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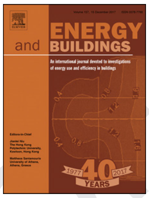

Social housing airtightness in Southern Europe

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ABSTRACT

An extensive airtightness measurement has been carried out on 159 social housing units built in southern Spain. The sample includes homes from multifamily buildings built since the origin of social housing models in 1950, through to the most recent examples developed under EPBD compliance requirements. Testing was developed between 2012–2017 using the standardised Blower Door pressurisation technique. The main purpose of this research is to present a wide-ranging, exhaustive study on the airtightness performance of social housing built in southern Spain; these properties are representative of other locations in southern Europe due to both to their climate conditions and their socio-economic and cultural component. The general performance of the housing stock in terms of normalised permeability at 50 Pa shows a mean value of 7 h^{-1}, similar to that found in other areas in Southern Europe, although with very significant variability between properties which are airtight and those which are highly permeable, all within a housing stock which is similar in terms of type and construction. Based on this information, it has been possible to develop a representative probabilistic description of the housing stock. The study provides useful information on the influence climatic location of buildings as well as age and other and other morphological and constructive parameters of residential buildings.

1. Introduction

Envelope airtightness is perhaps one of the most important parameters for defining ventilation processes in buildings [1]. This airtightness, although it affects many aspects, is the determining factor with regards to infiltration. Determination of infiltration performance is therefore based fundamentally on analysis of the airtightness of buildings [2,3]. Understanding and characterising airtightness, as well as identifying air leakage pathways in housing stock, is fundamental in order to prioritise both research and intervention efforts, and to design policies to improve the housing stock by decision-makers in the public and private sectors. This is a critical aspect in terms of the European Union's decarbonisation strategy, developed through the 2030 and 2050 strategies, which place special emphasis on adapting existing housing stock.

The most widely-accepted method in the scientific community for evaluating airtightness is the pressurisation and depressurisation test, known as the Blower Door Test. Although single-family properties have been widely studied over the last three decades, there is limited information on airtightness in multifamily dwellings, especially in the Southern Europe area.

Research into the airtightness of the envelope of buildings, mainly residential buildings, is highly developed in the USA [2,4–7], where the most comprehensive databases and the widest variety of infiltration models are available. The Lawrence Berkeley National Laboratory (LBNL), in collaboration with the US Energy Department, has generated a database with more than 100,000 analyses, mainly single-family dwellings, based on airtightness test measurements carried out using pressurisation/depressurisation techniques throughout the country over several decades. This database, where the main variables influencing airtightness have been studied, both for existing properties [1,8,9] and new-builds [7,10,11], contains several analyses which are worthy of note. These studies have allowed the airtightness of the properties built in different periods to be characterised quantitatively, regionally and typologically. However, these databases include basically single-family houses, as opposed to the predominance of collective housing buildings in southern Europe [12], mainly apartment buildings or blocks of flats — multi-unit blocks mainly constitute the whole of social housing, as well as specific construction types and techniques, climates and socio-cultural factors, which makes it difficult to apply the general models derived from these studies.

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Northern and central European countries are particularly worthy of note, as they have a more deeply rooted tradition of controlling the airtightness of properties. The research carried out in Ireland [13,14], an in-depth study presenting the results of the air permeability test of 28 single-family properties built between 1944 and 2008, each in different stages of refurbishment, is of particular interest, along with other studies in the United Kingdom [15] and Estonia [16].

The research carried out in France focuses on central and southern Europe [17–21]. Researchers have typically focused on determining air leakage paths and studying the airtightness patterns for different types of construction and insulation, both in single-family and some multi-family dwellings. There is also a series of studies carried out on small samples in the European Mediterranean area, such as those for Greece [22], Italy [23] and Portugal [24–27].

In northern Spain there is a study of 120 new-build properties (EPBD-compliant), but these are not very representative of actual housing stock [28]. This same area of the north of the Iberian Peninsula is also the subject of research by the University of Valladolid on social properties [29] and a methodology to Spain [30], along with studies that evaluate the energy impact of airtightness and age of air [31].

We developed a previous study in the southern Spain area analysing recently built open gallery residential buildings, where we refined methodology and located main leakage pathways, which allowed to propose an initial airtightness predictive model for this building-type [32].

The main purpose of this research is to present a wide-ranging, comprehensive study on the airtightness-performance of the multi-family housing stock in Andalusia — block of flats. This can be very representative of other locations in southern Europe due both to climatic conditions [30] — the region includes a set of climates that represent the majority of those present in the Mediterranean area- and the sharing of similar socio-economic and cultural components [34,35].

This study deals with current regional social housing stock. This includes housing from 1950 (the origin of today social housing types) when public policies that raise the construction of this type of housing are put in place as a response to the housing problem in the large cities after the Spanish Civil War and the continuous migratory flows from the countryside to the city, through to the most recent examples of social housing. Having been developed throughout southern Spain, the study provides a wide range of data, both for comparison between groups and as representation of the influence of the climate and of different local uses. A detailed description of the types of buildings that make up this period (and which have been a fundamental part of the sample under study), as well as their construction characteristics, can be found in the inventory of social envelopes prepared by the University of Seville, which, although centred on the city of Seville, can be extrapolated to a large extent to other urban centres in the southern European region [33].

2. Methods

2.1. Sampling

Stratified random sampling has been carried out to select buildings that are part of the sample for the pressurisation/depressurisation tests. The sample has been stratified in this work according to the two main attributes considered with the greatest potential to establish differences [9,23] interms of the buildings envelope's construction solutions: firstly, climatic zone location and, secondly, the time period of building regulations [34]. Those drive parameters may have the possibility of determining the behaviour of the envelope when establishing the usual geometrical parameters as well as the possible constructive particularities of each zone. In accordance with the identified characteristics at housing stock level and the different groupings, the size of the sample used is 159 dwellings from collective housing buildings which have been identified as particularly representative of the building types, their evolution and their geographical distribution — hence climate response. Several home-units have been chosen within the same building-development, to identify variations within the sample that share identical construction and typological characteristics.

Although the regional climate can generally be defined as Mediterranean (Köppen: *Csa),* there are several different variants in the area [35,36], covering *Bsh* areas in transition to *Bwh* (Almeria area), through others where the *Csa* type transitions to *Bsk* (Granada area). However, climatic zoning associated with the national energy labelling procedure has been adopted for a more detailed classification, as it provides a greater degree of subregional detail [37]. The buildings chosen were in different climate areas within the region, with winters ranging from very mild (zone A) to cold (zone C), and summers from warm (zone 3) to hot (zone 4). The selected building complexes, or building-sample groups, located in the five most representative climatic zones of the region. Although Andalusia has a wide range of climatic zones, we have select the most common ones, i.e. where most of the properties in the region are concentrated.

As initial hypothesis of the sample treatment the possibility of groupings in the airtightness patterns is considered, based mainly on the temporary period of its construction, more specifically on the different building and design regulations, as well as the influences in the constructive modes of the climatology of the area (for each location), as previous studies have seem to indicate [30,32]. Regulations can be divided in three time-periods. An initial one where, despite different standards on design, there are no effective measures to control building envelopes [34]. This period runs from the end of the Second World War to the end of the 1970s. It was at this point that, due to the energy crisis of the 1970s, the vast majority of European countries introduced the first energy regulations associated with the performance of buildings [38,39] (in the case of Spain, in 1979), where envelope requirements and the general introduction of thermal insulation layers modifies usual fabrics construction [40]. This intermediate period covers the post-oil crisis developments up to the implementation of the EPBD in the first decade of the 2000s where a general improvement of the thermal envelope is expected. The three regulatory-groups to be considered will therefore be: pre-79, post-79 and EPBD-compliant (CTE 06). Social collective housing in the area share many similarities, especially in terms of size and functional program, being constrained by the specific regulations derived of state protection (a comprehensive study of size, construction and morphology aspects of social multifamily buildings has been developed in [34] and [33]) allowing proper comparison of the population of this stock.

The housing population of the region (N) is composed by 568,455 homes (from collective housing buildings). The sample, which we will call n, is a subset of the population N. Since this is an experimental research project with regional scope which aims to establish a normal distribution, it has been determined that the sample size most in line with our exploratory field should be around 150 units — in this case flats. The sample size was finally set at 159 units after considering the established sizes of the properties to be selected within the building. Once the results are obtained, population variance, and, in consequence, errors in the selection of the 159 sample units, can be known by means of the equation:

$$e = \sqrt{\frac{z^2\sigma^2}{n}} \quad (1)$$

Table 1
Number of social dwellings built and studied according to climatic zone in Andalusia.

Climatic zone	No. social dwellings built	No. social dwellings of the sample	% social dwellings built	% social dwellings of the sample
A3 (Csa)	189,838	40	33	25
A4 (Csa, Bsh)	64,645	16	11	10
C3 (Csa > Bsk)	35,248	14	6	9
C4 (Csa)	21,408	13	4	8
B4 (Csa)	257,316	76	45	48
TOTAL	**568,455**	**159**	**100**	**100**

Table 2
Working life per year of construction for the population.

Year of construction	Working life	Accumulated working life	Percentage established
1950–1980		150	37
1950–1960	40		
1960–1970	50		
1970–1980	60		
1980–2010		240	51
1980–1990	70		
1990–2000	80		
2000–2010	90		
Total	390		88

Table 3
Number of social dwellings built and studied according to Andalusia building regulations.

Regulations	No. social dwellings built	No. social dwellings of the sample	% social dwellings built	% social dwellings of the sample
Pre-79	271,206	54	48	34
Post-79	272,529	86	48	54
EPBD-compliant	24,720	19	4	12
TOTAL	568,455	159	100	100

The sample items have been chosen randomly to ensure they have the same likelihood of being chosen. The selection procedure involved identifying different strata (a total of twelve) for the climatic zone combination (Table 1) and applicable standards (Table 3). A fundamental aspect in the distribution of the chosen samples is the representation of the different climatic zones that make up the Andalusia region, to analyse the possible influence of the location and the climate performance of the different sets of buildings.

Table 1 shows the frequency and percentage of properties belonging to the sample for the climatic zones considered: A3 (40 cases), A4 (16 cases), B4 (76 cases), C3 (14 cases) and C4 (13 cases). The percentages of the properties in the sample show similar results to those of the population, except for the redistribution carried out so that climatic zone C3 has a minimum of 3 buildings and 13 cases, and there is at least one case per climatic zone for each of the two main regulatory periods.

To design the sample set with respect to applicable regulations, it was deemed appropriate to establish a bias in the groups, since, if we consider the life expectancy of these buildings to be 100 years under normal conditions and within the economic parameters (Table 2), it is the 1979–2010 group that has most impact on the current stock of properties, due to its projected longer working life in the future.

The sample set has been classified and grouped according to the regulatory period, the distribution of which is shown in Table 3. Both the intermediate and the more recent group have been given priority, in proportion to their expected working life and greater future influence on social housing building stock.

The data on the different buildings, such as year of construction, climatic zone, regulations and number of properties measured, are set out in annex 1.

2.2. *Pressurisation and depressurisation tests*

The evaluation of each building was carried out by testing different houses of the same. The airtightness of each flat was measured with the standardised fan pressurisation method [18] and the specific methodology developed in [41]. The “Minneapolis Blower Door Model 4” equipment was used with an automated performance testing system (flow range at 50 Pa 25–7800 m^3/h, accuracy ± 3%). Depressurising and pressurising tests were carried out to determine the airtightness of the building envelope. All the exterior openings: windows and doors were closed; ventilation ducts were sealed. Measurements were made at 5 Pa pressure difference steps from 20 to 70 Pa. The bases for the measurement were developed based on UNE EN 13829:2002 [42] Method B test was considered more representative when categorising the sample, as it represents the performance of the property’s general envelope. This is the most commonly established procedure in the European area. However, these procedures present some constraints for a complete characterisation of the envelope throughout the test. In order to ensure better adaptation to the performance of multi-flat l buildings, a set of complementary methods have been incorporated into the previous base method. In [41] we develop a methodology with adapted protocols to test individual flats within a building, allowing the discrimination between the outdoor-leakage and the leakage to other inner-zones. In this kinds of multi-flats buildings, the percentage of air leakage to other building areas outside the flat is around 1.6–8.4% of the total (Table 4x). This procedure has been validated previously in [32] and backed by Jesús et al. [30].

The analysis and treatment of the data obtained from the blower door tests have been based on the procedures and methods validated by Sherman [6]. The airtightness performance of the housing envelope will be defined fundamentally by its air change

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Table 4
Air flow to other building areas outside the flat.

Leakage paths	Air flow (m3/h) [min-max]	% of the total [min-max]
In contact with common areas	21–125	1.25–6.78
Adjacent dwellings	30–60	1.6–3.6
Total	81–155	1.6–8.4

rate at 50 Pa [n_{50}] and its flow exponent [n], as the main parameter representing the airtightness of the properties analysed, since normalisation of this parameter allows comparison with properties of different sizes and geometries. The building's floor area and height (and, therefore, its volume) are parameters considered during the test. This parameter, unlike most studies carried out in the US, is widely used in analyses of the European regional area [43–45].

3. Results

3.1. General assessment of the sample

The measurements have been made considering the different sealing conditions of each home [41], which has allowed to individualize the specific behaviour of the different components of the dwelling. However, test-method B has been considered the most representative to categorize the sample, as this represents the normal operational conditions of the dwelling envelope.

The general parameters of the sample — B method — are represented grouped by building-development. Table 4 shows the basic parameters of the tests, having adopted the mean value between those obtained in the pressurisation and depressurisation tests, since their variability is lower than the accuracy of the equipment used (5%) (Table 5).

On the total air flow exchanged (V_{50}), the sample performance values identify a mean value per property of 978 m^3/h (Method B, at 50 Pa). However, their variability is high in all cases, with a large global standard deviation value (σ: 453 m^3/h), with widely differing extreme values, ranging from 377 to 2892 m^3/h, i.e. between a minimum value of about half the median and a maximum value approximately equivalent to three times the median value. This factor is strongly influenced by the size of the property, and does not provide any specific information on the actual degree of airtightness of the property compared to the general group (Table 6a).

The results of the airtightness tests on the whole sample have been weighted by their volume, obtaining the n_{50} parameter, allowing the inter-comparison of flats with different characteristics. Although a virtually linear relationship between the two values would be expected, some distortion can be identified in the higher range values (Table 6b). There is a suitable linearity adjustment (square-R: 96.6%; p-value < 0.05) since the points are distributed randomly around the observations-predictions boundary, with no curvature identified in the values. However, the variability is only partially constant, due to alterations in the higher-value region, where divergence increases. If the Z-score of the result of the normalised air rate is evaluated relative to volume (n_{50}), the presence of a certain linear relationship can be identified which, although significant, is weak as a predictor variable ($p < 0.05$.); R^2:5.58%). This aspect indicates that there may be a certain distortion in the comparison of properties (introduction of bias in the normalisation) at the extremes (properties with little interior volume compared to those with high volumes), possibly over-estimating height in properties as an influential factor, even though the influential points show moderate leverage ($3 < l < 5$). This aspect must be considered as an uncertainty in assessing the extreme components of the sample.

The median value for the air change rate at 50 Pa is 6.52 h^{-1}, with a mean value of 7.01 h^{-1}. As in the previous parameter, the dispersion is noticeable among the groups of buildings, and, particularly importantly, among flats in the same building. The mean amplitude value, expressed in terms of standard deviation, is σ: 2.59 h^{-1}, which may be considered high, with a 37% coefficient of variation (Fig. 1).

In the individual dwellings value distribution while the standardised kurtosis and bias values (Table 6) may be associated with a normal one (in the range 2 to −2), differences in standard deviation and coefficients of variation indicate that, from a behavioural point of view, the sample may include sub-populations, aspect of special interest for a further development of predictive models. The grouping towards low n_{50} values (left of the distribution) at the peak in the density curve generates a bias in the distribution, which is reflected in the standardised bias parameter. The dispersion observed in the values for n_{50}, mainly in the intra-group analysis — same building development and common characteristics, can be attributed to the stochastic component which is inherent in the construction of the buildings studied, although this factor will be analysed later to segregate this variable component from those factors associated with morphological or construction patterns. The typical buildings characteristics for this stock is described in [46], with relatively little influence of factors of binary factors as elements as air barrier — not used in the area —, neither different construction solutions on basements and similar, although relative position of dwellings within the building will analysed later.

It is therefore possible to establish that the sample — as a whole — does not fit well to normal performance and is always positive, and biased, with left asymmetry (typical scenario of environmental phenomena with a high stochastic component [47]). Use of normal distributions — at individual dwelling levels — is not always appropriate in this case, and the alternative of transforming the data may result in loss of information or detail. It is therefore possible to use multivariate models based on asymmetric distributions [48]. The Birnbaum-Saunders (BS) distribution, which is used extensively in representing physical phenomena, has been identified as particularly suitable (p-value for rejection > 0.05) for describing this model, given its given its proximity to the inverse Gaussian function [49] (Table 7).

At building grouping level there are groups that reach extreme average values of up to almost 16 h^{-1}; such as the case of some properties from the 1970 s. The lowest air change rate at 50 Pa values are found in EPBD-compliant new-buildings in the coldest areas (median of 2.74 h^{-1} and minimums of almost 2.5 h^{-1}), and in recently refurbished buildings, with a median value of 3.00 h^{-1}.

The following can be identified in the study sample (Fig. 2): significantly *leptokurtic* behaviours, with a significant grouping around their own central values, as in the case of groups P15 or P28, or, conversely, *platykurtic* distributions, with low concentration around the central and values and widely distributed, as in groups P4, P14 or P34, as well as actions that can be associated with typically *mesokurtic* behaviours (associated with *normal* distributions), as in the case of P23 or P35. Outliers can also be identified in two of the groups (P 32 and P 33). In the first case, this indicates the presence of construction systems coherent with results associated with their morpho-constructive characteristics,

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Table 5
Statistical values of the main parameters resulting from the pressurisation and depressurisation tests (average values grouped by development).

Sample		V_{50} (m^3/h)		n_{50} (h^{-1})					
ID.	**No. prop.**	**Med**	***std***	**Med**	***std***	**Coefficient Variation**	**Range**	**Standard Bias.**	**Standard Kurtosis**
1	4	758	*73.41*	5.13	*0.39*	0.087	1.071	0.725	0.471
2	3	1,038	*44.58*	7.93	*0.34*	0.054	0.764	-1.159	
3	3	954	*89.82*	5.73	*0.57*	0.118	1.368	0.635	
4	4	1,054	*198.87*	6.58	*1.01*	0.175	2.58	0.297	-1.073
5	4	951	*142.52*	6.89	*1.03*	0.173	2.824	0.013	-0.121
6	1	1,025	*0*	3.89	*0*				
7	1	1,675	*0*	13.14	*0*				
8	3	807	*296.11*	7.68	*2.82*	0.368	6.245	1.187	
9	2	1,053	*44*	7.16	*0.16*	0.032	0.323		
10	2	651	*16*	3.01	*0.13*	0.062	0.265		
11	1	1,277	*0*	11.62	*0*				
12	1	1,294	*0*	10.12	*0*				
13	3	880	*23.51*	6.24	*0.54*	0.112	1.164	-1.217	
14	4	1,184	*440.68*	7.32	*1.92*	0.291	4.65	0.342	-1.392
15	3	1,040	*174.17*	9.48	*1.58*	0.224	3.599	-1.112	
16	2	1,564	*139*	12.3	*1.09*	0.126	2.186		
17	1	1,876	*0*	11.8	*0*				
18	1	2,624	*0*	14.68	*0*				
19	2	830	*50*	5.11	*0.31*	0.085	0.615		
20	4	925	*371.56*	6.46	*2.59*	0.409	6.913	1.261	1.181
21	4	929	*226.03*	6.8	*1.65*	0.26	4.304	1.129	0.72
22	4	824	*201.13*	4.36	*0.53*	0.139	1.46	0.712	0.429
23	8	1,455	*204.13*	8.41	*1.13*	0.136	3.218	1.373	-0.062
24	8	635	*37.35*	6.46	*0.38*	0.062	1.15	0.774	-0.382
25	8	739	*75.01*	3.93	*0.34*	0.093	1.186	-0.71	0.395
26	1	2,892	*0*	15.57	*0*				
27	7	1,480	*135.64*	8.45	*0.86*	0.107	2.524	0.496	-0.465
28	10	1,439	*202.28*	9.06	*1.38*	0.153	4.313	1.198	-0.043
29	8	826	*82.93*	5.3	*0.51*	0.106	1.571	-0.744	-0.31
30	7	719	*201.88*	4.17	*0.87*	0.199	2.37	0.901	-0.562
31	5	1,531	*172.9*	8.37	*0.09*	0.012	0.257	0.118	-0.263
32	8	1,281	*127.49*	6.9	*0.69*	0.104	2.254	1.869	1.735
33	8	823	*90.53*	4.7	*0.52*	0.117	1.873	-0.347	0.805
34	5	1,281	*78.43*	7.38	*0.48*	0.07	1.063	0.531	-1.476
35	8	886	*70.39*	4.95	*0.28*	0.061	0.925	-0.438	-0.017
36	7	1,995	*342.66*	9.95	*1.64*	0.169	4.983	1.916	1.598
37	4	486	*53.14*	2.74	*0.48*	0.19	1.233	1.315	1.054
Tot	159	978	*452*	6.52	*2.59*	*0.371*	*13.06*	***4.11***	*1.317*

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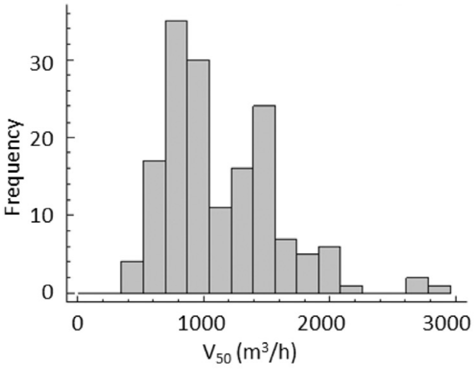
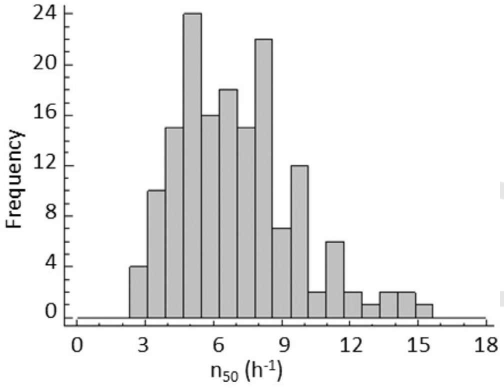
Table 6
V_{50} and n_{50} histograms.





Mean: 1128	*Mean: 7.01*
Median: 978	*Median: 6.52*
Standard Deviation: 453	*Standard Deviation: 2.59*
Coefficient of Variation: 40.17%	*Coefficient of Variation: 37.07%*
Minimum: 377	*Minimum: 2.50*
Maximum: 2892	*Maximum: 15.56*
Standardised Bias: 5.95	*Standardised Bias: 4.11*
Standardised Kurtosis: 4.39	*Standardised Kurtosis: 1.32*

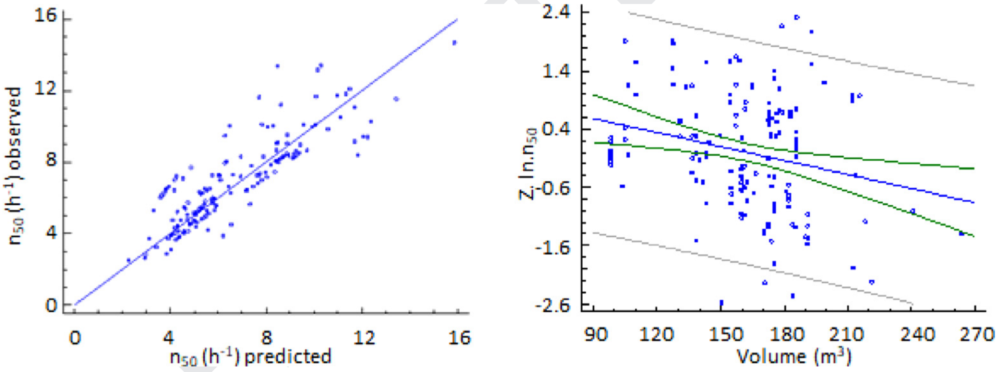


Fig. 1. Correlations between n_{50} and V_{50}.

along with greater potential for establishing predictive procedures for the results. In the second case, this indicates the presence of a larger random component within the units which make up the building groups, where airtightness depends not only on reproducible aspects but also on other individual influences which are more difficult to control and evaluate.

The lowest variability can be found in a group of recent construction (2012), with the greatest variation being in properties from the 1960s, standing at around 40% (Fig. 2). This aspect appears to indicate a strong connection between variability and age of the properties, which can be associated with the different processes of deterioration and individual evolution of the units. However, this aspect is not entirely generalizable, as there are old building developements with little variation, and contemporary buildings with wide ranges.

The present findings have been contrasted with the results of previous studies on collective properties carried out in southern Europe (Table 8). Sample values from single-family homes, as well as from those studies with a small number of cases, have been discarded for the sake of representativeness. The n_{50} values of the different studies are shown in Table 7 (mean, minimum and maximum values of the samples), as well as the number of properties tested to establish the representativeness of these values.

This comparison shows that the average values of n_{50} for the sample properties are centrally positioned relative to those obtained in similar studies carried out in southern Europe. Indeed, a representative value of this indicator of approximately 7 h^{-1} is obtained for housing stock in Southern Europe. However, the dispersion observed in the n_{50} values in the sample is significant, it being higher than the values recorded in databases of other southern regions. This may be due to the bigger size of our sample and the fact it includes buildings with a range of construction types from different periods, an aspect which may be overlooked in some databases of similar size (greater possibility of bias produced by a specific type of building in the sample). In general, the values with the lowest air permeability (low values of n_{50}) are obtained in the most modern buildings, especially those adapted to comply with the EPBD. In general terms, when the oldest dwellings groups are included, the recorded n_{50} values are higher than required in design standards of northern and central Europe countries, where airtightness of residential buildings (normally ranging between 3 h^{-1} and 4 5 h^{-1}) has traditionally been highly regulated [50]. Some properties in southern Spain – not necessarily the most modern ones – had n_{50} values which are almost as low as these standards, while, in contrast, the least airtight properties are over four times higher than these references. Although older buildings

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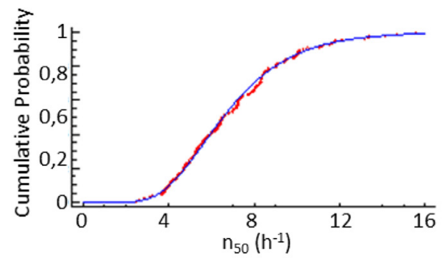
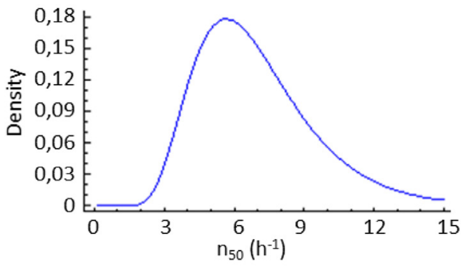
Table 7
Adjustment of the n_{50} sample to the Birnbaum-Saunders distribution.

 *Cumulative likelihood for n50*	 *Likelihood density function for n_{50} (BS distribution).*
$$f(x)=\frac{\sqrt{\frac{x-\mu}{\beta}}+\sqrt{\frac{\beta}{x-\mu}}}{2\gamma\left(x-\mu\right)}\phi\left(\frac{\sqrt{\frac{x-\mu}{\beta}}-\sqrt{\frac{\beta}{x-\mu}}}{\gamma}\right)$$	Birnbaum-Saunders adjusted distribution form = 0.369 scale = 6.512

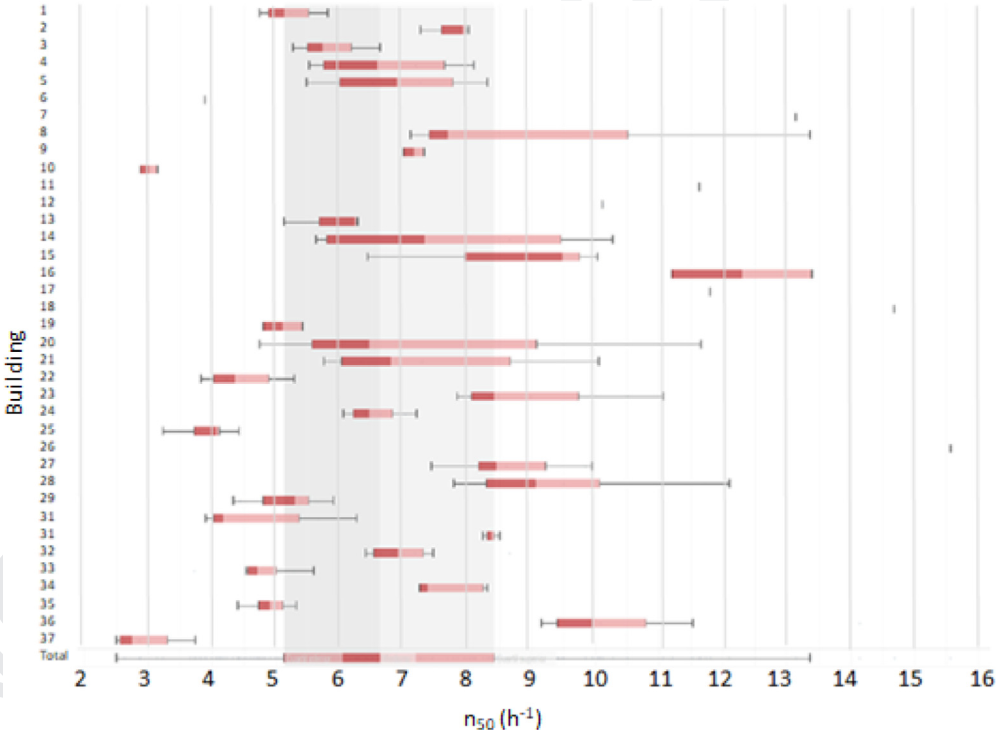


Fig. 2. Box plots of the air change rate at 50 Pa (n_{50}) by development.

predominate, this latter group also includes relatively recent buildings. This consideration indicates that there is significant potential for reducing the porosity of the envelope within the housing stock, and this situation, as identified, shows great similarities to the Mediterranean area.

3.2. Influence of parameters on airtightness

The selection of the most influential parameters in the air tightness of buildings has been made following the indications provided by a recent international review [49]. Because the object of study of this thesis focuses on multi-family dwellings, and all those that constitute the study sample have been built with the same constructive system of pillars and concrete slabs, the parameters that have been considered appropriate for the study, and their classification, are those represented in Fig. 3.

3.2.1. Relation to climatic zones

For proper comparison of the possible underlying data structures, the z-score of the transformed values were analysed for adjustment to a normal distribution (log) of n_{50} [m^3]. When applying a complete randomness hypothesis in the distribution of results, i.e. understanding that it is possible to obtain any value in all climatic zones, this would indicate that all properties belong to the same group and there is no organisational structure: z-value scores above 1.65 would indicate a significance outside of random-

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Table 8
Airtightness parameters in tests on collective properties in Southern Europe.

Country	Study	Type	Test Year	No. tests	n_{50} (h^{-1}) mean	n_{50} (h^{-1}) minimum	n_{50} (h^{-1}) maximum
Italy	1 [22]		2011	20	7.3	3.2	10.6
	2 [22]	Refurbished	2011	6	4.9	2.1	6.4
Portugal	3 [25]	Refurbished		25	6.8	3.2	13.0
	4 [25]	Not Refurbished		24	8.9	3.8	15.0
Greece	5 [45]		2005	40	6.7	1.87	13.1
North Spain	6 [28]	New buildings	2017	9	7.1	3.23	13.4
	7 [27]	EPBD-compliant	2013	120	3.5	0.8	6.8
South Spain	8 [33]	Open Gallery	2013–2015	45	5.7	3.2	8.7
	9	Actual stuty	2013–2017	159	7.0	2.8	15.6

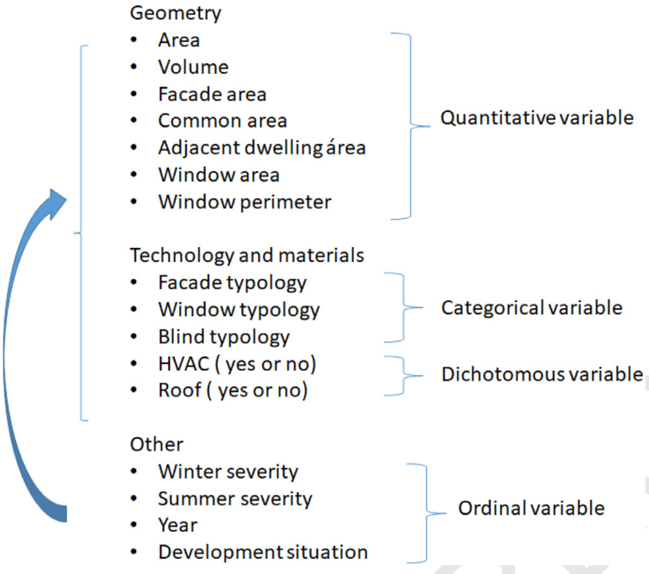

Fig. 3. Classification of selected parameters.

Table 9
Correlation between n50 and geometric parameters.

	A_{FAC}	A_{ADJ}	A_{AC}	P_W	A_W
n_{50} MB	−0.199	−0.0358	0.3017	−0.1594	−0.1096
Std.	0.0125	0.6523	0.0001	0.0451	0.1684

ness ($p < 0.10$ for $z > |1.65|$ and $p < 0.05$ for $z > |1.96|$); it would be unlikely that the pattern of performance comes from a random process for a given level of significance [52]. The results of this analysis have been grouped together (Fig. 4) both by specific climatic zone (a) and for winter (b) and summer (c) severities. The null hypothesis would be that all the results belong to the same group and have no localisation pattern.

The analysis of these subsets does not reveal a defined pattern of performance, since, in the analysis by climatic zones (Fig. 4a), although the lowest n_{50} values can be associated with one of the coldest zones (C3), reaching values below 3 h^{-1}, the dispersion of values is highly significant. The mean distribution values of this set are above those of the A4 zone. The lowest airtightness results are found in a temperate zone (B4), an intermediate position in terms of climatic severity in winter, where they exceed 14 h^{-1} and have a central value above 7 h^{-1}. This is followed by the C4 zone (severe winter and severe summer), with highly concentrated values around the central positions above 7 h^{-1}.

The analysis of the distributions of each of the climatic zones, while indicating that several sub-populations coexist, does not seem to be directly linked to the zones, nor is there any evidence of a possible hierarchical relationship: groupings C3–A4; A3–C4;C4–B4 (not rejectable at 95% for $p > 0.05$).

If the results are grouped together according exclusively to the severity of the winter weather (Fig. 4b), the lower airtightness results are associated with the coldest areas (winter severity C: w.C), although with significant variability, especially in the central quartiles, with values ranging from just under 4 to over 7 h^{-1}, showing very similar performance to that of the mildest winter areas (w.A.). However, this pattern is not identified in the sequence from zone w.B to w.A, reaching the maximum permeability values in the w.B severity zone, but with a very wide range of responses, including values below 5 h^{-1}. Most of the values of the three distributions are located within the randomness zone (central quartiles and most of the outer quartiles), with only some of their extreme values being significant. Both zone w.A relative to w.B (K-S p:0.0021), and w.B relative to w.C (K-S p:0.0044), can be assumed as independent distributions (*p-values* < 0.05), but it cannot be refuted that zone w.A and w.C – hot and cold – (K-S p:0.47) actually represent the same distribution (Fig. 4b) This aspect invalidates the assumption – apparently intuitive – that there is a gradation of airtightness in accordance with the severity of winter.

In contrast, if the summer severity grouping (Fig. 4c) is used, a somewhat more homogeneous and hierarchical performance can be identified both with the warmer zone, summer severity 4: s.4, and with the one with less airtightness compared to s.3 – milder summers –. This is most evident in the central values: s.4-median above 7 h^{-1}, with the bands of the central quartiles located between 5 and somewhat less than 9 h^{-1}. In contrast, the mildest summer has central values below 6 h^{-1} and a central band between 4.5 and 7.5 h^{-1}. However, as in the previous case, most of the values are located in the randomness zone, with only some extreme values showing significance ($z > |1.96|$ for 95% confidence), and this occurs in both extremes for both groups. Moreover, the contrast tests show that the possibility of both actually being the same distribution cannot be ruled out (*p*-values $< < 0.05$).

This aspect, was previously analysed in [32], but limited to a specific building-type and time period, showing a similar performance of the sample. It can be stated that airtightness is not clearly dependent on climatic location, but rather this could be attributed fundamentally to local differences and to construction particularities in the different geographical locations. This finding would be consistent with the similarity of the representative values for hot and cold areas, as described above.

3.2.2. Relation to age and regulatory periods of buildings

General analysis would seem to indicate a certain relationship with the age of the properties, as, in general, more recent properties tend to have lower airtightness values than older ones, that is true in the case of the minimum values. This assumption — since it is possible to attribute better construction processes and less degradation to the most recent properties — is apparently intuitive, but does not seem to present itself linearly. This compo-

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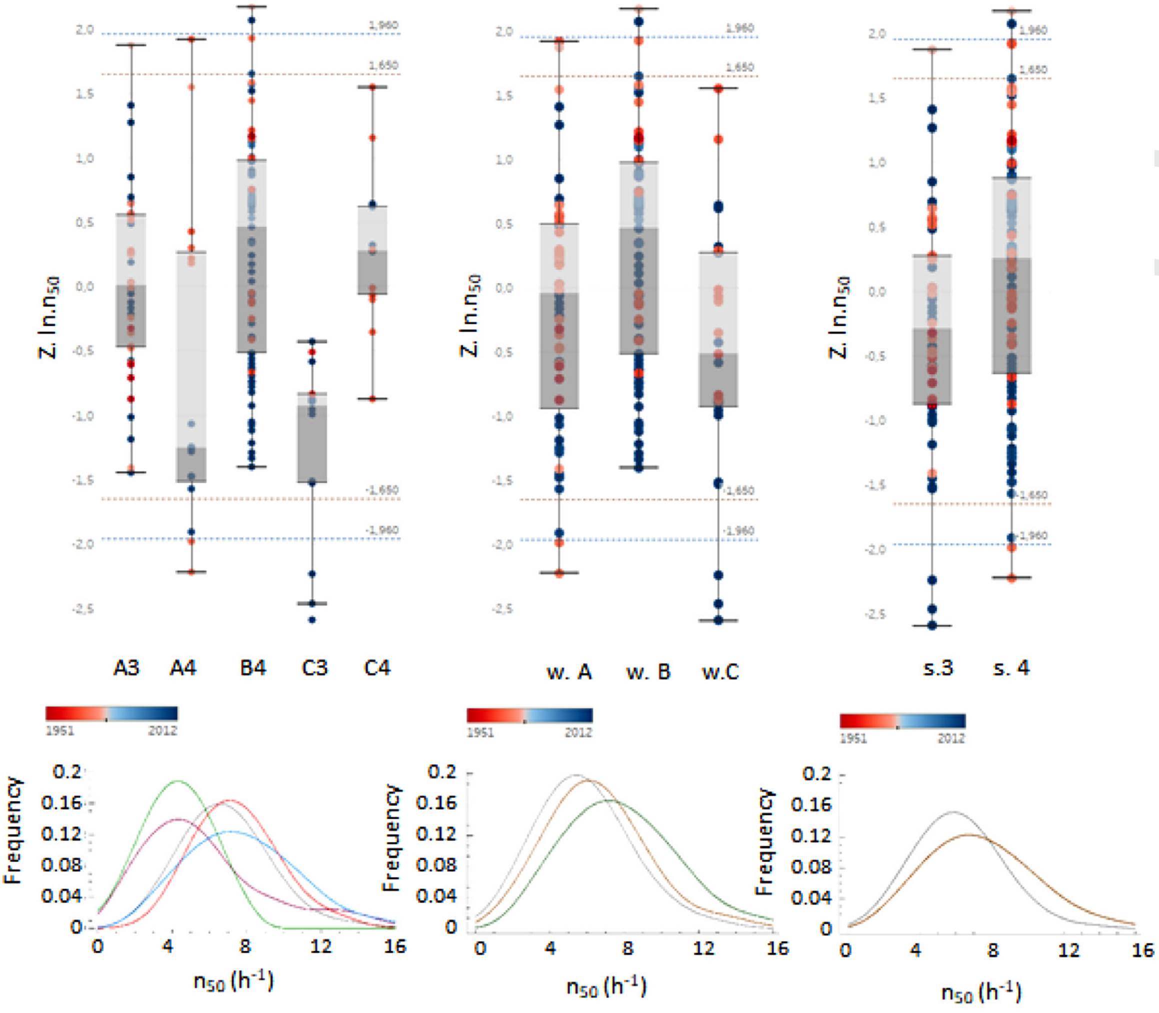

a) Climatic zone b) Winter severity c) Summer severity

Fig. 4. Box plots of the air change rate at 50 Pa (n_{50}) by climatic zone (a), climatic severity in winter (b) and in summer (c).

nent, shows a certain irregularity and dispersion over the different decades (Fig. 5), and cannot be identified clearly, at least not with such a direct relationship as in previous studies of other geographical areas [2,53].

Since there appears to be an underlying grouping in terms of time periods, it has been explored whether this is more closely related to the application of different standards than to year of construction. The gradual adoption of construction rules that imply better control of the performance of the envelope defines a potential factor to predict the performance of the different properties, or at least to categorise them. However, this trend is not verified as such, and it is in the intermediate period that higher mean values can be found. It is not possible to attribute a direct influence from the standards in force during the period, since none of this regulations regarding properties (social or otherwise) establish specific requirements for the airtightness of buildings. Only the requirements derived from the Technical Building Code — EPBD transposition —, which applies to buildings designed after 2007, partially delimit airtightness through the degree of permeability allowed in window frames, in accordance with the climatic zone.

The analysis according to the grouping by regulatory periods is shown in Fig. 6, where the data grouped by periods, together with the general evaluation for comparison, are represented in their quartile distribution. The three distributions show some irregularities in their distribution, particularly in the case of EPBD-compliant properties.

This analysis shows the absence of a clearly identifiable trend, beyond the fact that the properties belonging to the third period (CTE-HE) present a significant improvement in airtightness in terms of central values, with a median of 5.20 h^{-1}, compared to the groups from the previous two regulatory periods, which show median n_{50} values above 6.50 h^{-1}. In contrast, this third group presents greater amplitude in the central band (quartiles 2 and 3), it being more common to find high and low values in this regulatory group than in the previous two, as well as the highest values of the sample within its upper band (excluding the outlier values). In general, the three groups show significant variability, and extreme data can be found in all groups, making it difficult to adequately categorise them. The group belonging to the NBE-CT79 regulation, despite having the highest central value, with a median of 6.80 h^{-1}, shows most compactness, contrary to the initial assumption on the progressive improvement of construction systems. The group from the first period performs similarly to the general group. There is no significant differentiation between the three distributions (K-S and other alternative tests, p-value < 0.05), meaning it is not possible to state that different regulatory periods generate differentiated distributions in the main population (C.I.: 95%).

When the results are grouped by time-period, although it is possible to identify some performance trends, these are not clearly

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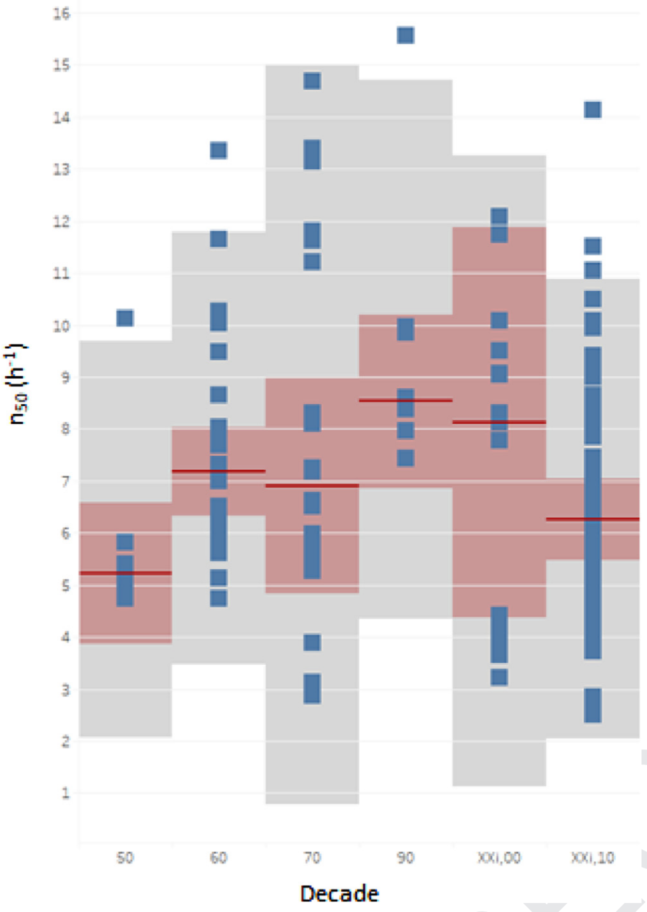

Fig. 5. Box plots of the air change rate at 50 Pa (n_{50}) grouped together by decade.

Annex 1

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ID.	Year	Standard	Climatic zone	City	No. of dwellings
1	1954	preCT79	A3	Cádiz	4
2	1968	preCT79	A3	Málaga	3
3	1971	preCT79	A3	Cádiz	3
4	1972	preCT79	A3	Cádiz	4
5	1974	preCT79	A3	Cádiz	4
6	1976	preCT79	A3	Málaga	1
7	1978	preCT79	A3	Málaga	1
8	1966	preCT79	A4	Huelva	3
9	1969	preCT79	A4	Huelva	2
10	1970	preCT79	A4	Huelva	2
11	1961	preCT79	A4	Huelva	1
12	1951	preCT79	B4	Seville	1
13	1963	preCT79	B4	Seville	3
14	1964	preCT79	B4	Seville	4
15	1965	preCT79	B4	Seville	3
16	1970	preCT79	B4	Córdoba	2
17	1973	preCT79	B4	Córdoba	1
18	1978	preCT79	B4	Seville	1
19	1959	preCT79	C3	Granada	2
20	1964	preCT79	C4	Jaén	4
21	1967	preCT79	C4	Jaén	4
22	2010	CT79	A3	Málaga	4
23	2011	CT79	A3	Cádiz	8
24	2012	CT79	A3	Cádiz	8
25	2007	CT79	A4	Almería	8
26	1993	CT79	B4	Seville	1
27	1998	CT79	B4	Córdoba	7
28	2004	CT79	B4	Seville	10
29	2010	CT79	B4	Seville	8
30	2011	CT79	B4	Seville	7
31	2011	CT79	B4	Seville	5
32	2010	CT79	B4	Córdoba	8
33	2011	CT79	C3	Granada	8
34	2011	CT79	C4	Jaén	5
35	2010	CT06	B4	Seville	8
36	2011	CT06	B4	Córdoba	7
37	2011	CT06	C3	Granada	4
Total:					159

associated either with age or possible obsolescence, or with belonging to the regulatory period (it is possible to find even high or low values in the three groups, all with similar likelihoods). Evolution over time could therefore be associated with the preeminence or appearance of different construction techniques or designs in each of the time bands, resulting in a significant influence on airtightness values. The possible existence of temporal relations in the morpho-construction solutions may explain why the airtightness variables depend on age, although this is more related to collinearity than to causality. This factor could explain the subgroupings within the periods, as well as the jumps in distribution (more obvious in periods where construction and design types are more limited (i.e. EPBD period).

3.2.3. *Relationship to dwelling position in the building*

Contrary to what might be expected, when analysed in terms of the degree of exposure, the dwellings with two adjacent façades forming an angle (type 4 dwellings) were the most airtight (median n50), followed by type 3 or open gallery dwellings. Although more exposed than others, they consisted primarily in the most recent buildings that as a rule was found to be less permeable. That finding was consistent with the distribution by building age (Fig. 7).

The highest n50 values were observed in types 1 and 5 (Fig. 7), particularly in the latter, which included buildings with three exposed façades, what would seem to indicate a relation with constructive processes, due to the increase of joints between façades.

The n50 findings for group 2, two confronted façades, stood at the middle of the sample. The most extreme values were nonetheless observed in this group, with both the most and the least airtight flats appearing with sufficient frequency in the first and fourth quartiles, in keeping with building age (Fig. 7).

Considering the wide variation in the values observed, this parameter would not appear to afford a valid classification criterion. The inter-group overlap revealed by the analysis of the distribution of values would imply that some of the subgroups formed part of the same population: types 4 and 3 on the one hand and 1 and 5 on the other. Nonetheless, the high intra-group variance in these same groups ruled out classification on such grounds.

3.2.4. *Relationship to geometry*

The n_{50} values — at dwelling level — are plotted against dwelling geometric characteristics in Fig. 8. Whilst the relationship between n_{50} and the various parameters may suggest some patterns, the values were too scattered to draw valid trends (Table 9).

Of all the parameters defining envelope morphology, those exhibiting a statistically significant relationship (at 95.0% confidence: p-value = 0.05) with dwelling air-permeability are: façade area (A_{FAC}), window perimeter (P_W) and delimiting surface with condominium areas (A_{CA}). Although some of the others appeared to be vaguely associated with permeability, the relationship was too weak to be deemed significant, due primarily to the scatter observed (Table 1).

3.2.5. *Relationship to technology and materials*

3.2.5.1. Façade typology. The distribution of n_{50} values for each group of envelopes and compared with the general distribution., is given in Fig. 9. Systems 1 and 5 both are clearly differentiated construction solutions (monolithic wall the first and inverted lay-

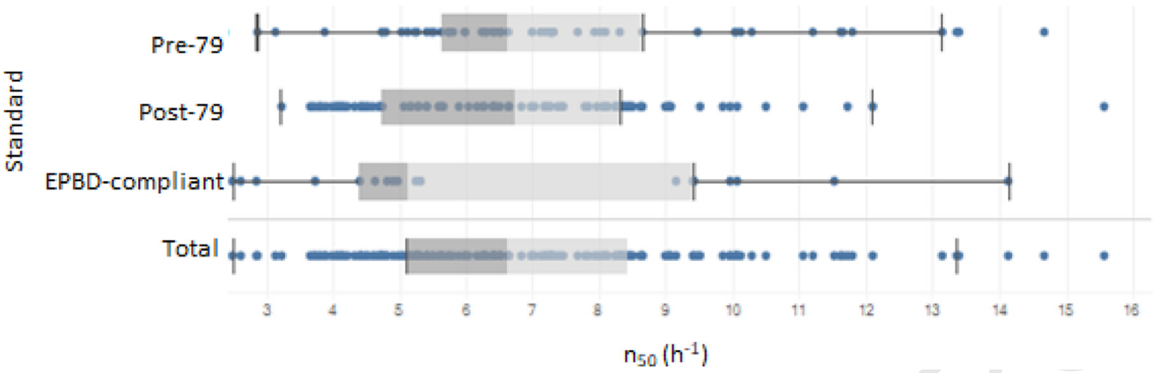

Fig. 6. Box plots of the air change rate at 50 Pa (n_{50}) grouped together by regulatory period.

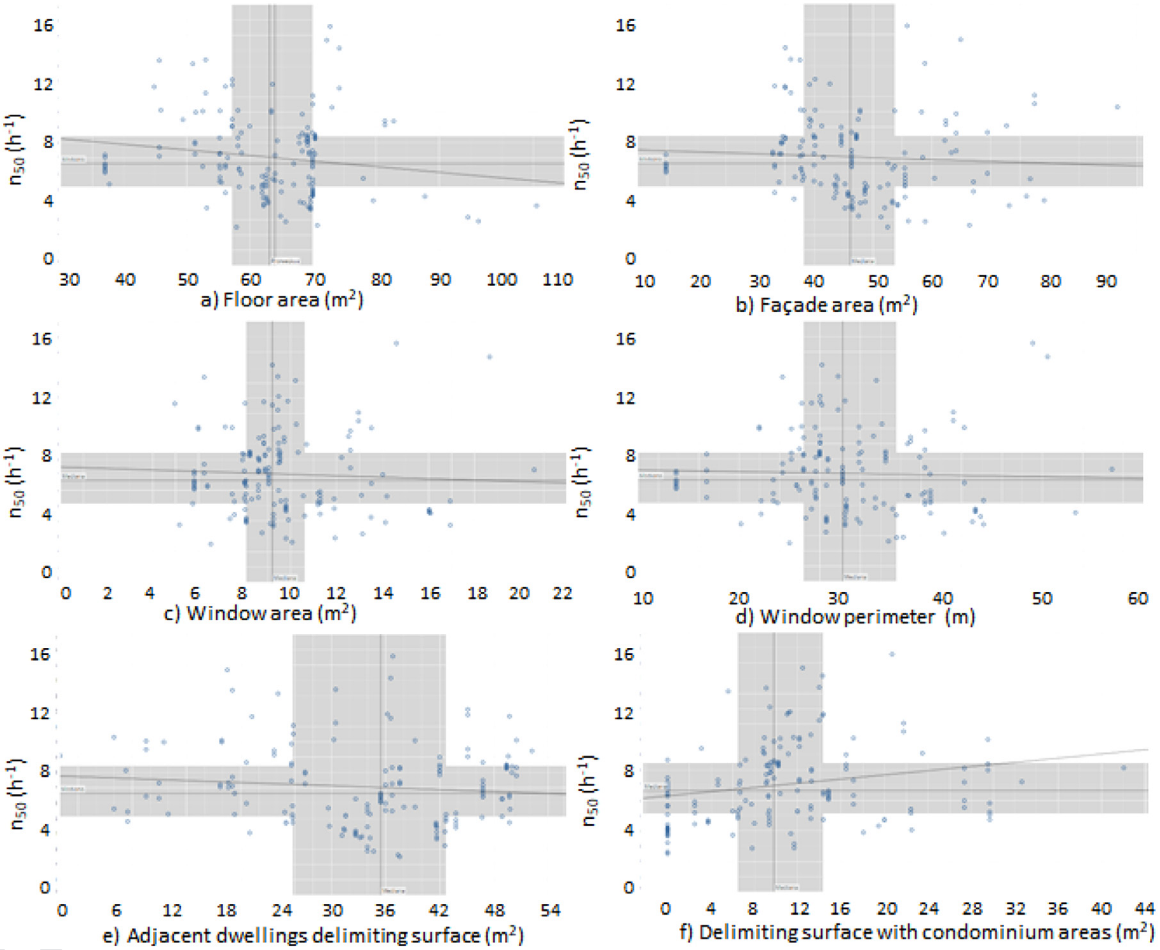

Fig. 7. Box diagram for the air change rate at 50 Pa (n_{50}) by exposure type (1: semi-detached, linearly aligned buildings with four units per storey; 2: semi-detached, linearly aligned buildings with two units per storey; 3: open gallery buildings; 4: stand-alone high rises; 5: semi-detached, linearly aligned buildings with two units per storey and building, located at the corner of the compound or in stand-alone buildings with H, T- or X-shaped ground plans).

ers the latter). Types 2, 3 and 4 are variations on the same constructive scheme incorporing different elements.

Wide variation was observed between samples, with significant differences by location. Types 1 and 2 exhibited similar median n_{50} values at around 6 h^{-1}, which was lower than the overall sample median (6.52 h^{-1}). The façade systems for which the lowest mean airtightness values were found were type 4, with an n_{50} value of nearly 10 h^{-1}, followed by system five, at around 8.5 h^{-1}. Outliers were observed in samples 1, 2 and 4.

Qualitatively speaking, one of the most significant features of single wythe facades, the oldest of the sample, was that they exhibited neither very low nor very high permeability (barring outliers), with values clustering significantly around the sample mean. Given that those enclosures, while less prone to air permeability, were primarily associated with the earliest part of the period studied, construction factors other than wall-composition that might determine such behaviour would need to be studied.

3.2.5.2. Blind typology. Further to the literature [54,55] and earlier research [32], one of the factors with the heaviest impact was the presence of blinds and their type. However, the variability of the test values is high, with n_{50} values rangingied from slightly over

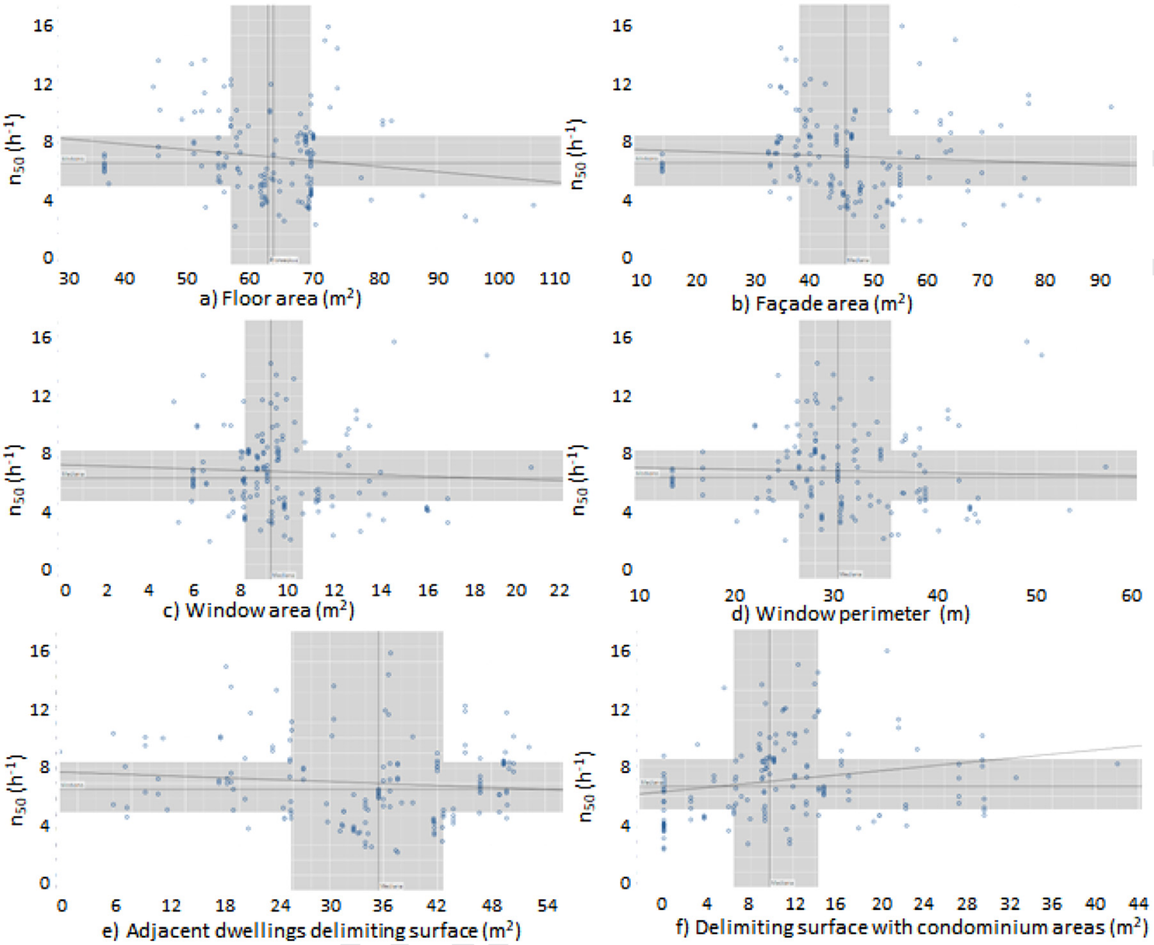

Fig. 8. Point graph for the air change rate at 50 Pa (n_{50}) by geometric parameter (dwelling values).

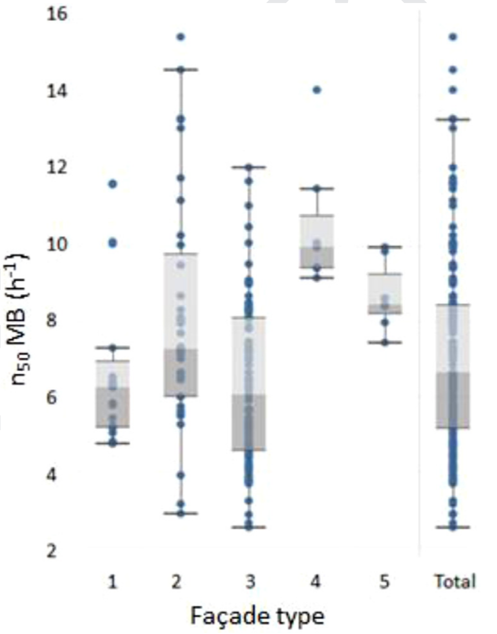

Fig. 9. Box diagram for air change rate at 50 Pa (n_{50}) by enclosure type (1: 1 or 1 and ½ foot brick fabric; 2: ½ foot brick fabric(or one-brick thick) outer wall + air cavity + hollow brick inner wall; 3: ½ foot brick fabric (or one-brick thick) outer wall + insulation layer + hollow brick inner wall; 4: ½ foot brick fabric (or one-brick thick) outer wall + air cavity + plasterboard inner wall; 5: fired clay panelling + air cavity + insulation + fired clay block).

2.5 h^{-1} to 8 h^{-1} (disregarding outliers) in dwellings with no blinds and from slightly under 3 h^{-1} to around 14 h^{-1} in those with blinds of different kinds.

Two groups of central tendency measures can be clearly observed in the n_{50} data given in Fig. 10: the median was over 7 h^{-1} in dwellings (B2, B3 and B4) with and under 5.5 h^{-1} in dwellings (B1) without blinds. In the comparison by developments (building level), the difference between the values for B1 and B4 narrowed, whereas the difference between B2 and B3 widened.

The utility of blind type as a predictor was observed to be limited, since the wide scatter in the n_{50} values, with variations ranging from 7.6 h^{-1} to slightly over 13 h^{-1}, along with the categorical nature of the variable, in turn, does not allow the establishment of predictions only based in this parameter. It could nonetheless be used for a qualitative classification: the lowest permeability values were observed to be more likely to be associated with housing with no blinds, where high n_{50} values were unusual. Usually the highest values can be found associated with the type of blind integrated in the envelope — especially at building level.

The distribution of the n_{50} values for buildings with (red) and without (blue) blinds revealed two clearly distinct behaviours (null hypothesis testing rejected statistical equality at 95 % confidence). This configured a dichotomous factor that divide into two groups of probability of behaviour, with those dwellings without blinds as the most airtightness usually.

3.2.5.3. Window typology. Window type may be another factor for classifying dwellings to determine airtightness [56,57]. Hinged windows (W_H) may as a rule be assumed to be more airtight than

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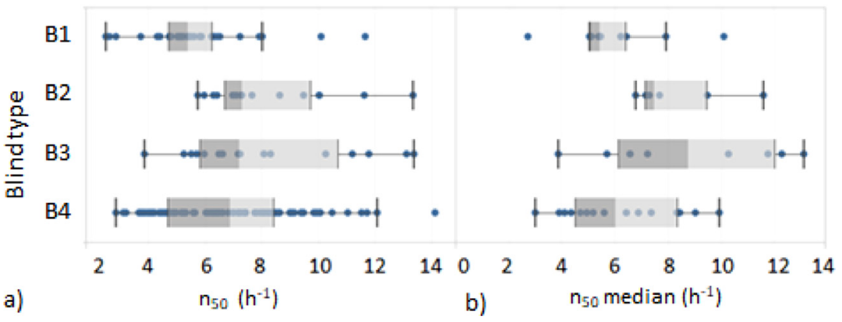

Fig. 10. n_{50} vs blind type values by individual dwellings (a) and building median (b) (P1: no blinds; P2: external blinds; P3: blinds in splayed openings; P4: compact windows blinds).

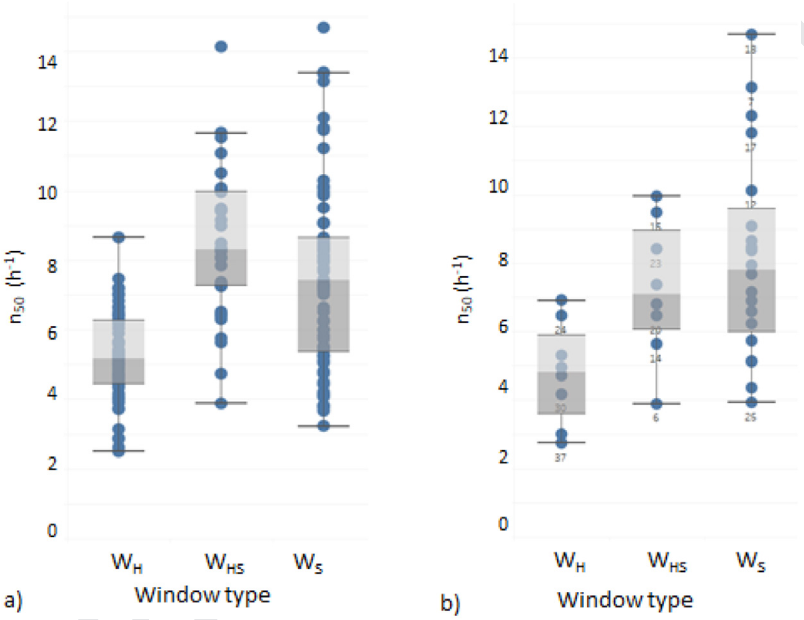

Fig. 11. n_{50} vs window type grouped by dwelling (a) and development (b)(WH: hinge opening windows; WS: sliding windows; WHS: hinged and sliding windows).

sliding windows (W_S), being these the types essentially present. The variation in the sample in terms of specifical models and sizes, accentuated by the stochastic nature of overall construction methods, material characteristics and window conservation, detracted substantially from the predictive capacity of this factor, however. In some dwellings with sliding windows, for instance, the n_{50} values were much lower than in others with hinged opening windows, even when the values were close to those associated with highly airtight dwellings (n_{50}: 3.231 h^{-1} to 4.41 h^{-1} in development 25). Conversely, in dwellings in the same building development with the same type of window the values were sometimes observed to vary widely, with standard deviations of over 3 h^{-1}.

As a rule, and especially when the findings were grouped by building-development (Fig. 11a), dwellings with hinged opening windows exhibited perceptibly lower middle values (median somewhat less than 5 h^{-1}) than the other two groups. The highest central and most extreme values were found for groups with sliding windows (median slightly under 8 h^{-1} and fourth quartile under 15 h^{-1}) and those with both types (median slightly over 7 h^{-1} and fourth quartile under 10 h^{-1}).

The host of combinations and compositions in the group with both types of windows (W_{HS}) delivered a wide range of n_{50} values, although the spectrum was narrower than for the sliding window group. That scatter distorted the results, however. When the values were grouped by development, the central values for this mixed window group stood between the open hinged and sliding window groups, although closer to the latter (Fig. 11b).

3.2.5.4. Dwelling position relative to the roof. An analysis of the entire population revealed that as a rule the dwellings located immediately under the roof were more likely to have high n_{50} MB values than those located on intermediate storeys, with a median probability 16 % higher than the sample as a whole. Those findings did not apply uniformly to all the buildings in the sample, however, for the highest n50 MB values in each development were not univocally associated with top storey dwellings (Fig. 12).

Three situations were identified in the findings on dwelling position relative to the roof (Fig. 12):

- Buildings where the top and intermediate storeys exhibited minimally different (<6%) median n_{50} values, attributable more to the intrisic variation in the building themselves than in dwelling position.
- A group of buildings with significant (>50 %) differences were observed between intermediate and clearly less airtight top storey dwellings.
- Outliers behauviours were found, where under-roof dwellings had a significant 20% lower mean permeability than intermediate units.

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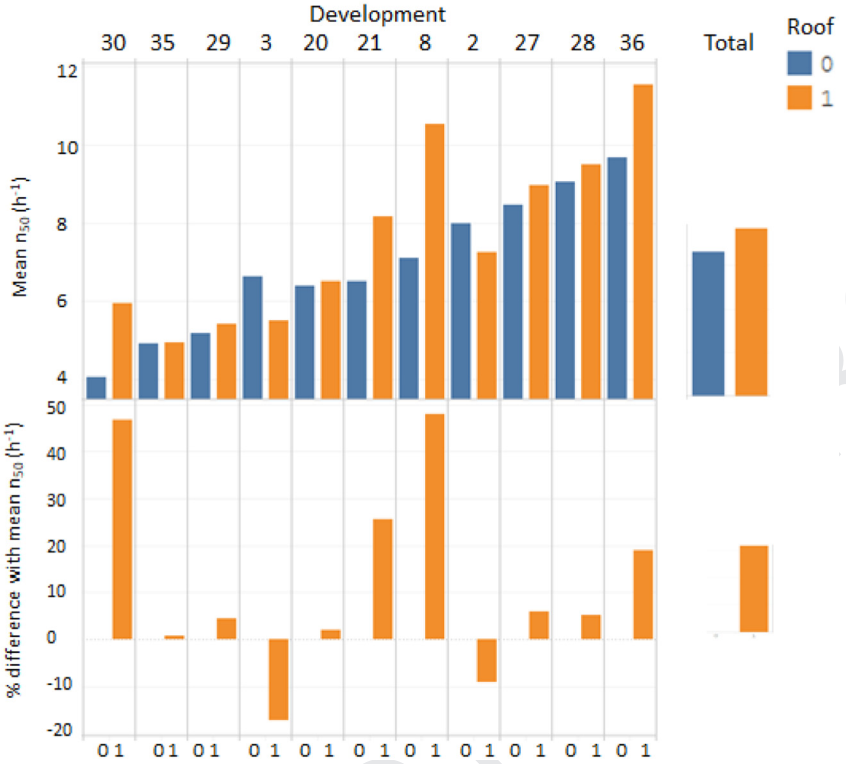

Fig. 12. Median and standard deviation for n_{50} by storey level (0: intermediate; 1: under roof).

4. Conclusions

This work has included analysis of a significant set homes from multi-family social housing, with high statistical representation, predominant in Southern European area countries. Social housing used can be a comparator given its typified nature and greater degree of replicability than other types of dwellings, less constrained in their characteristics. The extensive study, both in terms of geographical locations and time-scale, has made it possible to cover different climatic zones, from mildest to severe (both hot and cold) within the usual locations of this regional area.

Regarding the conformation of the housing stock and, in consequence, linked to the airtightness values, contemporary properties tend to be more homogeneous in their basic characteristics (morphological ratios, construction systems, etc.) and show less variability in the configuration parameters. In contrast, the older age group (i.e. properties built before 1979, assuming the existence of a transition zone during the period of change) shows greater dispersion in basic parameters and typological approaches. This aspect has a clear influence on the results of the airtightness of the properties and their values distribution.

The general performance (normalised permeability under operational conditions) of the housing stock is average compared to other similar housing in Southern Europe, with a mean value of 7 h^{-1} (median 6.52 h^{-1}). This value is similar to that found in other areas of Southern Europe, although far from the target values in countries with a more long-standing tradition of envelope control. This would indicate that the building stock in Southern Europe shares similar airtight performances, which is a contribution of special interest when designing common interventions in the area. The possible existence of different variability levels for each sub-area should be taken into account, what could lead to the development of a complementary parameter the characterization. A fundamental aspect in this housing stock, is the identification of a significant dispersion of values, ranging from very airtight properties to ones which have very little airtightness. Particularly relevant is the presence of the intra-building dispersion, or between buildings of similar characteristics, variations which are not related to construction or geometric parameters. This aspect is indicative of problems of consistency in the quality of construction processes. This aspect generates great difficulty in the precise predictive models proposal and in the development of retrofitting policies.

The social building stock/ can be classified in four subsets /according to their airtightness:

- High airtightness dwellings, with values between 2.5 and 5.1, with a low potential of improvements (25,1%).
- Normal airtightness dwellings, the largest group as they represent half of those studied, with values ranging 5.1 and 8.4 (49.7%).
- Low airtightness dwellings, with values above 8.4 air change rate those representing highly permeable models (23.9%).
- and finally dwellings with abnormal performance, with values above 13.4 which usually respond to particular situations of alteration or deterioration (1.3%).

The two factors which are usually fundamental in determining airtightness have been assessed in the analysis, namely relationship to climatic zone and age or year of construction. A reasoned categorisation has been analysed and provided, based on both the statistical analysis and possible factors influencing airtightness. This analysis has made it possible to identify underlying behavioural structures, which, although they may have collinearity with zones and periods, can provide factors of relevance for predictive models. The fundamental values and oscillation bands associated to the different constructive systems, types of window, and specific location in the buildings have been highlighted, as well as their categorization; together with the bands of results associated to temporal period and geographical location. This analysis allows to draw an overview of the improvement potentials and the selec-

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tion of those buildings with greater sensitivity to the intervention. These should be specifically undertaken in future work.

4.1. Further work

This works aims to provide the basis to develop a predictive model adjusted to the specificities of collective housing buildings in Southern Europe. The assessment and establishment of the sensitivities of the main parameters will support this work. Along, the investigation of the collinear relationships between factors will be undertaken is subsequent works. These should be specifically studied in future work.

Uncited references

[51].

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