Article

The Importance of In Situ Characterisation for the Mitigation of Poor Indoor Environmental Conditions in Social Housing

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Abstract: The energy efficiency improvements in existing buildings have become priority concerns of the European Union to encourage energy efficiency amongst residents and buildings as well as facility managers. The characterisation of the building stock plays an important role in the definition of energy renovation strategies. In Portugal, there are over 120,000 social housing flats. This paper focused on the holistic characterisation of a social housing neighbourhood concerning the “in situ” assessment of the indoor environmental conditions and thermal comfort over one year as well as air permeability tests of the flats and evaluation of the energy consumption. The hygrothermal monitoring campaign was carried out using thermo-hygrometer sensors to record the indoor air temperature and relative humidity of a large number of flats over a 12-month period. The airtightness of these flats was determined resorting fan pressurisation test (blower door test). A relationship between the users’ modifications in the flats and their consequence over the air permeability was pursued and the importance of balconies and exhaust fans for the flats’ air permeability was discussed. The hygrothermal monitoring campaign of the case study was carried out, in order to assess the indoor thermal comfort according the ASHRAE 55 standard. The results show a significant discomfort rate, suggesting that the users are living in unhealthy environmental conditions and the issues that most contribute to the poor indoor environmental conditions that characterise this building stock. In addition, the energy, gas, and water consumption of the flats were collected, and a statistical analysis was performed. Correlations between the variables were observed and two clusters were identified. Cluster 1 includes the lower energy consumption flats, but no real impact on the thermal comfort was found as the entire dataset presented low indoor air temperatures.

Keywords: air temperature monitoring; social housing; comfort assessment; building airtightness; energy and water consumption

Citation: Oliveira, R.; Vicente, R.; Almeida, R.M.S.F.; Figueiredo, A. The Importance of In Situ Characterisation for the Mitigation of Poor Indoor Environmental Conditions in Social Housing. *Sustainability* **2021**, *13*, 9836. <https://doi.org/10.3390/su13179836>

Academic Editor: Marc A. Rosen

Received: 5 May 2021

Accepted: 27 August 2021

Published: 1 September 2021

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1. Introduction

The global energy resources are mainly consumed in urban centres, which represent nearly 75% of global primary energy supply, resulting in environmental consequences [1]. In regard to building context, the European directive on the energy performance of buildings (EPBD) has been proposed via new European Union rules on the use of energy, establishing a set of targets for the energy consumption of new and existing buildings, leading to the achievement of nearly zero energy buildings (nZEBs) [2].

In several European countries, the massive construction of new buildings has progressively decreased in the last two decades, prioritising the rehabilitation and refurbishment of existing buildings, since older buildings are the least energy efficient and represent the largest share of the European building stock and are clearly targeted by the recent EPBD recast [3]. The energy consumption of the building sector in the next 50 years will mainly

be ruled by the existing building stock and its rate of refurbishment. Data predictions indicate that without a significant change in the refurbishment rate, the non-retrofitted building stock is estimated to represent around 80% of the total energy consumption of European buildings by 2050 [4].

The social housing sector comprises over 26 million houses, about 11% of existing dwellings in Europe (Housing Europe data) [5] and approximately 3% in Portugal [6]. Adequate housing is recognised in a number of international human rights instruments, and thus social housing plays an important role in society, aiming to provide dwellings to low-income families, either for renting or for purchase. However, the energy performance of these buildings is usually below average due to their construction characteristics and to their generally deteriorated conditions due to the lack of maintenance. In fact, strong indicators of poor housing conditions have been found in a social housing context, increasing the risk of health problems among its occupants [7].

In the literature, numerous examples are reported of severe and chronic health impacts on the occupants as a result of exposure to elevated concentrations of indoor pollutants such as particulate matter, formaldehyde, mould, and nitrogen dioxide [8]. Additionally, thermal comfort can be assessed by temperature and humidity parameters, which are also indicators of an adequate indoor environment, which is dependent of the hygrothermal conditions [9]. In this sense, poor hygrothermal conditions lead to the occurrence of anomalies on the building level such as dampness and mould, with obvious negative health consequences for the occupants [10].

The current lifestyle of the occupants and their educational level are identified as major obstacles for the acceptance of energy saving practices, or to invest in highly efficient HVAC systems [11]. For example, the age of the users has an effect on energy consumption, which could have a four times difference in heating demand between single seniors and single adults, and two times difference between coupled seniors and coupled adults [12]. In addition, the real indoor environmental condition assessment of social housing by monitoring is necessary to pursue new energy efficient solutions compatible with the users' occupation habits [13].

Several authors have studied the indoor environmental quality in social housing by using real data from the monitoring of indoor hygrothermal conditions [10,14–17]. Ioannou et al. (2018) [15] evaluated thermal comfort using real-time measurements in 17 social residential buildings and compared it with the users' thermal perception. Their findings showed that even when the indoor temperatures presented discomfort conditions (evaluated according to ISO 7730 [18]), occupants reported a neutral sensation. Aside from thermal comfort assessment, in-use monitoring data are fundamental for accurate simulation of the building energy performance. Moreover, Escandón et al. (2017) [14] and Oliveira et al. (2020) [17] demonstrated that in-use monitoring, using multi-residential social housing as a case study, allowed sufficient information to develop energy simulation models, in order to minimise the performance gap between real and estimated behaviours of the occupants.

Among all the influencing parameters that affect the indoor environment of buildings, ventilation (natural or mechanical) is one of the most important, either regarding thermal comfort or energy consumption. Additionally, ventilation also provides fresh air and removes contaminated air into a space. In a social housing context, typically, no specific ventilation system is designed, and fresh air admission is dependent of uncontrolled infiltration through the building envelope and window openings. However, controlling airtightness is crucial in achieving an energy efficient building, since uncontrolled air admission could be responsible for approximately 25% of the total heating demand [19,20] and the ventilation-related heating requirements can be decreased up to 30% by reducing the buildings' leakage [21]. On the other hand, fresh air is crucial for the indoor air quality (IAQ) as well as to reduce the condensation risk and associated problems, mainly in the context of social housing, in which these issues are persistent [22]. In the last two decades, several international standards and national codes [23,24], for instance, the Passive House

and Minergie concepts, started imposing limit values for building airtightness, typically using the air change rate at a pressure difference of 50 Pa (ACH_{50}) as the control parameter, calculated from the results of the blower door test.

Several experimental studies to evaluate building airtightness have been carried out, mainly in cold climate countries [19,25,26]. Sinnott (2016) [26] investigated the airtightness of nine semi-detached social housing buildings in Ireland and the results show that the ACH_{50} values ranged between 3.9 h^{-1} and 17.1 h^{-1} . Moreover, the investigation indicated the boxed-out waste and soil pipes from the ground floor as the most relevant leakage paths and showed that existing wall vents were partially or fully obstructed by the occupants. In recent years, in southern European countries, several experimental studies focusing on the airtightness of social housing buildings have also been published [27–30]. Fernández-Agüera et al. (2016) [29] investigated 45 units of multi-residential social housing buildings in Spain using the blower door test and found an average air change rate of 50 Pa of 5.72 h^{-1} . Later, Fernández-Agüera et al. (2019) [30] developed a predictive model for airtightness estimation by using morphological parameters. The results point out the total window area and the perimeter length of the buildings as the most important parameters to explain the variability airtightness.

This paper aims at presenting a holistic experimental characterisation campaign that can be the basis of identifying and prioritising refurbishment interventions and to mitigate the causes of the poor indoor environmental conditions toward a future scenario where the occupants can affordably achieve comfortable conditions inside their flats. The research included hygrothermal monitoring, air permeability testing, and collecting the energy and water consumption of a large number of flats of a social housing neighbourhood located in Aveiro city, Portugal. The main results of the monitoring and testing are presented. Additionally, a cluster analysis combining them with the energy and water consumptions of the occupied flats was performed.

2. Case Study Presentation

2.1. The Multi-Residential Social Housing Neighbourhood

The case study is located in the central part of Portugal, in the coastal region of Aveiro, and was constructed in 1989 under the city council administration to respond to the lack of housing in that decade. During that period, the Government launched several initiatives aiming to build social housing neighbourhoods in the country's main cities. To this end, several typified projects were created, which were replicated in various regions. Therefore, similar typological and constructive features can be found in other cities. The representativeness of these buildings enhances the impact of the findings and thus constitutes an important added-value of the research.

Aveiro is characterised by a mild Mediterranean climate. Figure 1 shows the average weather parameters (outdoor air temperature and relative humidity) taken from the Portuguese Sea and Atmosphere Institute (IPMA) [31].

Figure 1. Weather data for Aveiro region: (a) air temperature; (b) relative humidity.

The neighbourhood is composed of groups of buildings with surrounding green recreation areas with a significant number of trees with variable dimensions that have direct influence over building shading and in wind exposure conditions. The neighbourhood is composed of 788 flat units distributed amongst 38 multi-residential buildings with two different heights: 32 buildings with four storeys, and six buildings with eight storeys (see Figure 2).

Figure 2. Aerial view of the social housing neighbourhood (image taken from Google Maps, <https://goo.gl/maps/1yqGe5YYUE1fytpM8>, accessed on 1 January 2021).

In the 80s the construction of the neighbourhood was initiated and built only for social housing purposes, however, along the years, numerous flats or entire buildings have been bought by private entities and resold. However, only the buildings that are currently used as social housing were included in this research.

Two different shape configurations of buildings are highlighted in Figure 2: type A, the most common buildings; and type B, which corresponds to the buildings in the centre of the neighbourhood. The representative storey of building type A is composed of six flats, with two or three bedrooms, and building type B is composed of two flats in each storey, both with four bedrooms. The layout of the flats was similar including all equivalent areas in the hall, kitchen, living/dinner room, balcony space (except for flat A6 on the ground floor level—see Table 1), bedrooms, and bathrooms. Regarding orientation, generally, the flats of building type A are east/west oriented, while building type B flats are north/south orientated (see Figure 2).

Table 1. Geometric characteristics of the flats.

Building Type	Flat Number	Typology	TFA (m ²)	Volume (m ³)	Total External Opaque Area (m ²)	Glazing Area (m ²)
1	T3	76.78	191.95	315.00	8.56
	2	T2	59.76	149.39	260.15	5.50
	3	T3	79.05	197.63	334.00	7.66
	4	T3	79.05	197.63	334.00	7.66
	5	T2	60.31	150.78	230.28	5.90
	6	T3	79.36	198.39	326.49	8.99
1	T4	91.20	227.99	367.84	10.34
	2	T4	91.20	227.99	367.84	10.34

Note: TFA: treated floor area; T: number of bedrooms.

Table 1 presents the geometric characteristics of the representative flats for the two building types (A and B).

2.2. Envelope Characterisation

The building design and construction was based on low-cost solutions using pre-fabricated elements for a fast build and is composed of a mixed system resourcing with prefabricated wall panels and prefabricated floor slab accounting for part of the whole building system. However, some smaller external envelope walls are hollowed brick masonry, which is the case of the ground floor walls that are composed of a double leaf brick cavity wall. The external envelope characterisation was performed by an in situ survey presented by Oliveira et al. (2020) [17]. The façades are composed of prefabricated panels in concrete with an additional brick masonry leaf on the inner side of the wall. Windows are single glazed with aluminium frames with exterior plastic roller-shutters to operate as shading devices.

A concrete slab composes the ground floor as well as the elevated floors. The roof is pitched, and the main structure is composed of a concrete truss.

3. Methodology

The research follows the premise “measure and inspect before acting”, targeting the assessment of essential information that is most useful for different actions: support numerical modelling validation, correlate building defects—potential causes and alert users about their actions, namely with respect to the ventilation needs and air permeability. To achieve robust conclusions, the hygrothermal monitoring lasted a whole year.

Section 3.1 describes the hygrothermal monitoring campaign carried out in the occupied flats; Section 3.2 describes the experimental tests concerning the air permeability of the occupied and unoccupied flats; finally, in Section 3.3, the procedure implemented to collect the energy and water consumption data of the occupied flats is explained. Figure 3 presents the detailed conceptual framework of the study describing the main steps of the methodology.

Figure 3. Conceptual framework of the study.

3.1. Hygrothermal Monitoring

In order to be most representative, the hygrothermal monitoring was carried out in eight buildings, covering the different geometries and orientations described in Section 2.1. Thermo-hygrometer sensors were installed into two occupied flats of each building (total of 16 flats monitored) identified in Figure 4 and the collected data were used to assess the indoor thermal comfort conditions. The sensors’ accuracy and resolution were ± 0.3 °C and 0.01 °C and $\pm 2\%$ and 0.01% for temperature and relative humidity, respectively.

Figure 4. Identification of monitored buildings.

Two thermal zones (TZ#) were identified in each flat: TZ01—bedrooms, living room and toilets; TZ02—kitchen and balcony. Figure 5 shows the location of the thermo-hygrometer sensors in the different types of flats.

Figure 5. Thermal zoning and location of the thermo-hygrometer sensors of the flats (no scale): (a) building type A and (b) building type B. # = flat number identification.

The monitoring campaign was carried out for a whole year. The sensors were distributed in accordance with the ISO 7726 (2001) recommendations [32] and positioned inside the compartments in order to avoid direct sun exposure from the glazed areas. The monitoring acquisition system was logged at 10 minute intervals due the monitoring system restrictions.

The thermal comfort assessment was carried out using the ASHRAE 55 model based on the psychrometric chart. In previous works carried out in the neighbourhood, combining numerical simulation and in situ measurements, the results show that the indoor air temperature can be assumed as a good approximation of the operative temperature, since no important radiative effects were identified and the air velocity inside the flats is low. The temperature differences between points of the same flat were always below 0.9 °C [17,33,34].

3.2. Air Permeability Assessment

The air permeability was assessed in 34 flats by fan pressurisation (blower door test). The experimental work included two test campaigns: in the first, 15 occupied and 19 unoccupied flats were tested; and in the second campaign, only the unoccupied flats were tested after a minor renovation. Thus, a total of 53 pressurisation and depressurisation tests were carried out.

For a simple identification of the flats, the following id code was implemented: door number of the building; number of the storey; and flat number within the storey. Table 2 summarises the identification of the flats.

Table 2. Flat identification.

Building Type	Occupied	Unoccupied
A	Bl.7.0.4; Bl.7.1.6	Bl.7.0.1; Bl.7.1.3
	Bl.8.0.6; Bl.8.1.1	Bl.8.2.4; Bl.8.3.3
	Bl.9.0.6; Bl.9.3.1	Bl.9.1.2; Bl.9.3.4
	Bl.26.0.1; Bl.26.1.6	Bl.26.1.3; Bl.26.3.3
	Bl.30.1.4; Bl.30.2.4	Bl.30.2.2
	Bl.31.2.6; Bl.31.3.2	Bl.31.0.5; Bl.31.0.6; Bl.31.2.2 Bl.31.2.5; Bl.31.3.1; Bl.31.3.4
B	Bl.39.0.2; Bl.39.2.2	Bl.39.2.1
	Bl.42.1.1; Bl.42.1.2	Bl.42.2.1; Bl.42.2.2; Bl.42.3.1

The tests were conducted with Retrotec 1000 blower door™ (Retrotec, Barchem, The Netherlands) equipment, following the methodology proposed by EN 13829 (2006) [23] and ISO 9972 (2006) [24]. The data specifications of the blower door apparatus are presented in Table 3.

Table 3. Technical data of the blower door equipment.

Description	Specifications
Minimum flow at 50 Pa	8.50 m ³ /h
Maximum flow at 50 Pa	10.19 m ³ /h
Fan	Flow accuracy: ±3%
Digital Gauge	Pressure accuracy: ±1 Pa

All blower door tests were carried out following the same protocol as method A described in [23]. All the openings in bathrooms and bedrooms were kept opened as well as the smoke extractors. The windows in the flats were closed and the interior doors remained opened during the test.

This campaign included flats with either open or closed balconies, as shown in Figure 6. Regarding the closed balconies situation, numerous cases corresponded to user interventions, namely through the installation of new windows, while others were original and unchanged from the architectural design.

Figure 6. Balcony configuration: (a) opened and (b) closed by interior windows.

Other particular conditions that may lead to a variation in the air permeability levels were observed in numerous flats such as different types of exhaust fans (see Figure 7). Despite the poor conditions of the covering exhaust fans, no action was taken before the permeability tests.

Figure 7. Exhaust hole: (a) without exhaust fan, (b) integrating an exhaust fan, and (c) with hood draw exhaust fan.

Further changes in respect to envelope air permeability of the flats were observed such as the sealing of pipework penetrations and fixed air inlet installed in the roller-shutter boxes in the main rooms. The air permeability indicator used was the air change rate at a pressure difference of 50 Pa based on the average from the results of pressurisation and depressurisation tests.

The second campaign of air permeability tests was conducted after the interior renovation, in which 19 flats without occupation were tested again, referred to as campaign C2 in Section 4.2. The aim of these renovation actions was to improve the overall living conditions and thus not directly focused on the air permeability of the flats. The renovation was carried out in all unoccupied flats and a short description of the actions is presented in Table 4.

Table 4. Description of the interior renovation actions carried out in the unoccupied flats.

Unoccupied Flats Identification	Construction Components and Items	Description of Activities
Bl.7.0.1; Bl.7.1.3 Bl.8.2.4; Bl.8.3.3 Bl.9.1.2; Bl.9.3.4 Bl.26.1.3; Bl.26.3.3 Bl.30.2.2; Bl.31.0.5 Bl.31.0.6; Bl.31.2.2 Bl.31.2.5; Bl.31.3.1 Bl.31.3.4; Bl.39.2.1 Bl.42.2.1; Bl.42.2.2 Bl.42.3.1	Interior components demolition	Removal and demolition of damaged coatings and illegal elements built (interior compartment walls, closed balconies, etc.).
	Walls and ceilings	Cleaning actions, crack repair and paint.
	Floors	Repair and substitution of floor covering and tiling.
	Windows	General inspection of windows and doors, with replacement of damaged blinds, window hinges and metal working.
	Joinery	General inspection with replacement fittings, handles and locks of the doors. Replacing of interior doors damaged.
	Service installations	Electricity network, with switching of damaged sockets and switches; Sewage removal and replacement of accessories; Replacement of galvanised iron pipes.

In summary, the air permeability campaigns were carried with the following objectives:

- Characterisation of the airtightness of the flats to provide important data concerning their thermal and energy performance. Since the flats are representative of a large building stock, these data can be useful for other studies in the social housing context;
- Understand the possible impact of the occupants' actions on the airtightness of the flats, either by improving it or the opposite. To fulfil this aim, the results of the occupied and unoccupied flats were compared (Campaign 2). The effect of user actions on the airtightness has already been discussed by other authors, which highlights the relevance of the topic [28,29,35]; and
- Understand the impact of the rehabilitation intervention on air permeability. Although the interventions were not directly targeted toward air leakage, some measures such as the new window installation and repair were expected to improve the airtightness.

3.3. Energy and Water Consumption Measurements

Data concerning the monthly consumption of electricity, gas, and water of the flats were collected during the monitoring period. Regarding the use of energy and water, one questionnaire per flat was also distributed to the users to assess their habits in what is related to the heating and water consumption (see Table 5). The energy and water consumption was collected from the existing metering devices in each flat.

Table 5. Energy and water consumption habits of the flat users.

Source	Usage	Type of Device
Electricity	Heating	Fan heater and electrical oil radiator
	Lightning	Halogen bulbs
	Other	Notebook and television,
Gas	Domestic Hot Water	Boiler
	Cooking	Stove and/or oven
Water	Showering	Shower and/or bath
	Cooking	-

The consumption data were organised and statistically analysed by clustering techniques to identify homogenous groups of flats with similar performance. Afterward, the information was combined to identify the possible impact of the energy consumption on the interior environmental conditions. For the clustering procedure, the agglomerative hierarchical method was applied using IBM SPSS Statistics (Version 25, Stanford University, Stanford, CA, USA) software.

4. Results and Discussion

4.1. Hygrothermal Analysis

Indoor hygrothermal conditions of 16 occupied flats were recorded during the monitored period. Winter data comprise the period from 22 October 2017 to 20 March 2018 and 22 September 2018 to 22 October 2018, while summer data comprises the period from 21 March 2018 to 21 September 2018.

The results obtained from the indoor hygrothermal monitoring are synthesised in Tables 6 and 7 for the winter and summer periods, respectively. The average air temperature during the winter was generally low and below 18 °C. Regarding the minimum temperature of the flats, extremely low values between 10 °C and 15 °C were observed, revealing higher levels of thermal discomfort. This is particularly concerning, since the exterior climate is quite mild (Figure 1), highlighting the importance of improving the building envelope.

The standard deviation of temperature indicates a lower thermal amplitude with an oscillation of 2–3 °C. Flats Bl.8.1.1 (with east orientation) and Bl.39.0.2 (north–south orientated) were the only ones with acceptable thermal conditions in all thermal zones, within the interval 18–19 °C of average indoor air temperature. Although this information was not collected, heterogeneous occupancy profiles can help justify these differences.

Regarding the relative humidity, the average results were generally within acceptable limits, ranging between 55% and 82%, however, the peak values are a motive for concern, since these trigger water activity on the wall and ceiling surfaces, leading to the development of mould and microorganisms.

In summer, the average air temperature varied between 19 °C and 24 °C (see Table 7). However, the results revealed that flats had a minimum temperature below 18 °C and above 30 °C for maximum temperature. Despite the mild temperature conditions in summer, the relative humidity average tended to be higher, with values above 65%, confirming the influence of the coastal climate.

Table 6. Maximum, minimum, average, and standard deviation of the indoor air temperature and relative humidity in the winter period.

Occupied Flat Identification	Thermal Zone	Winter Period	
		Temperature (°C)	Relative Humidity (%)
		Max.; Min.; m ± s	Max.; Min.; m ± s
Bl.7.0.4	TZ01	25.13; 12.72; 16.94 ± 3.11	92.63; 38.61; 71.81 ± 8.10
	TZ02	29.75; 13.01; 19.05 ± 3.73	96.28; 29.44; 62.65 ± 9.33
Bl.7.1.6	TZ01	26.79; 13.54; 17.57 ± 2.87	84.93; 29.23; 67.62 ± 7.92
	TZ02	33.93; 12.94; 17.64 ± 3.07	95.71; 24.85; 68.23 ± 11.36
Bl.8.0.6	TZ01	25.71; 12.88; 17.57 ± 3.13	85.03; 45.56; 66.68 ± 7.36
	TZ02	27.21; 12.45; 17.35 ± 3.19	94.77; 43.22; 69.46 ± 9.12
Bl.8.1.1	TZ01	27.42; 13.91; 18.41 ± 2.89	87.53; 33.66; 67.80 ± 9.23
	TZ02	30.82; 14.27; 19.03 ± 3.01	92.76; 26.40; 63.87 ± 10.17
Bl.9.0.6	TZ01	25.05; 14.34; 17.10 ± 2.57	99.58; 42.26; 88.43 ± 7.80
	TZ02	30.56; 15.18; 19.00 ± 2.91	96.22; 43.83; 79.46 ± 7.92
Bl.9.3.1	TZ01	26.58; 10.39; 16.66 ± 3.78	94.10; 30.94; 74.03 ± 9.24
	TZ02	28.16; 10.62; 17.19 ± 3.26	90.08; 25.09; 65.31 ± 9.75
Bl.26.0.1	TZ01	26.62; 13.04; 17.37 ± 3.19	91.18; 34.27; 66.62 ± 9.28
	TZ02	27.79; 12.48; 17.46 ± 3.21	95.79; 31.55; 67.80 ± 10.98
Bl.26.1.6	TZ01	23.06; 12.23; 16.97 ± 2.89	91.81; 38.79; 67.97 ± 8.10
	TZ02	28.25; 11.48; 17.22 ± 3.15	97.68; 32.03; 67.88 ± 10.85
Bl.30.1.4	TZ01	24.81; 12.65; 17.02 ± 2.75	95.95; 39.74; 73.41 ± 8.58
	TZ02	31.26; 14.46; 17.39 ± 2.62	97.77; 38.54; 71.78 ± 8.21
Bl.30.2.4	TZ01	29.72; 12.49; 16.91 ± 2.96	86.32; 32.09; 63.81 ± 9.51
	TZ02	29.30; 11.31; 16.65 ± 2.97	93.58; 29.80; 65.81 ± 11.33
Bl.31.2.6	TZ01	29.93; 12.07; 17.39 ± 3.49	95.27; 29.48; 72.60 ± 11.17
	TZ02	34.16; 12.07; 18.03 ± 3.58	94.53; 20.26; 69.75 ± 11.06
Bl.31.3.2	TZ01	34.16; 11.77; 17.40 ± 3.61	96.21; 25.09; 73.02 ± 10.36
	TZ02	28.06; 11.05; 17.26 ± 3.49	99.15; 28.12; 74.82 ± 10.86
Bl.39.0.2	TZ01	26.87; 13.89; 19.23 ± 2.73	86.51; 35.86; 62.53 ± 7.21
	TZ02	26.69; 13.22; 18.01 ± 2.61	85.92; 34.87; 67.39 ± 7.91
Bl.39.2.2	TZ01	26.09; 12.52; 17.27 ± 2.85	82.74; 37.17; 64.70 ± 6.51
	TZ02	26.75; 12.31; 16.80 ± 2.84	83.34; 36.83; 66.49 ± 6.53
Bl.42.1.1	TZ01	26.52; 12.13; 17.61 ± 3.33	94.75; 23.67; 64.02 ± 11.38
	TZ02	25.31; 10.00; 16.05 ± 3.27	94.78; 38.04; 74.36 ± 9.12
Bl.42.1.2	TZ01	28.39; 12.04; 16.99 ± 3.31	87.34; 46.85; 68.03 ± 7.96
	TZ02	26.61; 9.75; 15.59 ± 3.61	88.55; 55.33; 72.70 ± 6.50

Note: m—average; s—standard deviation.

Table 7. Maximum, minimum, average and standard deviation of the indoor air temperature and relative humidity in the summer period.

Occupied Flat Identification	Thermal Zone	Summer Period	
		Temperature (°C)	Relative Humidity (%)
		Max.; Min.; m ± s	Max.; Min.; m ± s
Bl.7.0.4	TZ01	25.54; 14.00; 19.91 ± 2.93	91.39; 52.18; 76.18 ± 4.45
	TZ02	31.98; 14.34; 22.25 ± 3.43	93.54; 39.11; 66.21 ± 6.42
Bl.7.1.6	TZ01	28.47; 14.98; 21.37 ± 2.77	83.03; 38.50; 68.16 ± 4.29
	TZ02	32.07; 13.91; 21.58 ± 3.04	95.13; 36.14; 68.38 ± 6.09
Bl.8.0.6	TZ01	26.94; 14.68; 21.21 ± 2.97	83.45; 49.26; 70.42 ± 3.99
	TZ02	28.25; 14.35; 21.26 ± 3.15	93.74; 51.55; 71.38 ± 5.25
Bl.8.1.1	TZ01	28.53; 15.91; 22.08 ± 2.76	87.53; 39.88; 70.04 ± 5.56
	TZ02	33.57; 14.27; 24.25 ± 2.73	93.98; 34.28; 66.98 ± 6.65
Bl.9.0.6	TZ01	26.53; 18.48; 21.44 ± 1.63	95.70; 56.17; 82.44 ± 4.63
	TZ02	30.14; 19.08; 23.16 ± 1.81	95.40; 56.39; 74.42 ± 5.19

Table 7. Cont.

Occupied Flat Identification	Thermal Zone	Summer Period	
		Temperature (°C)	Relative Humidity (%)
		Max.; Min.; m ± s	Max.; Min.; m ± s
Bl.9.3.1	TZ01	30.48; 13.52; 21.95 ± 3.70	90.02; 51.33; 70.47 ± 5.69
	TZ02	31.77; 13.14; 22.10 ± 3.23	83.02; 36.19; 65.33 ± 5.29
Bl.26.0.1	TZ01	26.89; 15.02; 21.24 ± 2.97	89.55; 47.91; 71.60 ± 5.25
	TZ02	28.71; 14.50; 21.30 ± 3.03	94.02; 38.61; 71.49 ± 5.89
Bl.26.1.6	TZ01	25.86; 12.99; 20.51 ± 3.63	87.30; 41.01; 71.03 ± 4.29
	TZ02	30.96; 14.10; 21.52 ± 3.31	96.83; 38.70; 70.84 ± 5.18
Bl.30.1.4	TZ01	27.32; 14.17; 20.94 ± 2.95	94.33; 52.64; 74.40 ± 4.57
	TZ02	32.01; 14.46; 21.58 ± 3.01	97.77; 50.77; 73.11 ± 4.78
Bl.30.2.4	TZ01	27.91; 14.31; 21.20 ± 3.17	88.74; 43.27; 67.26 ± 5.15
	TZ02	29.49; 13.64; 20.74 ± 3.08	90.70; 39.10; 68.78 ± 5.82
Bl.31.2.6	TZ01	26.63; 14.47; 21.88 ± 3.18	90.56; 49.36; 69.27 ± 4.96
	TZ02	34.66; 14.47; 22.26 ± 3.34	91.92; 36.85; 68.22 ± 5.99
Bl.31.3.2	TZ01	30.39; 12.40; 21.77 ± 3.71	96.21; 43.91; 71.52 ± 6.77
	TZ02	30.40; 12.65; 21.40 ± 3.46	98.26; 39.53; 73.39 ± 6.45
Bl.39.0.2	TZ01	28.74; 15.26; 22.52 ± 2.96	80.51; 40.71; 65.16 ± 3.87
	TZ02	27.38; 14.43; 20.96 ± 2.79	85.92; 39.88; 72.21 ± 5.21
Bl.39.2.2	TZ01	28.71; 14.46; 21.34 ± 3.06	80.22; 54.85; 67.86 ± 3.64
	TZ02	27.65; 14.27; 21.63 ± 3.13	83.15; 46.76; 68.45 ± 4.51
Bl.42.1.1	TZ01	28.34; 13.91; 21.21 ± 3.37	89.62; 38.39; 68.55 ± 6.34
	TZ02	27.73; 12.39; 19.53 ± 3.88	92.52; 49.61; 76.66 ± 4.96
Bl.42.1.2	TZ01	27.01; 13.84; 20.93 ± 3.28	86.50; 53.85; 71.26 ± 4.94
	TZ02	26.28; 16.91; 21.53 ± 1.96	83.25; 56.56; 76.07 ± 3.11

Note: m—average; s—standard deviation.

ASHRAE 55 [36] proposes a method for thermal comfort evaluation based on the definition of a comfort zone in a psychometric chart. This graphic method is applicable for metabolic rate between 1.0 and 1.3 met and for clothing insulation between 0.5 and 1.0 clo. This method was applied to the entire dataset and, as an example, the results for the two thermal zones of flat Bl.26.0.1 are presented in Figure 8. Five regions were defined in the discomfort zone for better understanding of the results: (A) low temperature; (B) low temperature and high humidity; (C) high humidity and balanced temperature; (D) high temperature and high humidity; and (E) high temperature. Region F corresponds to the comfort zone.

The results confirm that the flat performance is characterised by large periods of discomfort due to low temperatures (region A) and overheating is not an issue in these buildings, as no records occurred in region E. The high humidity ratio is also motive for concern (region C) since these conditions may enhance the occurrence of mould problems inside the flats. From the results, a similar pattern was observed between the two thermal zones of the flat, indicating a homogeneous thermal environment inside the flat.

A summary of the discomfort rate in all flats is presented in Table 8. Only the results of TZ01 are included, since the performance of the thermal zones were identical and TZ02 (kitchen and balcony) represented a smaller area. Overall, the flats presented high discomfort rates, even in the case of the most comfortable flat (Bl.7.1.6), only 31.2% of the time the hygrothermal conditions were within the comfort limits. On the other hand, Bl.9.0.6 presented the lowest comfort rate, 5.4%. Regarding the discomfort associated with regions B, D, and E, the flats presented marginal periods of discomfort.

Figure 8. ASHRAE 55 thermal comfort model: flat BL.26.0.1.

Table 8. Discomfort rate of occupied flats for thermal zone TZ01.

Occupied Flat Identification	Discomfort Rate (%)					Comfort Rate (%)
	A	B	C	D	E	F
Bl.7.0.4	62.0	0.0	25.7	0.0	0.0	12.3
Bl.7.1.6	49.4	0.0	19.0	0.4	0.0	31.2
Bl.8.0.6	49.8	0.0	25.3	0.0	0.0	24.9
Bl.8.1.1	48.5	0.0	27.7	1.2	0.1	22.5
Bl.9.0.6	45.2	3.4	46.0	0.0	0.0	5.4
Bl.9.3.1	47.5	0.0	25.7	2.3	0.0	24.5
Bl.26.0.1	50.4	0.0	28.2	0.0	0.0	21.3
Bl.26.1.6	52.0	0.0	23.2	0.0	0.0	24.8
Bl.30.1.4	54.3	0.0	28.7	0.2	0.0	16.8
Bl.30.2.4	55.3	0.0	17.6	0.7	0.0	26.3
Bl.31.2.6	48.0	0.0	26.2	0.0	0.0	25.8
Bl.31.3.2	48.3	0.1	26.8	2.2	0.0	22.6
Bl.39.0.2	45.1	0.0	24.7	1.6	0.0	28.6
Bl.39.2.2	50.6	0.0	18.6	0.6	0.0	30.2
Bl.42.1.1	53.8	0.0	21.1	1.6	0.2	23.3
Bl.42.1.2	57.2	0.0	25.9	0.3	0.0	16.6

The results confirm that discomfort of the flats was mostly associated to low temperatures (region A), with Bl.7.0.4 presenting the highest discomfort rate, with a value of 62.0%. Besides the issues due to low temperatures, discomfort due to high humidity ratio (region C) was also identified in several flats. This discomfort rate was always below 30%, except in flat Bl.9.0.6, which presented 46.0% of the records in region C, mostly affected by poor ventilation that was noticed by the authors during the experimental campaign.

4.2. Air Permeability Analysis

4.2.1. Air Permeability of Occupied and Unoccupied Flats—Campaign 1

The ACH₅₀ results obtained in the first campaign, C1 (34 tests) are depicted in Figure 9, separately for the occupied (Figure 9a) and unoccupied (Figure 9b)) flats. The results correspond to the average values of pressurisation and depressurisation tests. The average and standard deviation of each set of buildings is also included in the plot.

Figure 9. Average and standard deviation Air Change rate at a pressure difference of 50 Pa (ACH₅₀) values: (a) occupied flats and (b) unoccupied flats.

The results were similar with the findings for equivalent buildings tested by other authors [26,29]. In the occupied flats, the results revealed an average value of ACH₅₀ that was slightly lower when compared with the results of the unoccupied flats, which indicates the commitment of the tenants to improve air tightness by minimising leakage points. On the other hand, the standard deviation was slightly higher, resulting in a coefficient of variation of 37 in the occupied flats and of 30 in the unoccupied ones.

The ACH₅₀ values ranged between 3.01 h⁻¹ and 11.21 h⁻¹ in the occupied flats, while, in the unoccupied, the values ranged from 4.40 h⁻¹ to 13.95 h⁻¹ (see Figure 10). The results obtained in the unoccupied set were, however, clearly influenced by the two outliers: Bl.7.0.1 and Bl.9.3.4, with a value of 12.01 h⁻¹ and 13.95 h⁻¹, respectively (see Figure 9b). These two flats were more degraded, which helps justify the higher air permeability. A larger variability was also found in the results of the occupied flats (see Figure 9a). This variability was mainly due to the users' interventions that sealed the fixed air inlets and the lack of maintenance of the roller-shutter boxes. These issues are common in social housing and their effects on the buildings' air permeability have already been reported by other authors in the literature [26,28].

Figure 10. ACH₅₀ box-plot of Campaign C1.

The possible effect of the balcony and exhaust fan in the results was analysed by dividing the sample into subsets, as shown in Figure 11. The average and standard deviation were calculated for each subset. To assess the effect of the balcony (see Figure 11a), the sample was divided into three subsets: closed balcony; opened balcony; and without balcony. However, when analysing the results, no clear trend was identified. The effect of the open balcony led to a reduction in the ACH_{50} , showing a positive feature in the case of the occupied flats, and an opposite effect situation occurred in the unoccupied ones. Nevertheless, in both the occupied and unoccupied flats, the best performance was found in the flats without balconies as the sources of infiltration were reduced. One must stress that the boundary conditions in the two scenarios were different. In the open balcony scenario, the boundary was composed of an opaque wall and a door, while in the closed balcony scenario, the boundary was the window, which is a leaky element.

Figure 11. ACH_{50} influence: (a) Balcony scenarios and (b) exhaust fan scenarios.

Concerning the effect of the exhaust fan, three scenarios (see Figure 11b) were established: integrating exhaust fan; integrating exhaust fan hood draw; and without the exhaust fan. Once again, no significant differences were identified among the datasets, indicating that the exhaust fan is not a relevant factor to explain the variability found in the results, which is in line with the results published by Ramos et al. (2015) [28].

4.2.2. Air Permeability of Unoccupied Flats—Campaign 2

The ACH_{50} results of the second campaign (C2) are presented in Figure 12. The plot also includes the results of the first campaign (C1), comparing and analysing the effect of the renovation in the flats' air permeability. As previously explained, the renovation was not focused on improving the air permeability of the external envelope. This statement was confirmed by the results, as the average ACH_{50} attained in C2 was only slightly lower when compared to the one in campaign C1, with 7.03 h^{-1} of ACH_{50} against 7.71 h^{-1} , respectively, corresponding to a global reduction of approximately 9%.

Although there was a similar average value, the variability of the results was significantly reduced when compared to C1 (see Figure 13). The renovation resulted in a more homogenous behaviour of the flats in terms of air permeability, reflected in the reduction in the coefficient of variation from 30 to 14.9.

Figure 12. Measured of ACH_{50} values of unoccupied flats: Campaigns 1 and 2.

Figure 13. ACH_{50} box-plots of campaigns C1 and C2.

The purpose of the tests was not a direct comparison with the initial situation. However, a discrepancy in the results showed in the flats' air permeability before and after renovation, confirming that this issue clearly depends on the execution quality and should be addressed with particularly measures in retrofitting actions. In fact, one would expect a more substantial impact on the air permeability due to some of the repair actions such as replacing windows, vents, and shutter boxes; however, no relevant effect was observed in the results.

4.3. Flats Consumption: Cluster Analysis

To find potential behavioural patterns, the monthly consumption data (electricity, water and gas) were analysed using cluster analysis. The hierarchical clustering technique based on Ward's linkage method [37] was implemented and the resulting dendrogram is presented in Figure 14a. The dendrogram clearly pointed to two obvious clusters: Cluster 1 included flats Bl.8.0.6, Bl.26.0.1, Bl.7.1.6, Bl.39.2.2, Bl.30.2.4, Bl.42.1.2, Bl.26.1.6, and Bl.7.0.4; and Cluster 2 included flats Bl.9.0.6, Bl.39.0.2, Bl.31.2.6, Bl.42.1.1, Bl.8.1.1, Bl.31.3.2, Bl.30.1.4, and Bl.9.3.1. According to Kaufman (1990) [38], the silhouette coefficient can support the selection of the number of clusters, and values above 0.50 indicate that the cluster homogeneity is strong. The silhouette coefficient was calculated for the 2-cluster result

and a value of 0.52 was obtained. The scatterplots of Figure 14b–d show the relationship between the consumption of the flats and the two clusters, identified with different marks. This representation of the results allows us to better understand the characteristics of the consumption that justified the clustering. In fact, the results clearly show that Cluster 1 is characterised by flats with lower consumptions, and on the other hand, Cluster 2 includes the flats where the consumptions were higher. Moreover, one can observe that this difference was consistent in the data of the three sources of consumption.

Figure 14. Data consumption of the occupied flats: (a) hierarchical clustering dendrogram. (b) Scatter plot of electricity vs. water, (c) electricity vs. gas, and (d) gas vs. water.

After clustering, we sought to identify possible differences in the hygrothermal performance of the fractions belonging to each of the clusters. To this end, the electricity consumption, the air permeability, and the indoor environment related variables are presented in Table 9 separately for each cluster. As the idea was to identify whether the increase in electricity consumption resulted from seeking to improve the levels of thermal comfort through portable heating equipment, only discomfort due to low temperatures was considered in the analysis—region A (see Section 4.1—Table 8). The discomfort rate was calculated by computing the percentage of time in which temperature and relative

humidity were in region A. In the analysis, the possible impact of different occupancy profiles was not considered.

Table 9. Interior environment data (in average) by cluster.

Cluster	Occupied Flat Identification	Electricity (kWh)	Air Change Hour (h ⁻¹)	Air Temperature (°C)	Relative Humidity (%)	Discomfort Rate (%)
1	Bl.7.0.4	531	3.9	18.4	74.0	62
	Bl.7.1.6	750	6.6	19.5	67.9	49.4
	Bl.8.0.6	561	5.5	19.4	68.5	49.8
	Bl.26.0.1	519	5.3	19.3	69.1	50.4
	Bl.26.1.6	581	8.9	18.7	69.5	52
	Bl.30.2.4	744	5.3	19.1	65.5	55.3
	Bl.39.2.2	405	8.1	19.3	66.3	50.6
	Bl.42.1.2	495	7.1	19.0	69.6	57.2
2	Bl.8.1.1	2024	7.7	20.2	68.9	48.5
	Bl.9.0.6	2709	3.6	19.3	85.4	45.2
	Bl.9.3.1	1769	3.0	19.3	72.2	47.5
	Bl.30.1.4	1105	9.8	19.0	73.9	54.3
	Bl.31.2.6	1034	3.7	19.6	70.9	48
	Bl.31.3.2	1794	11.2	19.6	72.3	48.3
	Bl.39.0.2	2673	9.6	20.9	63.8	45.1
	Bl.42.1.1	1642	5.6	19.4	66.3	53.8

The differences found in terms of indoor temperature, although small in absolute terms, confirmed a trend of lower temperatures in Cluster 1 where energy consumption was also lower. However, it is important to note that the sample was very homogeneous, representative of a population from a similar socioeconomic status, and, therefore, the differences were not very pronounced. An identical conclusion was obtained from the discomfort rate analysis with a 5% reduction in Cluster 2. No relationship was found between the air permeability and energy consumption.

Figure 15 shows the relationship between electricity consumption and discomfort rates (Figure 15a) and the results of the blower door test (Figure 15b). The results confirm the trend of attaining lower values of discomfort in apartments with higher electricity consumption, presenting a coefficient of determination of 0.40. This trend was less evident in Cluster 1, which was more homogeneous, pointing to a scenario where users are apparently neutral to thermal discomfort as no additional electric devices for heating were used. According to Monteiro et al. (2017) [11], this condition is mostly the result of the fragile economic situation of the inhabitants of social housing. Future refurbishment actions should therefore be targeted to guarantee that occupants can affordably achieve comfortable conditions inside their flats.

Regarding the relationship between electricity consumption and air permeability, it was not possible to identify any pattern, since the sample had a high dispersion.

Figure 15. Scatterplot analysis: (a) thermal discomfort and electricity consumption; (b) ACH_{50} and electricity consumption; (c) thermal discomfort and ACH_{50} .

5. Conclusions

In this research, a monitoring campaign was performed to evaluate the indoor hygrothermal conditions and air permeability of a multi-residential social housing neighbourhood. Furthermore, a hierarchical cluster analysis based on energy, gas, and water consumption was carried out. The following conclusions can be drawn:

- The hygrothermal comfort of all occupied flats was assessed and long periods of thermal discomfort (average values) with indoor temperatures below 18 °C during the winter season were observed. In summer, although peak temperatures were measured (several flats reaching maximum values higher than 28 °C), the average temperatures were below 24 °C. The results of the comfort analysis carried out with the graphical method of ASHRAE 55 revealed high thermal discomfort in the majority of the occupied flats, mainly associated to low temperatures. No overheating problems were observed. Furthermore, periods of discomfort due to high levels of humidity were observed in all flats.
- In the first campaign of the air permeability assessment (C1), the ACH₅₀ average value was 6.65 h^{−1} for the occupied flats and 7.71 h^{−1} for the unoccupied flat. The standard deviation was slightly higher for the occupied flats, possibly due to the users' interventions in the building envelope, which led to different values of air permeability. The importance of the balcony areas with respect to the air permeability was identified and the lower value of ACH₅₀ is evident in that scenario.
- In the cluster analysis, two clusters of flats were identified. Cluster 2 included the flats with higher consumption, while the opposite was observed for Cluster 1. No strong correlation between electricity consumption and improvement in reducing the discomfort rate was observed.

Author Contributions: Conceptualisation, R.O., R.V., R.M.S.F.A., and A.F.; methodology, R.O., R.V., R.M.S.F.A., and A.F.; software, R.O. and A.F.; validation, R.O., R.V., R.M.S.F.A., and A.F.; formal analysis, R.O., R.V., R.M.S.F.A., and A.F.; investigation, R.O.; writing—original draft preparation, R.O.; writing—review and editing, R.O.; supervision, R.V., R.M.S.F.A., and A.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Foundation for Science and Technology (FCT)—Research Centre for Risks and Sustainability in Construction (RISCO), University of Aveiro, Portugal [FCT/UIDB/ECI/04450/2020].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable.

Acknowledgments: The authors would like to thank the City Council of Aveiro for providing information and access to the case study buildings.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. United Nations 2018 Sustainable Development Goals: Affordable and Clean Energy. Available online: <https://www.un.org/sustainabledevelopment/energy/> (accessed on 13 November 2020).
2. Directive 2010/31/EU (recast) Directive 2010/31/EU (recast) of the European Parliament and of the Council of 19 May 2010. *Off. J. Eur. Union. Eur. Commission* **2010**, 13–35. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32010L0031> (accessed on 25 August 2021).
3. Directive 2018/844/EU Directive 2018/844/EU of the European Parliament and of the Council of 30 May 2018. *Off. J. Eur. Union* **2018**, 75–91. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG (accessed on 25 August 2021).
4. Pfeiffer, A.; Koschenz, M.; Wokaun, A. Energy and building technology for the 2000 W society—Potential of residential buildings in Switzerland. *Energy Build.* **2005**, *37*, 1158–1174. [[CrossRef](#)]
5. European Commission. *Energy Efficiency in Public and Residential Buildings*; European Commission: Brussels, Belgium, 2015.

6. Alves, S.; Andersen, H.T. Social housing in Portugal and Denmark: A comparative perspective. In Proceedings of the European Network for Housing Research (ENHR), Lisbon, Portugal, 28 June–1 July 2015; pp. 1–18.
7. Evans, G.W.; Kantrowitz, E. Socioeconomic Status and Health: The Potential Role of Environmental Risk Exposure. *Annu. Rev. Public Health* **2002**, *23*, 303–331. [[CrossRef](#)]
8. Alonso, C.; Oteiza, I.; Martín-Consuegra, F.; Frutos, B. Methodological proposal for monitoring energy refurbishment. Indoor environmental quality in two case studies of social housing in Madrid, Spain. *Energy Build.* **2017**, *155*, 492–502. [[CrossRef](#)]
9. World Health Organization. *WHO Guidelines for Indoor Air Quality: Dampness and Mould*; World Health Organization: Geneva, Switzerland, 2009.
10. Ramos, N.M.M.; Almeida, R.M.S.F.; Simões, M.L.; Delgado, J.M.P.Q.; Pereira, P.F.; Curado, A.; Soares, S.; Fraga, S. Indoor hygrothermal conditions and quality of life in social housing: A comparison between two neighbourhoods. *Sustain. Cities Soc.* **2018**, *38*, 80–90. [[CrossRef](#)]
11. Monteiro, C.S.; Causone, F.; Cunha, S.; Pina, A.; Erba, S. Addressing the challenges of public housing retrofits. *Energy Procedia* **2017**, *134*, 442–451. [[CrossRef](#)]
12. Guerra-Santin, O.; Bosch, H.; Budde, P.; Konstantinou, T.; Boess, S.; Klein, T.; Silvester, S. Considering user profiles and occupants' behaviour on a zero energy renovation strategy for multi-family housing in the Netherlands. *Energy Effic.* **2018**, *11*, 1847–1870. [[CrossRef](#)]
13. Guerra-Santin, O.; Boess, S.; Konstantinou, T.; Romero Herrera, N.; Klein, T.; Silvester, S. Designing for residents: Building monitoring and co-creation in social housing renovation in the Netherlands. *Energy Res. Soc. Sci.* **2017**, *32*, 164–179. [[CrossRef](#)]
14. Escandón, R.; Suárez, R.; Sendra, J.J. On the assessment of the energy performance and environmental behaviour of social housing stock for the adjustment between simulated and measured data: The case of mild winters in the Mediterranean climate of southern Europe. *Energy Build.* **2017**, *152*, 418–433. [[CrossRef](#)]
15. Ioannou, A.; Itard, L.; Agarwal, T. In-situ real time measurements of thermal comfort and comparison with the adaptive comfort theory in Dutch residential dwellings. *Energy Build.* **2018**, *170*, 229–241. [[CrossRef](#)]
16. Ioannou, A.; Itard, L. In-situ and real time measurements of thermal comfort and its determinants in thirty residential dwellings in the Netherlands. *Energy Build.* **2017**, *139*, 487–505. [[CrossRef](#)]
17. Oliveira, R.; Figueiredo, A.; Vicente, R.; Almeida, R.M.S.F. Impact of unoccupied flats on the thermal discomfort and energy demand: Case of a multi-residential building. *Energy Build.* **2020**, *209*, 109704. [[CrossRef](#)]
18. ISO. *EN ISO 7730. Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort using Calculation of the PMV and PPD Indices and Local thermal Comfort Criteria*; ISO: Geneva, Switzerland, 2005.
19. Kalamees, T. Air tightness and air leakages of new lightweight single-family detached houses in Estonia. *Build. Environ.* **2007**, *42*, 2369–2377. [[CrossRef](#)]
20. Meiss, A.; Feijó-Muñoz, J. The energy impact of infiltration: A study on buildings located in north central Spain. *Energy Effic.* **2014**, *8*, 51–64. [[CrossRef](#)]
21. Bell, M.; Lowe, R. Energy efficient modernisation of housing: A UK case study. *Energy Build.* **2000**, *32*, 267–280. [[CrossRef](#)]
22. Diaz Lozano Patino, E.; Siegel, J.A. Indoor environmental quality in social housing: A literature review. *Build. Environ.* **2018**, *131*, 231–241. [[CrossRef](#)]
23. ISO. *EN ISO 13829. Thermal Performance of Buildings: Determination of Air Permeability of Buildings—Fan Pressurization Method*; ISO: Geneva, Switzerland, 2013.
24. ISO. *ISO 9972. Thermal Performance of Buildings—Determination of Air Permeability of Buildings—Fan Pressurization*; ISO: Geneva, Switzerland, 2015.
25. Pan, W. Relationships between air-tightness and its influencing factors of post-2006 new-build dwellings in the UK. *Build. Environ.* **2010**, *45*, 2387–2399. [[CrossRef](#)]
26. Sinnott, D. Dwelling airtightness: A socio-technical evaluation in an Irish context. *Build. Environ.* **2016**, *95*, 264–271. [[CrossRef](#)]
27. Fernández-Agüera, J.; Sendra, J.J.; Domínguez, S. Protocols for Measuring the Airtightness of Multi-Dwelling Units in Southern Europe. *Procedia Eng.* **2011**, *21*, 98–105. [[CrossRef](#)]
28. Ramos, N.M.M.; Almeida, R.M.S.F.; Curado, A.; Pereira, P.F.; Manuel, S.; Maia, J. Airtightness and ventilation in a mild climate country rehabilitated social housing buildings—What users want and what they get. *Build. Environ.* **2015**, *92*, 97–110. [[CrossRef](#)]
29. Fernández-Agüera, J.; Domínguez-Amarillo, S.; Sendra, J.J.; Suárez, R. An approach to modelling envelope airtightness in multi-family social housing in Mediterranean Europe based on the situation in Spain. *Energy Build.* **2016**, *128*, 236–253. [[CrossRef](#)]
30. Fernández-Agüera, J.; Domínguez-Amarillo, S.; Sendra, J.J.; Suarez, R. Predictive models for airtightness in social housing in a Mediterranean region. *Sustain. Cities Soc.* **2019**, *51*, 101695. [[CrossRef](#)]
31. IPMA (Instituto Português do Mar e da Atmosfera). Available online: <http://portaldoclima.pt/pt/> (accessed on 1 February 2017).
32. ISO. *EN ISO 7726. Ergonomics of the Thermal Environment. Instruments for Measuring Physical Quantities*; ISO: Geneva, Switzerland, 2001.
33. Oliveira, R.; Figueiredo, A.; Almeida, R.; Vicente, R. Airtightness and summer thermal discomfort in social housing—A Portuguese case study. In Proceedings of the 42th IAHS World Conference on Housing—The housing for the dignity of mankind, Naples, Italy, 10–13 April 2018; p. 89.

34. Figueiredo, A.; Oliveira, R.; Vicente, R.; Almeida, R.; Janeiro, C. Linking thermal building behaviour with human occupation. In Proceedings of the 42th IAHS World Conference on Housing—The Housing for the Dignity of Mankind, Naples, Italy, 10–13 April 2018; p. 127.
35. Sinnott, D.; Dyer, M. Airtightness and Ventilation of Social Housing in Ireland—A review of Field Measurements and Occupant Perspectives Pre- and Post- Retrofit. In Proceedings of the 34th AIVC Energy Conservation Technologies for Mitigation and adaption in the Built Environment: The Role of Ventilation Strategies and Smart Materials, Athens, Greece, 25–26 September 2013.
36. ASHRAE. *Standard 55—Thermal Environmental Conditions for Human Occupancy*; ASHRAE: Peachtree Corners, GA, USA, 2013.
37. Ward, J.H. Hierarchical Grouping to Optimize an Objective Function. *J. Am. Stat. Assoc.* **1963**, *58*, 236–244. [[CrossRef](#)]
38. Kaufman, L.; Rousseeuw, P. *Finding Groups in Data: An Introduction to Cluster Analysis*; John Wiley & Sons, Inc.: New York, NY, USA, 1990; ISBN 9780470317488.