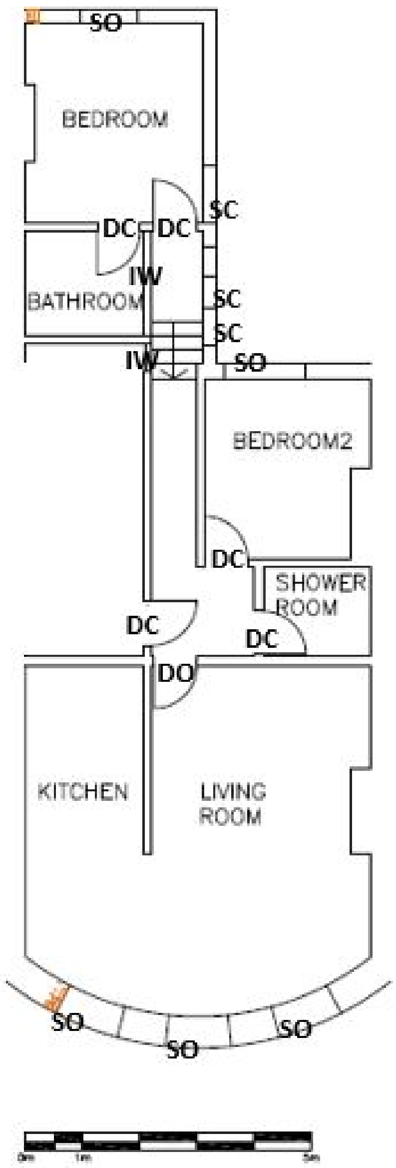
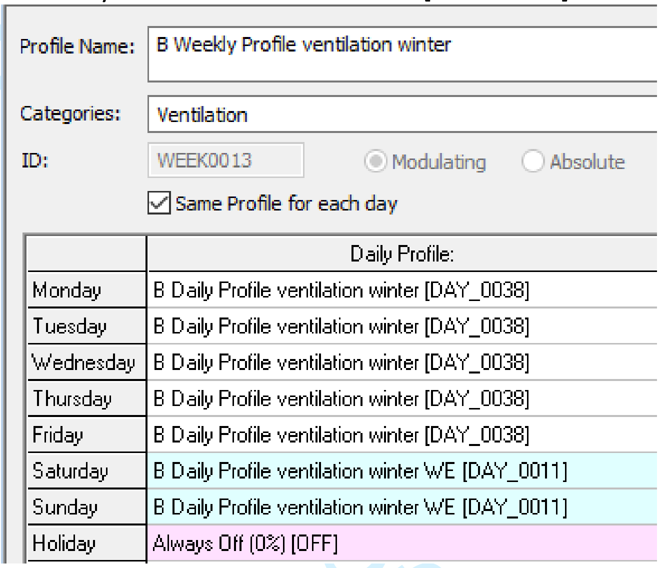


FIGURE 0.7 CS2: FLOOR PLAN WITH ANNOTATED REFERENCE ID FOR EACH OPENING

Ref. ID	SC	SO	DC	DO	IW
Description	External window sash closed	External window sash open	door closed	door open	Internal window
Exposure Type [G]	semi-exposed wall	semi-exposed wall	Internal	Internal	Internal
Opening	Window - sash	Window - sash	Window / door side hung	Window / door side hung	Custom/sharp edge orifice
Openable Area %	5	10	100	100	0
Max Angle Open °	-	-	90	90	-
Proportions	-	-	Length/Height < 0.5	Length/Height < 0.5	-
Equivalent Orifice Area (% of Gross)	5.242	10.484	103.226	103.226	0
Crack Flow Coefficient [H] ($s^{-1}\,m^{-1}\,Pa^{-0.6}$)	0	0	1.3	0	0
Crack Length (% of Opening Perimeter) [H]	0	0	100	0	0
Opening Threshold (°C) [I1]	0	0	0	0	0
Degree of Opening[I2]	off continuously	Annual Profile ventilation	off continuously	on continuously	off continuously

No:	Annual Ventilation Profile:	End month:	End day:
1	off continuously [OFF]	Jan	4
2	B Weekly Profile ventilation winter [WEEK0013]	Apr	22
3	off continuously [OFF]	May	1
4	B Weekly Profile ventilation summer [WEEK0011]	Jul	28
5	off continuously [OFF]	Sep	2
6	B Weekly Profile ventilation summer [WEEK0011]	Oct	1
7	B Weekly Profile ventilation winter [WEEK0013]	Dec	18
8	off continuously [OFF]	Dec	31

B Weekly Profile ventilation winter [WEEK0013]



Profile Name: B Weekly Profile ventilation winter

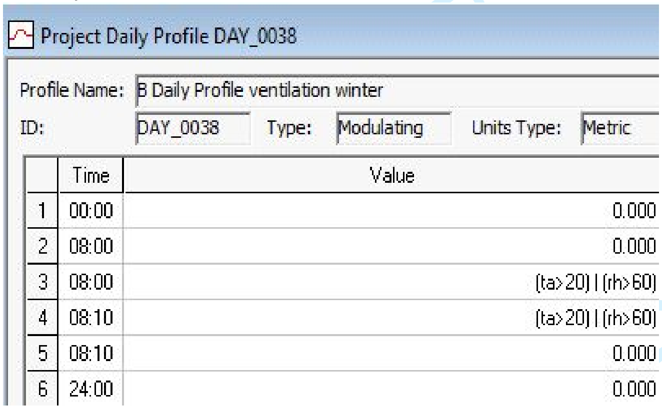
Categories: Ventilation

ID: WEEK0013 Modulating Absolute

Same Profile for each day

	Daily Profile:
Monday	B Daily Profile ventilation winter [DAY_0038]
Tuesday	B Daily Profile ventilation winter [DAY_0038]
Wednesday	B Daily Profile ventilation winter [DAY_0038]
Thursday	B Daily Profile ventilation winter [DAY_0038]
Friday	B Daily Profile ventilation winter [DAY_0038]
Saturday	B Daily Profile ventilation winter WE [DAY_0011]
Sunday	B Daily Profile ventilation winter WE [DAY_0011]
Holiday	Always Off (0%) [OFF]

B Daily Profile ventilation winter [DAY0038][12]



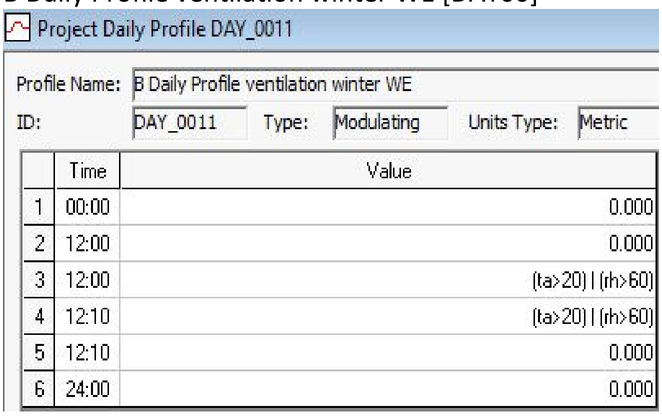
Project Daily Profile DAY_0038

Profile Name: B Daily Profile ventilation winter

ID: DAY_0038 Type: Modulating Units Type: Metric

<table>
<tr><th></th><th>Time</th><th>Value</th></tr>
<tr><td>1</td><td>00:00</td><td>0.000</td></tr>
<tr><td>2</td><td>08:00</td><td>0.000</td></tr>
<tr><td>3</td><td>08:00</td><td>(ta>20) | (rh>60)</td></tr>
<tr><td>4</td><td>08:10</td><td>(ta>20) | (rh>60)</td></tr>
<tr><td>5</td><td>08:10</td><td>0.000</td></tr>
<tr><td>6</td><td>24:00</td><td>0.000</td></tr>
</table>

B Daily Profile ventilation winter WE [DAY00]



Project Daily Profile DAY_0011

Profile Name: B Daily Profile ventilation winter WE

ID: DAY_0011 Type: Modulating Units Type: Metric

<table>
<tr><th></th><th>Time</th><th>Value</th></tr>
<tr><td>1</td><td>00:00</td><td>0.000</td></tr>
<tr><td>2</td><td>12:00</td><td>0.000</td></tr>
<tr><td>3</td><td>12:00</td><td>(ta>20) | (rh>60)</td></tr>
<tr><td>4</td><td>12:10</td><td>(ta>20) | (rh>60)</td></tr>
<tr><td>5</td><td>12:10</td><td>0.000</td></tr>
<tr><td>6</td><td>24:00</td><td>0.000</td></tr>
</table>

[12] (ta>20) I (rh>60) is a formula profile that means that the window is open when indoor temperature is higher than 20°C or indoor relative humidity is higher than 60% within the time step when the formula is applied.

B Weekly Profile ventilation summer [WEEK0011]

Profile Name: B Weekly Profile ventilation summer

Categories: Ventilation

ID: WEEK0011 Modulating Absolute

☑ Same Profile for each day

	Daily Profile:
Monday	B Daily Profile ventilation summer [DAY_0012]
Tuesday	B Daily Profile ventilation summer [DAY_0012]
Wednesday	B Daily Profile ventilation summer [DAY_0012]
Thursday	B Daily Profile ventilation summer [DAY_0012]
Friday	B Daily Profile ventilation summer [DAY_0012]
Saturday	B Daily Profile ventilation summer WE [DAY_0010]
Sunday	B Daily Profile ventilation summer WE [DAY_0010]
Holiday	Always Off (0%) [OFF]

B Daily Profile ventilation summer [DAY0012][13]

Project Daily Profile DAY_0012

Profile: B Daily Profile ventilation summer

ID: DAY_0012 Type: Modulating Units Type: Metric

	Time	Value
1	00:00	0.000
2	08:00	0.000
3	08:00	(ta>24)
4	08:30	(ta>24)
5	08:30	0.000
6	16:00	0.000
7	16:00	(ta>24)
8	19:00	(ta>24)
9	19:00	0.000
10	24:00	0.000

B Daily Profile ventilation summer [DAY0010]

Project Daily Profile DAY_0010

Profile: B Daily Profile ventilation summer WE

ID: DAY_0010 Type: Modulating Units Type: Metric

	Time	Value
1	00:00	0.000
2	12:00	0.000
3	12:00	ta>24
4	19:30	ta>24
5	19:30	0.000
6	24:00	0.000

[13] (ta>24) is a formula profile that means that the window is open when indoor temperature is higher than 24°C.

Systems database

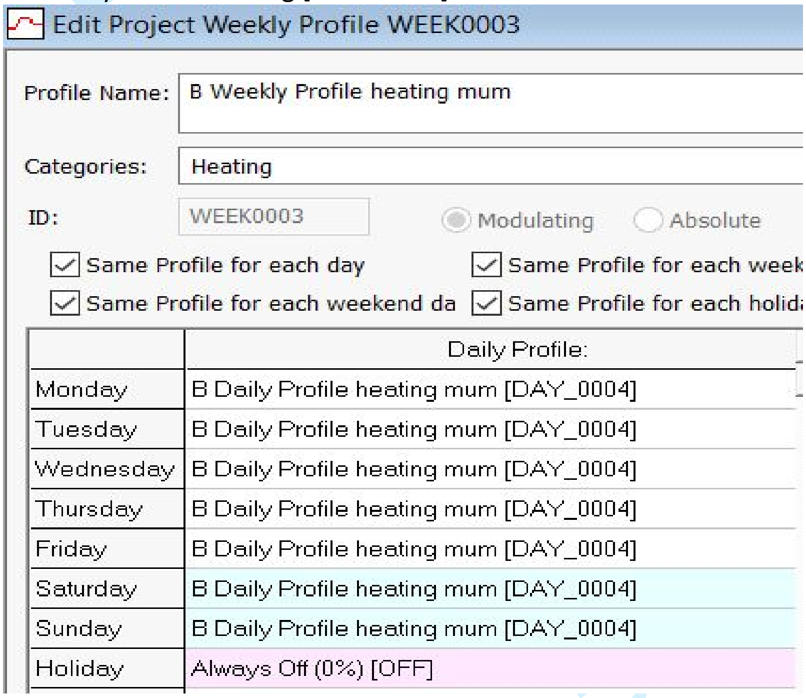
Heating/DHW System	**UK/NCM type**	**Fuel**	**Seasonal efficiency**	**SCoP** [J]	**DHW Delivery efficiency**
Combi boiler ALPHA in tech 26 XE	Central heating using waters: radiators	Natural gas	0.8100	0.7228	0.7400

Template Name	**bathroom**	**bedroom**	**bedroom2**	**circulation**	**kitchen**	**living**	**shower room**
Room Type	Heated or occupied	Heated or occupied	Heated or occupied	Heated or occupied	Heated or occupied	Heated or occupied	Heated or occupied
Heating	1	1	1	1	1	1	1
Aux. Vent System	None	None	None	None	None	None	None
DHW System	1	None	None	None	None	None	none
Heating Plant Radiant Fraction [K]	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Heating Profile	Annual Profile heating	Annual Profile heating	Annual Profile heating	Annual Profile heating	off continuously	Annual Profile heating	Annual Profile heating
Heating Setpoint (°C)	Profile: thermostat	Profile: thermostat	Profile: thermostat	Profile: thermostat	-	Profile: thermostat	Profile: thermostat
DHW Pattern of Use Profile	Annual Profile DHW	-	-	-	-	-	-
DHW Consumption [L]	4 l/h(max)	-	-	-	-	-	-

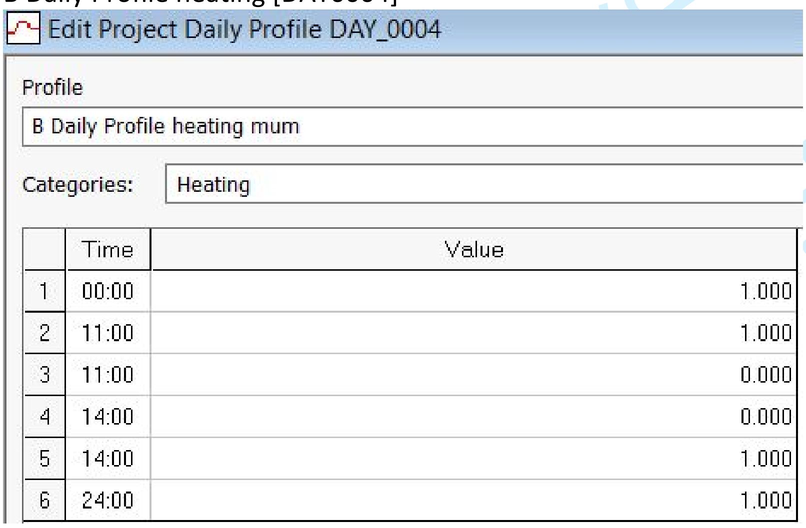
Annual Profile Heating

No:	Weekly Profile:	End month:	End day:
1	on continuously [ON]	Jan	5
2	B Weekly Profile heating mum [WEEK0003]	Feb	19
3	B Weekly Profile heating [WEEK0043]	Apr	25
4	on continuously [ON]	May	1
5	B Weekly Profile heating [WEEK0043]	May	24
6	off continuously [OFF]	Sep	20
7	B Weekly Profile heating [WEEK0043]	Dec	18
8	on continuously [ON]	Dec	31

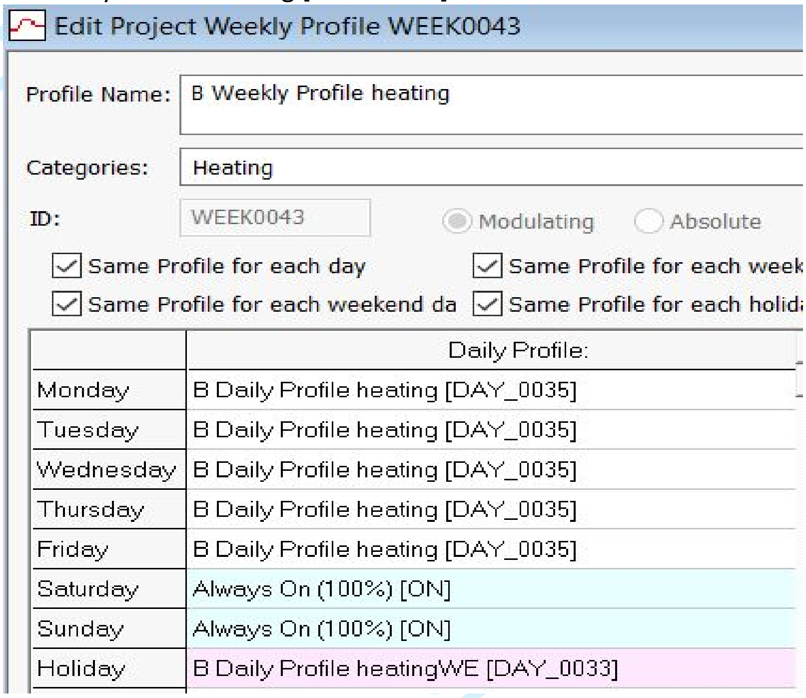
B Weekly Profile heating [WEEK0003]



B Daily Profile heating [DAY0004]



B Weekly Profile heating [WEEK0043]


Edit Project Weekly Profile WEEK0043

Profile Name: B Weekly Profile heating

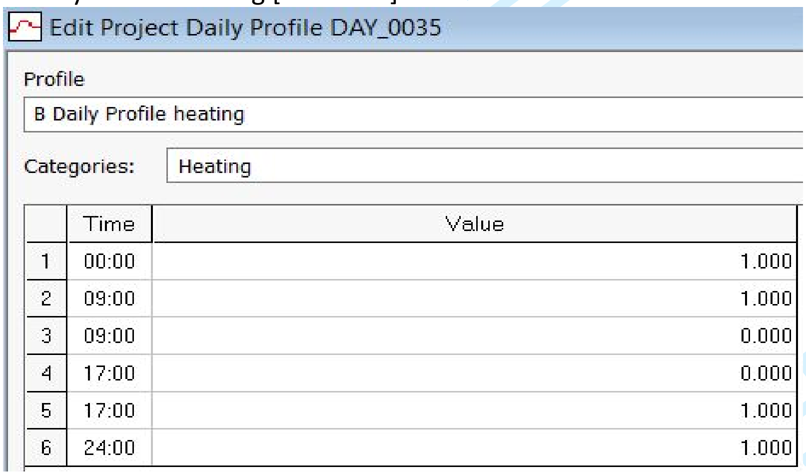
Categories: Heating

ID: WEEK0043 Modulating Absolute

Same Profile for each day
Same Profile for each week
Same Profile for each weekend da
Same Profile for each holid

	Daily Profile:
Monday	B Daily Profile heating [DAY_0035]
Tuesday	B Daily Profile heating [DAY_0035]
Wednesday	B Daily Profile heating [DAY_0035]
Thursday	B Daily Profile heating [DAY_0035]
Friday	B Daily Profile heating [DAY_0035]
Saturday	Always On (100%) [ON]
Sunday	Always On (100%) [ON]
Holiday	B Daily Profile heatingWE [DAY_0033]

B Daily Profile heating [DAY0035]


Edit Project Daily Profile DAY_0035

Profile
B Daily Profile heating

Categories: Heating

	Time	Value
1	00:00	1.000
2	09:00	1.000
3	09:00	0.000
4	17:00	0.000
5	17:00	1.000
6	24:00	1.000

Annual Profile Thermostat

No:	Weekly Profile:	End month:	End day:
1	constant 12 [WEEK0046]	Jan	5
2	constant 22 [WEEK0052]	Apr	25
3	constant 12 [WEEK0046]	May	1
4	constant 21 [WEEK0046]	May	24
5	constant 12 [WEEK0046]	Sep	15
6	constant 22 [WEEK0052]	Dec	18
7	constant 12 [WEEK0046]	Dec	31

Heat Gains

Room template	Heat gains	Max sensible gain	Max latent gain	Occ. Density	Variation profile	Fuel	Max power consumption
Bathroom	People [M1]	100 W/person	40 W/person	1 person	Annual profile occupancy bath	-	-
	Tungsten lighting [M2]	12 W/m²	-	-	Annual profile occupancy bath	Electricity	12 W/m²
Bedroom	People [M1]	90 W/person	25 W/person	1 person	Annual profile occupancy bed	-	-
Bedroom2	People [M1]	90 W/person	25 W/person	1 person	Annual profile occupancy bed	-	-
	Washing machine [M3]	-	-	-	Annual profile washing machine	Electricity	940 W
Kitchen	Dish washer [M3]	-	-	-	Annual profile dish washer	Electricity	700W
	Hobs [M4]	293W	-	-	Annual profile hobs	Gas	1000W
	Oven [M4]	147W	-	-	Weekly profile oven	Electricity	970W
	People [M1]	110 W/person	50 W/person	1 person	Annual profile occupancy kitchen	-	-
	Tungsten lighting [M2]	12 W/m²	-	-	Annual profile occupancy kitchen	Electricity	12 W/m²
	Refrigerator-Freezer [M3]	60W	-	-	on continuously	Electricity	60W
Living	DVD standby [M3]	4W	-	-	on continuously	Electricity	4W
	People [M1]	110 W/person	50 W/person	2 people	Annual profile occupancy living	-	-
	Tungsten lighting [M2]	12 W/m²	-	-	Annual profile occupancy living	Electricity	12 W/m²
	tv [M3]	50W	-	-	Annual profile occupancy living	Electricity	50W
	tv standby [M3]	1W	-	-	on continuously	Electricity	1W

Air exchanges

Room template	**Auxiliary ventilation** N1 Variation profile: annual profile occupancy bath	**Infiltration** N2 ON continuously
Bathroom	15 l/s	-
Bedroom	-	0.5[14] ACH
Bedroom2	-	0.5 ACH
Circulation	-	0.5 ACH
Kitchen	-	-
Living	-	0.5 ACH
Shower room	15 l/s	-

2.3 Thermographic survey samples

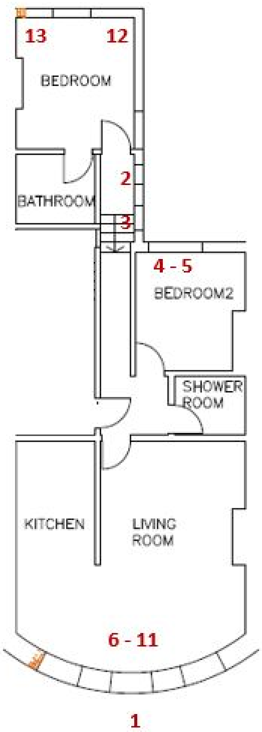


FIGURE 0.8 CS2: FLOOR PLAN WITH ANNOTATED THE POSITION WHERE EACH THERMAL IMAGE WAS TAKEN

THERMOGRAM 1: THE FRONT WALL FROM THE OUTSIDE, SHOWING THE HEAT LOSS TAKING PLACE THROUGH THE SINGLE GLAZED SASH WINDOWS.

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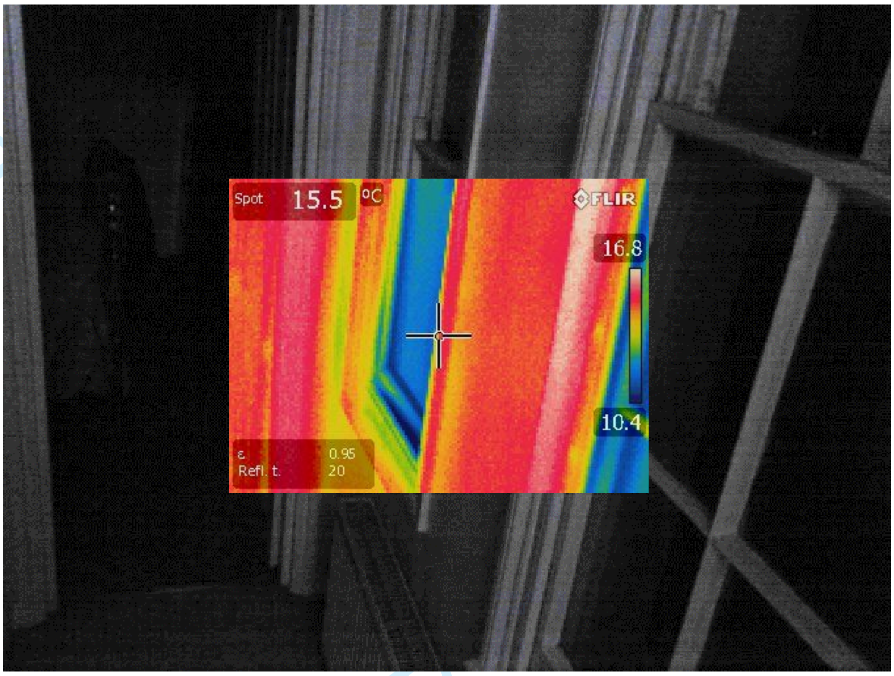
[14] The initial value assigned to the air leakage in all rooms was 0.7 ACH, which is lower than the value suggested by CIBSE for old leaky windows (CIBSE, 2015). This value was used because both front and back windows are on partially sheltered walls. This value was initially confirmed by the visual survey, which took note of the overall good condition of all the windows in the dwelling, although being them prevalently the original single glazed sash. The overall good condition of the windows was also confirmed by the questionnaire and interview with the occupants, which did not consider the windows particularly leaky. The air leakage value was finally changed into 0.5 ACH during the following calibration stage. The value finally used is also in accordance with the one used in previous research on similar properties of the same period (IES, 2009; Porrit, 2012).


7
BEDROOM
2
BATHROOM
3
BEDROOM2
SHOWER ROOM
KITCHEN
LIVING ROOM
6
5
4
1

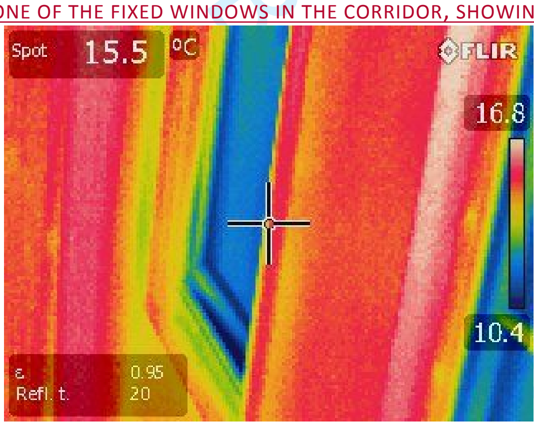
1

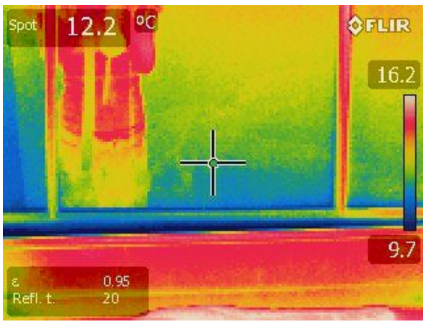
1



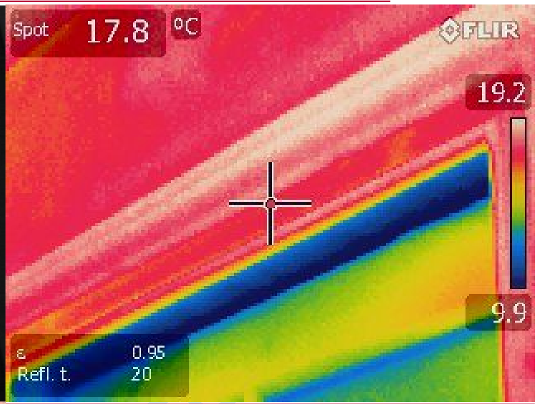
2

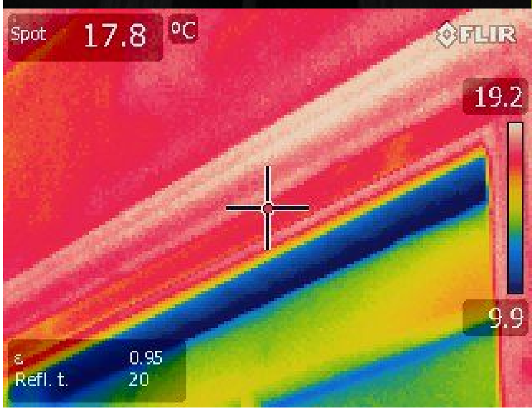
Thermogram 2: One of the fixed windows in the corridor, showing the air leakage taking place through the window frame.



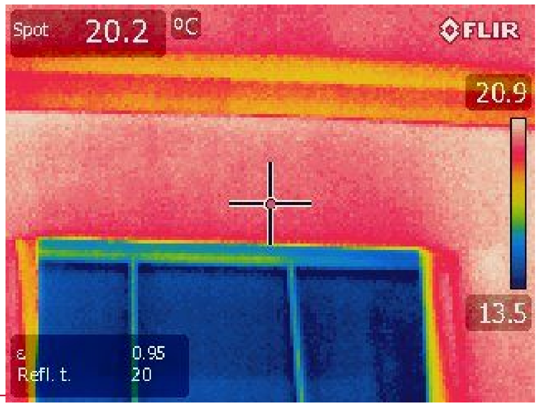


3


Spot 17.8 °C
FLIR
19.2
9.9
ε 0.95
Refl. t. 20

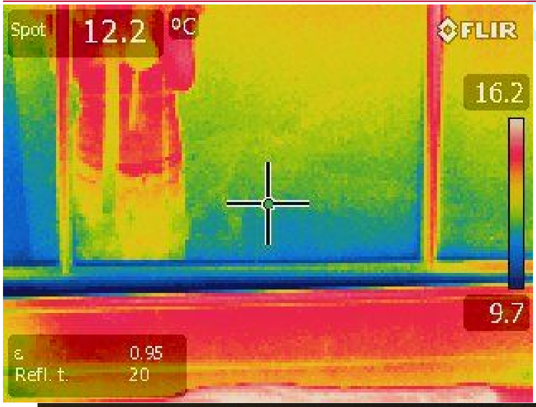

Spot 17.8 °C
FLIR
19.2
9.9
ε 0.95
Refl. t. 20

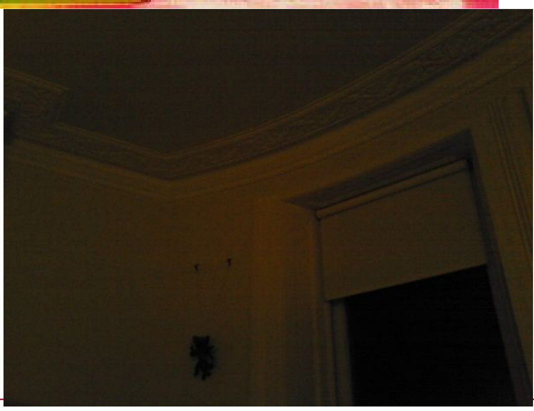
4 

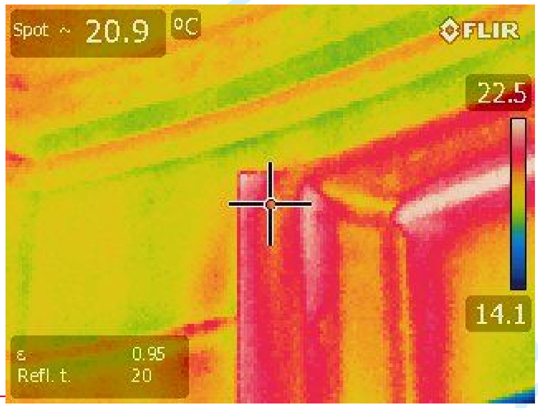


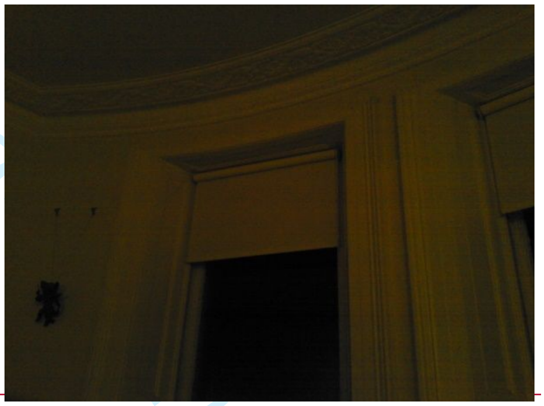
5 

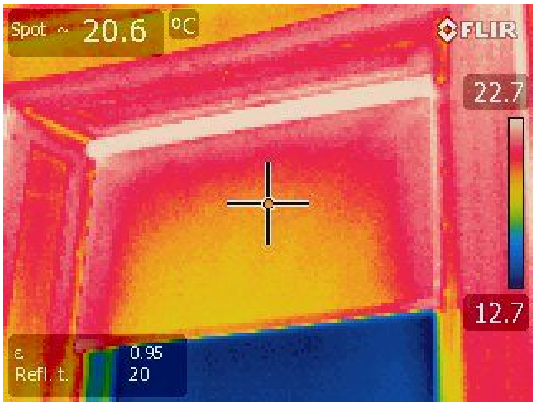
Thermogram 3: the sash window in the guest bedroom, showing the air leakage taking place through the window frame.



6 







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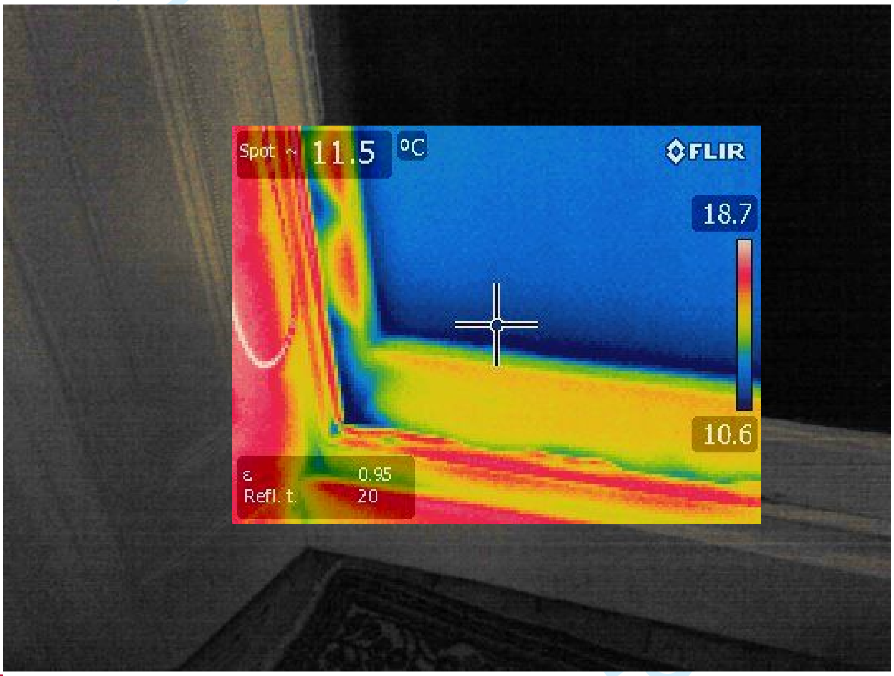
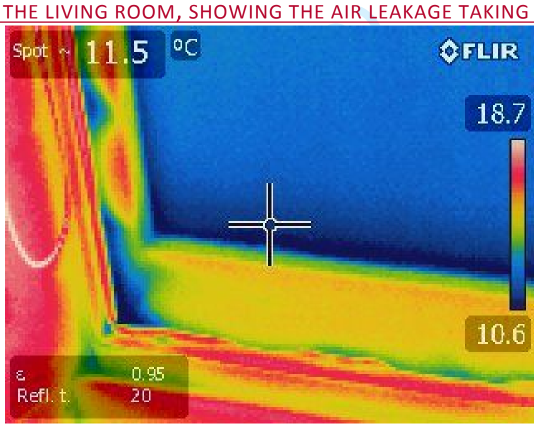
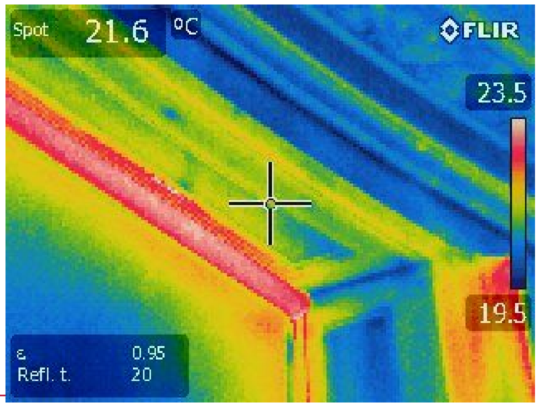


~~8~~ 4

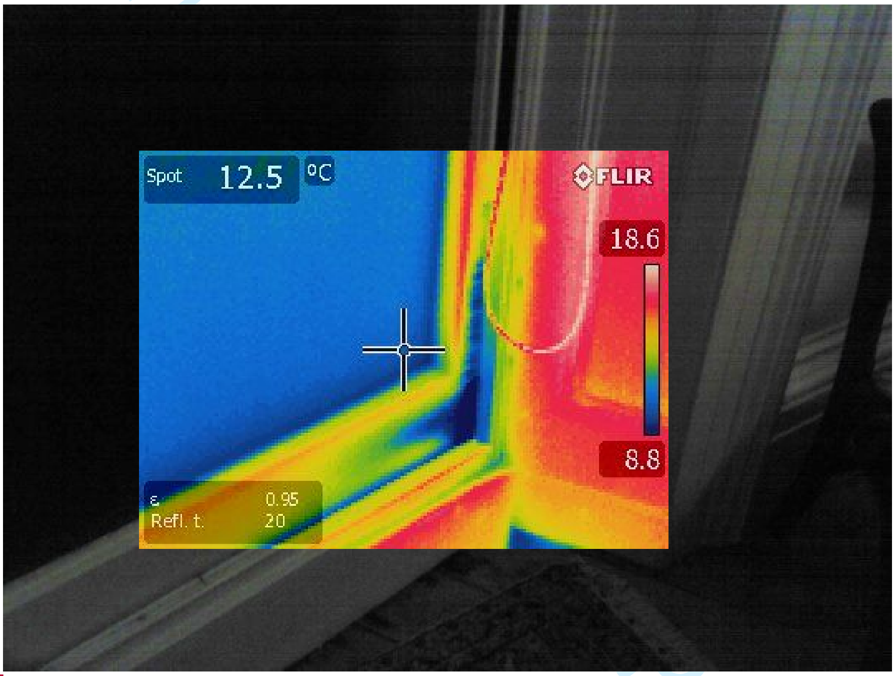
THERMOGRAM 4: ONE SASH WINDOW IN THE LIVING ROOM, SHOWING THE AIR LEAKAGE TAKING PLACE THROUGH THE



WINDOW FRAME AT THE CORNERS.

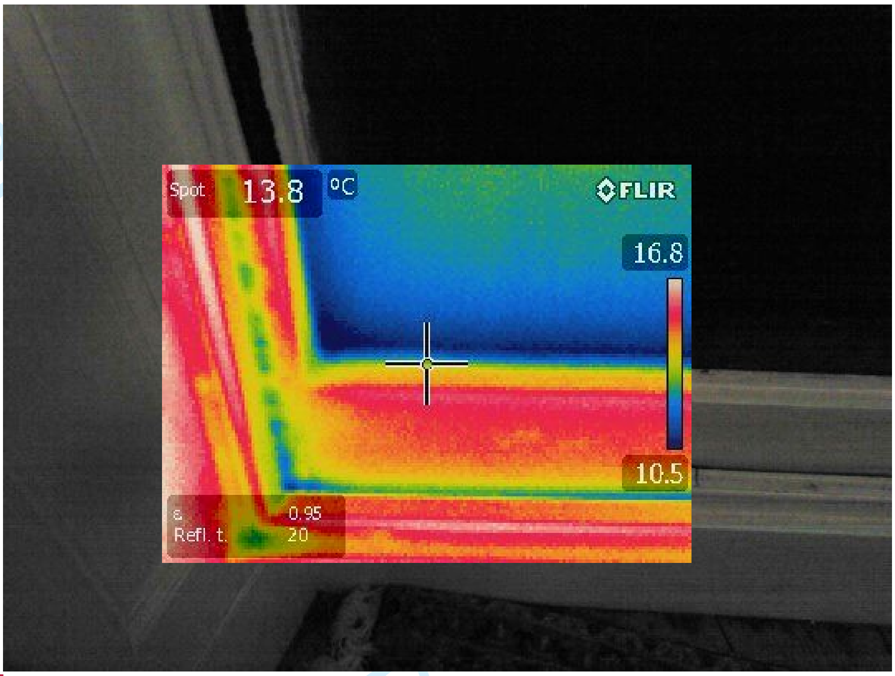


~~9~~



~~10~~ <u>5</u>

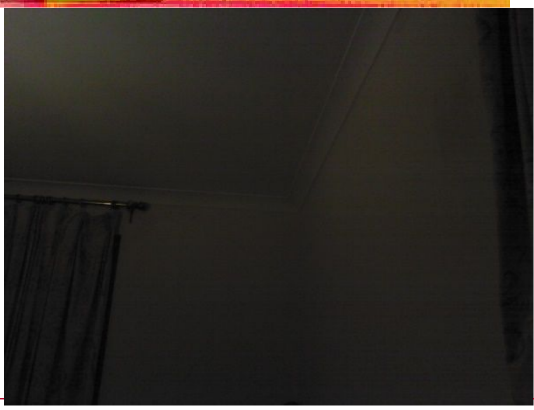
<u>Thermogram 5: one sash window in the living room, showing the air leakage taking place through the window frame at the corners.</u>

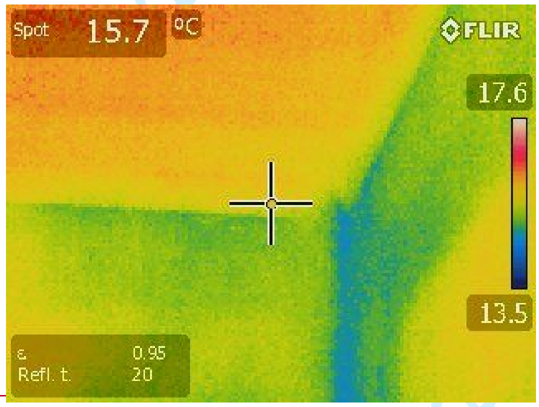


~~11~~ 6

THERMOGRAM 6: ONE SASH WINDOW IN THE LIVING ROOM, SHOWING THE AIR LEAKAGE TAKING PLACE THROUGH THE WINDOW FRAME AT THE CORNERS.

~~12~~





~~13~~ 7

THERMOGRAM 7: CORNER OF THE MASTER BEDROOM, SHOWING THE HEAT LOSS TAKING PLACE THROUGH THE EXTERNAL WALL (ON THE RIGHT) AND THE ADIABATIC CONDITION WITH THE ADJACENT FLAT (ON THE LEFT).

2.4 Model calibration

Energy data

GAS	kWh	ELECTRICITY	kWh
measured 15.11.2017-15.11.18	15505.00	measured 15.11.2017-15.11.18	2289.00
simulated annual	15218.10	simulated annual	2095.80
measured average per month	1292.08	measured average per month	190.75
simulated average per month	1268.18	simulated average per month	174.65
PD	**-1.85**	**PD**	**-8.44**
measured 15.11.17/19.2.18	7689.00	measured 15.11.17/30.5.18	1222.00
simulated 15.11.17/19.2.18	7349.20	simulated 15.11.17/30.5.18	1234.10
PD	**-4.42**	**PD**	**0.99**
measured 19.2.18/30.5.18	4759.00	measured 30.5.18/20.9.18	576.00
simulated 19.2.18/30.5.18	4660.80	simulated 30.5.18/20.9.18	492.00
PD	**-2.06**	**PD**	**-14.58**
measured 30.5.18/20.9.18	473.00	measured 20.9.18/25.11.18	491.00
simulated 30.5/20.9	491.60	simulated 20.9.18/15.11.18	369.70
PD	**3.93**	**PD**	**-24.70**
measured 20.9.18/15.11.18	2584.00		
simulated 20.9.18/15.11.18	2716.50		
PD	**5.13**		
n	4.00	n	3.00
ΣaD/n	3876.25	ΣaD/n	763.00
$\Sigma(aD-sD)^2$	82311.61	$\Sigma(aD-sD)^2$	37326.24
Σ(aD-sD)	286.90	Σ(aD-sD)	193.20
ΣaD	15505.00	ΣaD	2289.00
NMBE	**1.85**	**NMBE**	**8.44**
RMSE	165.64	RMSE	136.61
CV(RMSE)	**3.70**	**CV(RMSE)**	**14.62**

Indoor conditions data

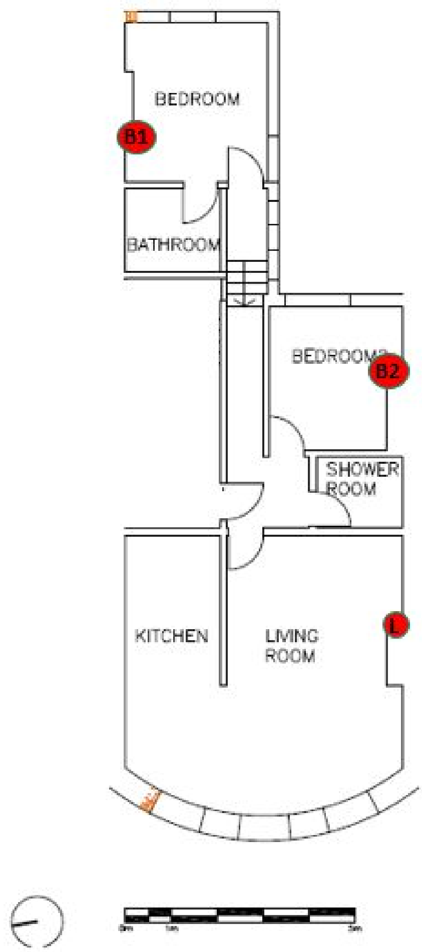


FIGURE 0.9 FLOOR PLAN OF THE CASE STUDY DWELLING N.2 (1ST FLOOR) WITH ANNOTATED POSITION OF TEMPERATURE AND RH DATA LOGGERS IN THE LIVING AREA (L) AND BEDROOM AREA (B1: MAIN BEDROOM; B2: GUEST BEDROOM)

Temperature living room 5th 5th May - 1st July 2017

___Simulated (2017 weather file)
___Measured

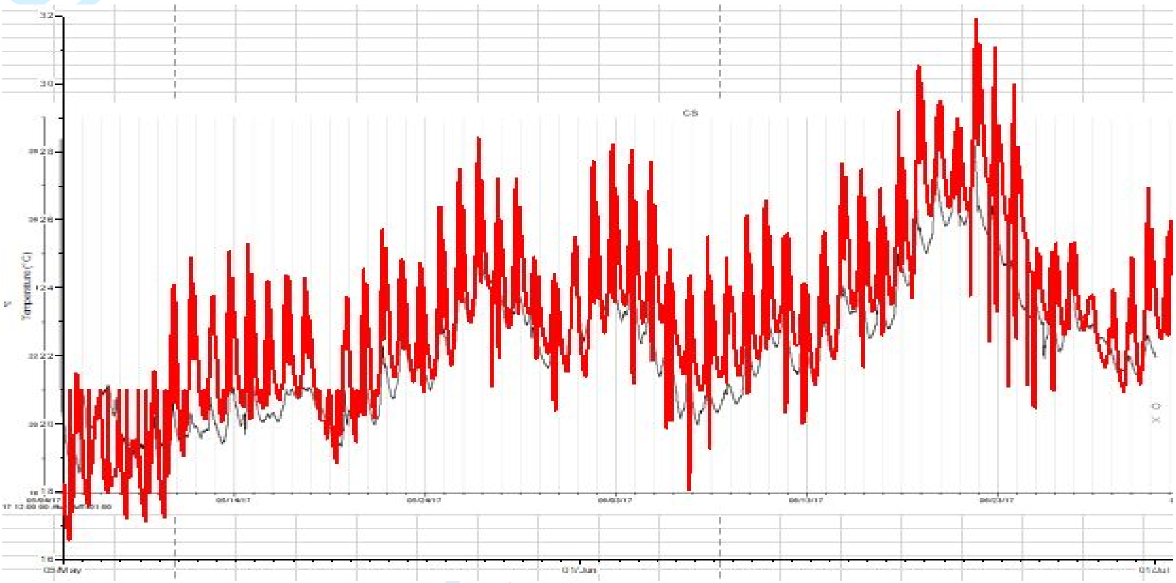


FIGURE 0.10 GRAPH SHOWING THE SIMULATED (IN RED) AND MEASURED (IN BLACK) INDOOR TEMPERATURE FROM THE 5th OF MAY TO THE 1st OF JULY 2017 IN THE LIVING ROOM.

Period	4th 5th May 2017 - 1st July 2017
Weather file	Brighton 2017
Data logging interval	10 minutes
Number of measurements	8274
NMBE	**-6.77%**
CV(RMSE)	**8.47%**

RH living room 5th May - 1st July 2017

___Simulated (2017 weather file)
___Measured

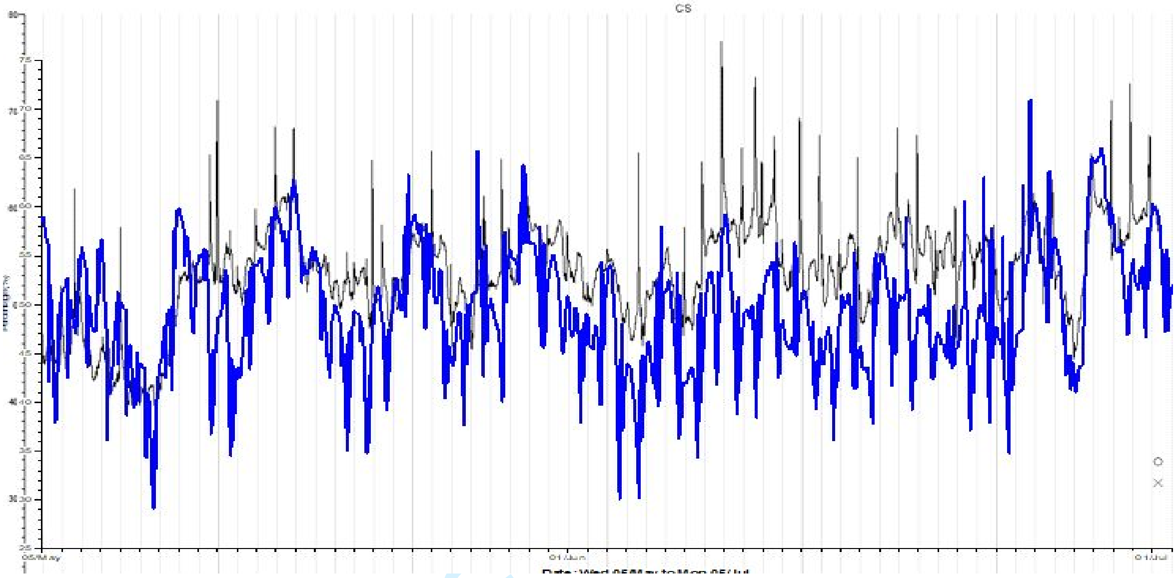


FIGURE 0.11 GRAPH SHOWING THE SIMULATED (IN BLUE) AND MEASURED (IN BLACK) INDOOR RELATIVE HUMIDITY (RH) FROM THE 5TH OF MAY TO THE 1ST OF JULY 2017 IN THE LIVING ROOM.

Period	5th May 2017 - 1st July 2017
Weather file	Brighton 2017
Data logging interval	10 minutes
Number of measurements	8274
NMBE	**10.76%**
CV(RMSE)	**14.15%**

Temperature living room 14th December 2017 - 14th February 2018

___Simulated (2017 weather file and average weather file)
___Measured

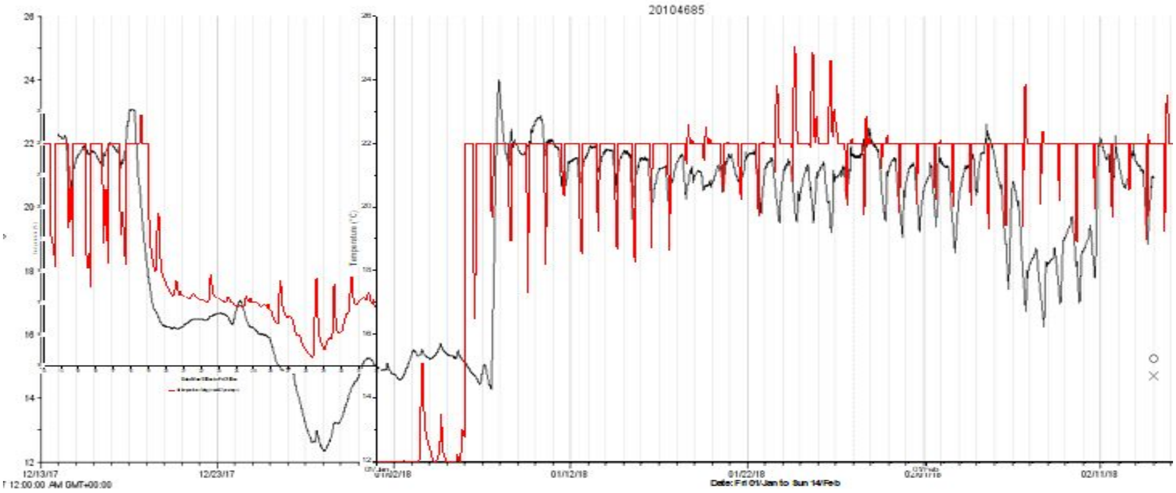


FIGURE 0.12 GRAPH SHOWING THE SIMULATED (IN RED) AND MEASURED (IN BLACK) INDOOR TEMPERATURE FROM THE 14TH OF DECEMBER 2017 TO THE 14TH OF FEBRUARY 2018 IN THE LIVING ROOM.

Period	14th Dec 2017 - 14th Feb 2018
Weather file	Brighton 2017 and Average Brighton Weather file
Data logging interval	30 minutes
Number of measurements	2976
NMBE	**-4.68%**
CV(RMSE)	**11.38%**

RH living room 14th December 2017 - 14th February 2018

___Simulated (2017 weather file and average weather file)
___Measured

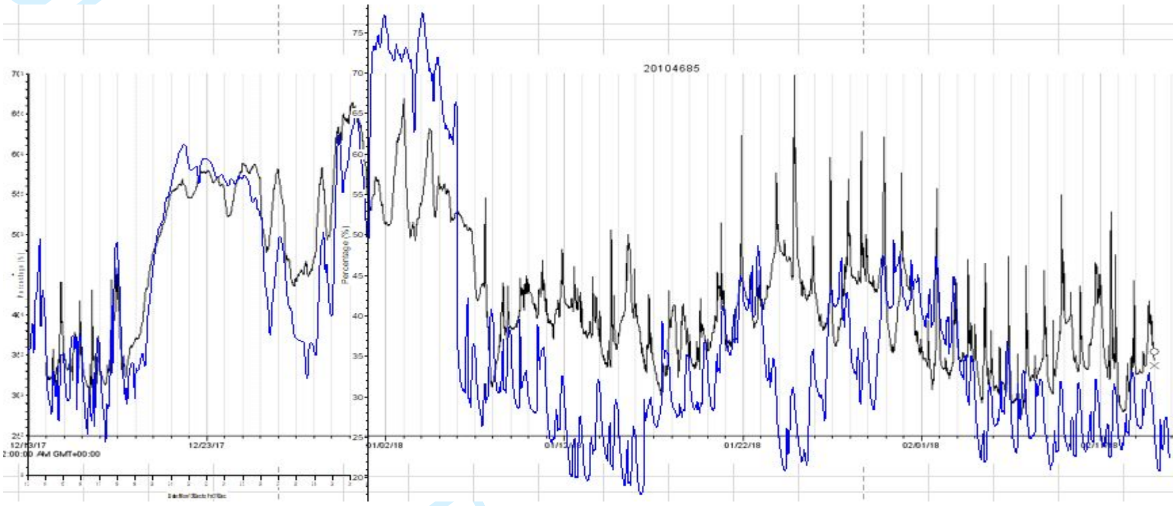


FIGURE 0.13 GRAPH SHOWING THE SIMULATED (IN BLUE) AND MEASURED (IN BLACK) INDOOR RELATIVE HUMIDITY (RH) FROM THE 14TH OF DECEMBER 2017 TO THE 14TH OF FEBRUARY 2018 IN THE LIVING ROOM.

Period	14th Dec 2017 - 14th Feb 2018
Weather file	Brighton 2017 and Average Brighton Weather file
Data logging interval	30 minutes
Number of measurements	2976
NMBE	**10.18%**
CV(RMSE)	**23.99%**

Temperature living room 30th May – 1st August 2018

___Simulated (average weather file)
___Measured

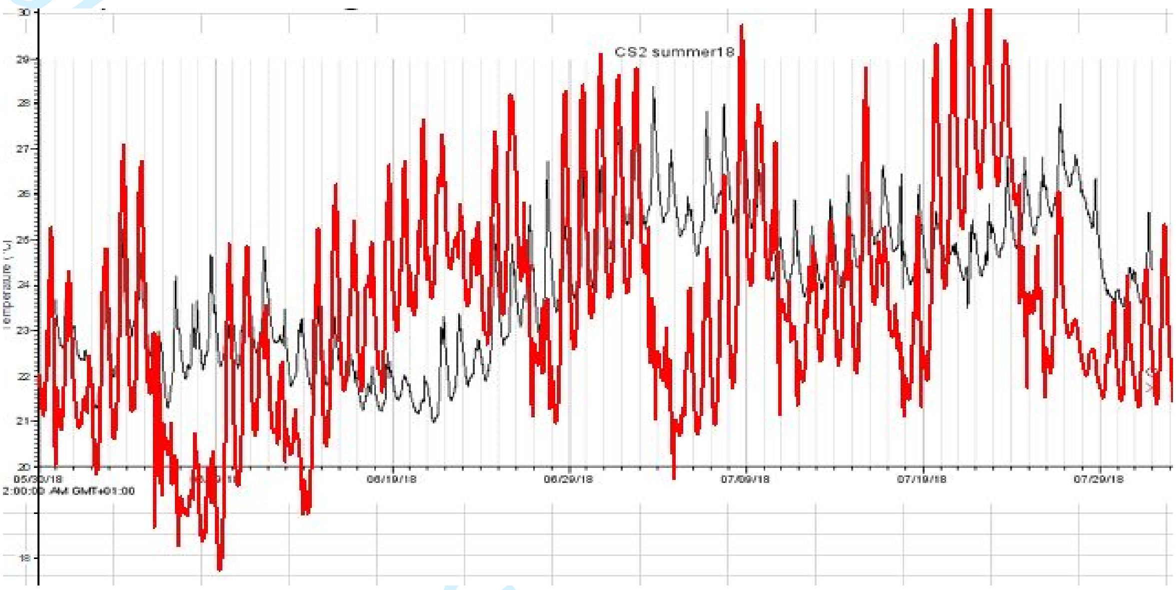


FIGURE 0.14 GRAPH SHOWING THE SIMULATED (IN RED) AND MEASURED (IN BLACK) INDOOR TEMPERATURE FROM THE 30TH OF MAY TO THE 1st OF AUGUST 2018 IN THE LIVING ROOM.

Period	30th May 2018 - 1st Aug 2018
Weather file	Average Brighton Weather file
Data logging interval	10 minutes
Number of measurements	8929
NMBE	**0.63%**
CV(RMSE)	**8.47%**

RH living room 30th May – 1st August 2018

___Simulated (average weather file)
___Measured

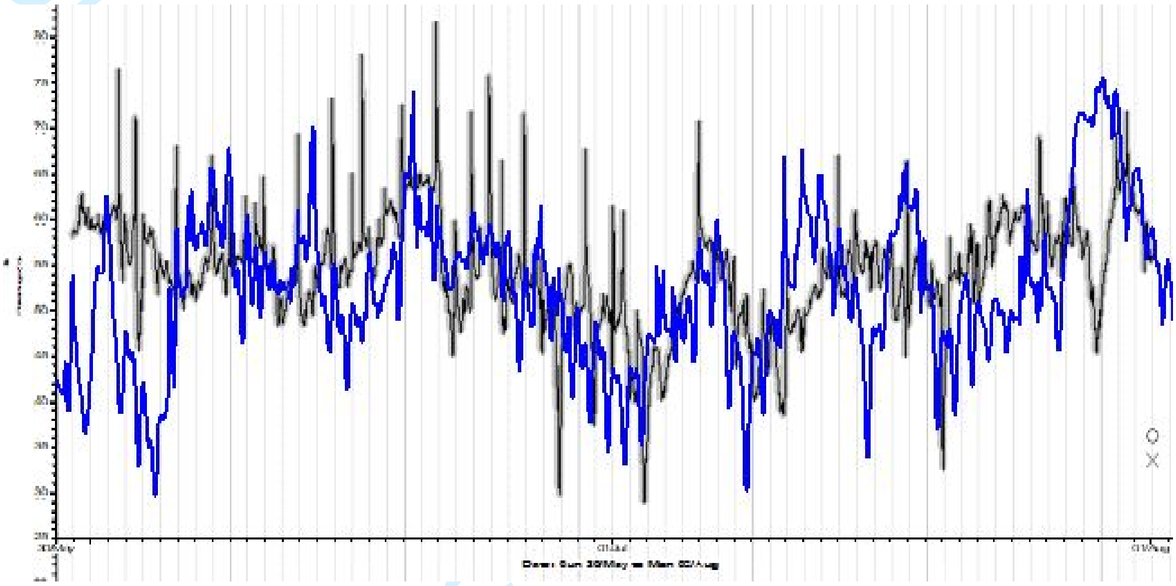


Figure 0.15 Graph showing the simulated (in blue) and measured (in black) indoor relative humidity (RH) from the 30th of May to the 1st of August 2018 in the living room.

Period	30th May 2018 - 1st Aug 2018
Weather file	Average Brighton Weather file
Data logging interval	10 minutes
Number of measurements	8929
NMBE	**5.07%**
CV(RMSE)	**15.96%**

Temperature master bedroom 30th May – 1st August 2018

___Simulated (average weather file)

___Measured

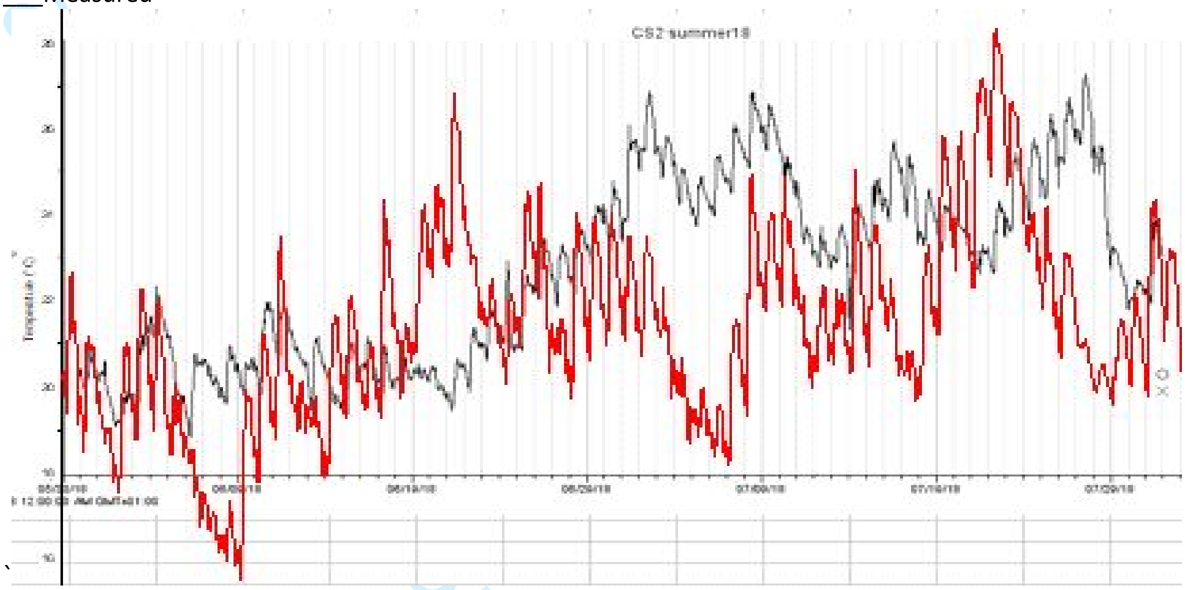


FIGURE 0.16 GRAPH SHOWING THE SIMULATED (IN RED) AND MEASURED (IN BLACK) INDOOR TEMPERATURE FROM THE 30TH OF MAY TO THE 1ST OF AUGUST 2018 IN THE MASTER BEDROOM.

Period	30th May 2018 - 1st Aug 2018
Weather file	Average Brighton Weather file
Data logging interval	10 minutes
Number of measurements	8929
NMBE	**4.14%**
CV(RMSE)	**11.34%**

RH master bedroom 30th May – 1st August 2018

___Simulated (average weather file)
___Measured

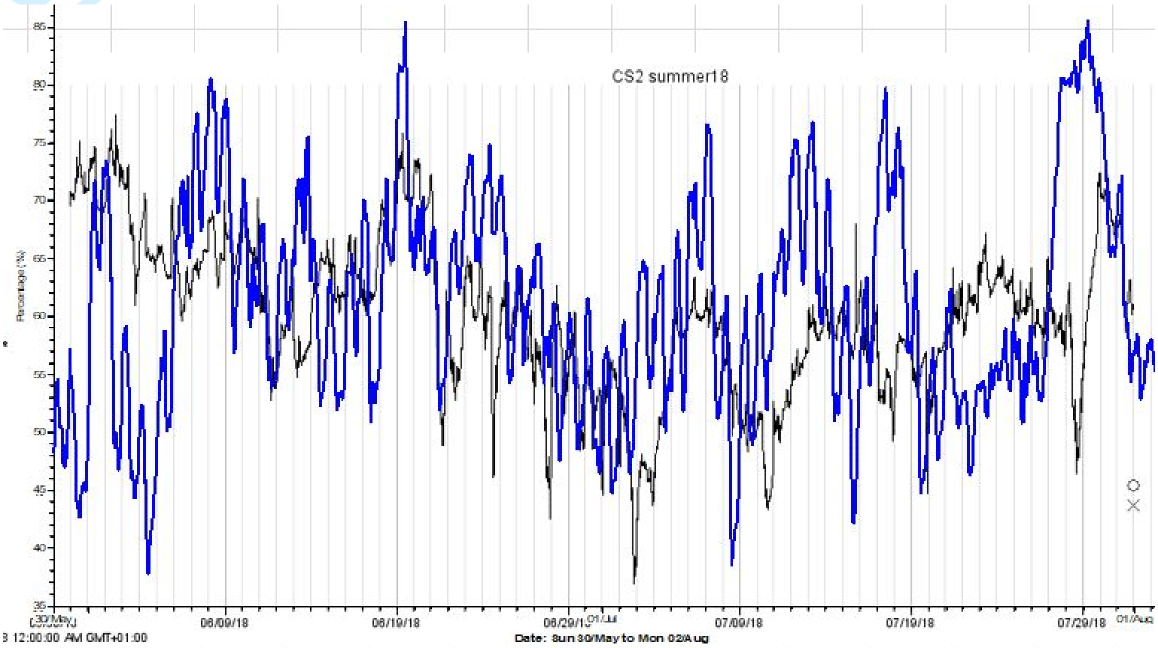


FIGURE 0.17 GRAPH SHOWING THE SIMULATED (IN BLUE) AND MEASURED (IN BLACK) INDOOR RELATIVE HUMIDITY (RH) FROM THE 30TH OF MAY TO THE 1ST OF AUGUST 2018 IN THE MASTER BEDROOM.

Period	30th May 2018 - 1st Aug 2018
Weather file	Average Brighton Weather file
Data logging interval	10 minutes
Number of measurements	8929
NMBE	**-1.48%**
CV(RMSE)	**17.82%**

Temperature Guest Bedroom 14th December 2017 - 14th February 2018

___Simulated (2017 weather file and average weather file)
___Measured

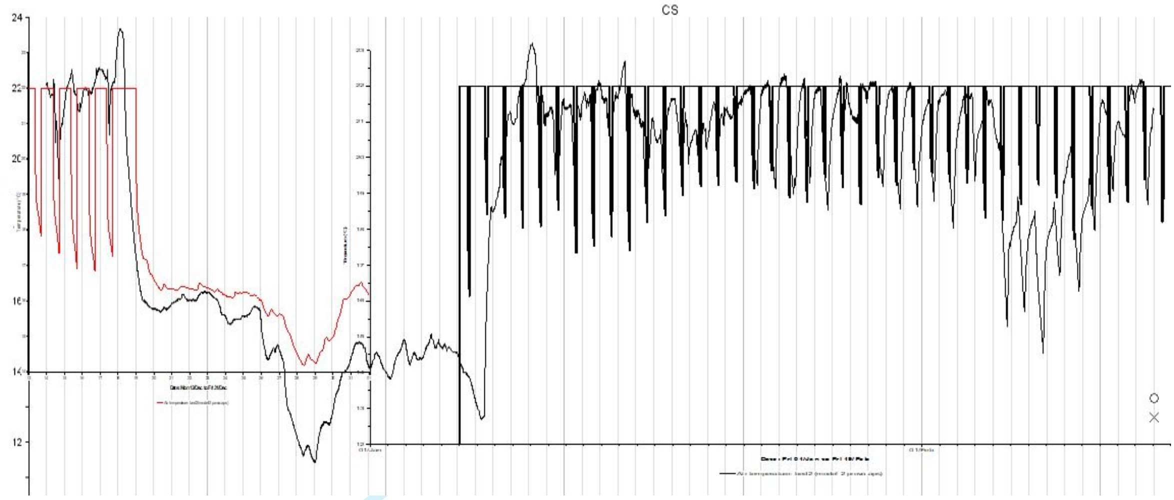


FIGURE 0.18 GRAPH SHOWING THE SIMULATED (IN RED FOR 2017 AND BOLD BLACK FOR 2018) AND MEASURED (IN LIGHT BLACK) INDOOR TEMPERATURE FROM THE 14TH OF DECEMBER 2017 TO THE 14th OF FEBRUARY 2018 IN THE GUEST BEDROOM.

Period	14th Dec 2017 - 14th Feb 2018
Weather file	Brighton 2017 and Average Brighton Weather file
Data logging interval	30 minutes
Number of measurements	2976
NMBE	**-4.54%**
CV(RMSE)	**7.22%**

RH Guest Bedroom 14th December 2017 - 14th February 2018

___Simulated (2017 weather file and average weather file)
___Measured

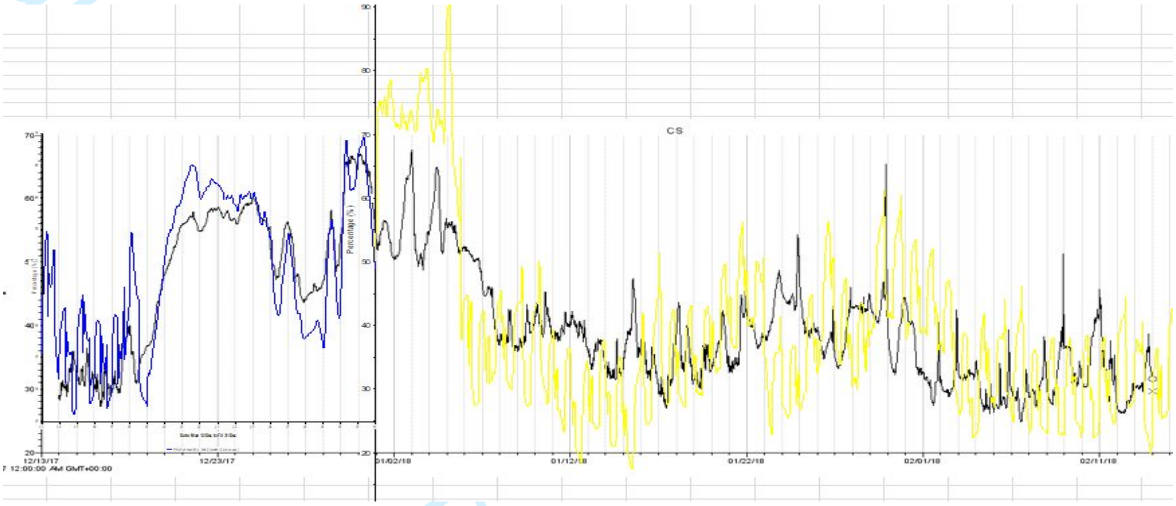


FIGURE 0.19 GRAPH SHOWING THE SIMULATED (IN BLUE FOR 2017 AND YELLOW FOR 2018) AND MEASURED (IN BLACK) INDOOR RELATIVE HUMIDITY (RH) FROM THE 14TH OF DECEMBER 2017 TO THE 14TH OF FEBRUARY 2018 IN THE GUEST BEDROOM.

Period	14th Dec 2017 - 14th Feb 2018
Weather file	Brighton 2017 and Average Brighton Weather file
Data logging interval	30 minutes
Number of measurements	2976
NMBE	**-2.96%**
CV(RMSE)	**14.37%**

Notes

[A1] 115mm for a half-brick wall (imperial size).

[A2] 227mm for a one-brick wall (imperial size).

[A3] 352mm= 227mm+10mm (mortar)+115mm for a one-and-half brick wall (imperial size).

[A4] 464mm= 227mm+10mm (mortar)+227mm for a two-bricks wall (imperial size).

[B1] 102.5 mm for a half-brick wall (metric size).

[B2] 215 mm for a one-brick wall (metric size).

[B3] 327.5 mm= 215mm+10mm (mortar)+102.5mm for a one-and-half brick wall (metric size).

[B4] 440mm= 215mm+10mm (mortar)+215mm for a two-bricks wall (metric size).

[B5] 552.5mm= 215mm+10mm (mortar)+215mm+10mm (mortar)+102.5mm for a two-and-half bricks wall (metric size).

[B6] 665mm= 215mm+10mm (mortar)+215mm+10mm (mortar)+215mm for a three-bricks wall (metric size).

[C] 30 to 50mm of cavity (depending on the overall thickness of the construction) for the vertical timber battens needed in the lath and plaster construction.

[D] 6 to 8 mm of wood, oak essence, for the lath on plaster construction. It has been decided to replace the default value (1025 MNs/gm) for the vapour resistivity of the oak layer in IES with the same vapour resistivity value (45 MNs/gm) of lime plaster. This was done to account for the overall permeability of the construction, given by the spacing of the lath, and for the contribution of the oak layer in the overall U-value of the construction.

[E1] A new material (lime plaster) was created and added to the materials library of the project, to simulate the lime-based plaster typically used in the regency buildings in Brighton.

[E2] 15mm of lime plaster was used to model the traditional plaster on lath construction.

[F] For these input values data from previous research have been used (IES, 2009; IES, 2015b; CIBSE, 2015).

[G] To calculate wind pressure, Macro-Flo uses coefficients provided for a range of exposure types.

[H] The Crack Flow Coefficient (CFC, a coefficient characterising the leakage properties of the crack) and the Crack Length (CL, the length of the crack around the opening, expressed as a percentage of the opening's perimeter length) have been given a value of zero for all the openings. For the internal doors generally closed it has been assigned a value for the CFC given by IES Tables (IES, 2015).

[I1] The opening threshold refers to the temperature in the room adjacent to the opening which, when exceeded, will trigger the opening of the window or door. Once open, it will remain so until the

Degree of Opening profile is zero, regardless of subsequent values of the adjacent room air temperature. In this research it has always been given a value of 0°C to ensure that the pattern of opening simply follows the Degree of Opening percentage profile.

[I2] The Degree of Opening is a Profile which determines when and to what degree the opening type is considered open.

[J] SCoP is the Seasonal Coefficient of Performance of the Heating System. The software automatically calculates the value of the SCoP for each system created, given the Boiler Seasonal Efficiency (manually inputted) and the Heating Delivery Efficiency (HDE), assigned to each system by default when using the UKNCM wizard.

[K] For the Heating Plant Radiant Fraction, the default value given by the software for the corresponding UK NCM Type was used, and namely 0.2 for the UK NCM type Central heating using water (radiators).

[L] DHW consumption was calculated using the formula: DHW=40+28N l/day (Energy Saving Trust, 2008) where N=number of people in the dwelling.

[M1] Values of heat gains from people were taken from CIBSE Guide A (CIBSE, 2015: Table 6.3) for male, female, or mixture of occupants.

[M2] Values of heat gains from lighting equipment were taken from CIBSE Guide A (CIBSE, 2015: Table 6.2).

[M3] Values of heat gains from typical domestic equipment were taken from CIBSE Guide A (CIBSE, 2015: Tables 6.15 and 6.16).

[M4] Values of heat gains from hooded cooking equipment were taken and adapted from CIBSE Guide A (CIBSE, 2015: Tables 6.18 and 6.20).

[N1] Values for the auxiliary ventilation were taken from CIBSE Guide A (CIBSE, 2015: Table 4.2(a)).

[N2] Values for the infiltration were taken from CIBSE Guide A (CIBSE, 2015: Table 4.24) and modulated based on the outcome of visual survey, interview, and thermographic survey.

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