Preliminary analysis results of Spanish residential air leakage database

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ABSTRACT

The air leakage impact on energy performance in buildings has already been broadly studied in USA, Canada and most European countries. However, there is a lack of knowledge in Mediterranean countries regarding airtightness. An extensive study has been carried out in order to characterize the envelope of the existing housing stock in Spain. Preliminary results of more than 401 dwellings tested are shown. The sample includes different typologies, year of construction and climate zones. Blower door tests were performed and thermal imaging was used to locate leakage paths.

Results indicate that the mean air change rate at 50 Pa of the whole sample was 7.52 h^{-1} and the mean air permability rate was 5.91 $m^3/h \cdot m^2$. Different parameters were statistically analysed. Climate zone was found to have a great impact on airtightness. Other parameters such as typology, retrofitting intervention, heating and refrigerating systems, construction technology or the position of the rolling shutters were also analysed. Regarding the year of construction, unlike the trend in other European countries, it is not clear that Spanish recent dwellings have a better performance of the envelope than the old ones.

KEYWORDS

Air leakage; residential buildings; fan pressurization test; Blower Door; database

1 INTRODUCTION

The concern for the energy performance of buildings, and specifically for air infiltration, has grown in the past few years. However, in the Mediterranean countries, and in the case of Spain in particular, climate benevolence and the tradition of ventilating naturally have led to very few studies focusing on this area (Fernández-agüera, Sendra, Suárez, & Oteiza, 2015; Jiménez Tiberio & Branchi, 2013; Montoya, Pastor, & Planas, 2011). Air infiltration has complemented natural ventilation, supplying the lack of specific ventilation systems.

In Spain the Technical Building Code (Ministerio de Fomento del Gobierno de España, 2006) requires the implementation of controlled ventilation systems in new buildings to ensure adequate indoor air quality. Therefore, it is essential to insist on the need for airtight envelopes to avoid oversized ventilation systems and excessive energy consumption. Infiltrations have been proved to be responsible for 10.5% to 25.4% of the energy demand in winter for residential dwellings built in Spain after 2006 (Meiss & Feijó-Muñoz, 2014).

Given the relevance of this matter, INFILES project, in which this research is included, aims to characterize the envelope of current buildings in Spain, in relation to airtightness. Through an extensive field study throughout the Spanish geography, apartments and houses of different typologies and years of construction have been analysed. The purpose of the study is the creation of a database that gathers air infiltration results and building characteristics to determine the factors that have a major impact on airtightness. Although the sample size is limited, and some sub-groups are not sufficiently represented, this study provides the basis of a wide national database to be extended over time.

Other countries have already developed databases with a great number of cases, which allow the estimation of the impact of regulations on building airtightness and provide statistical data to establish the impact of building characteristics on building airtightness (Leprince, Kapsalaki, & Carrié, 2017). The most relevant one has been developed in US (ResDB) since 90' and contains building envelope air leakage data from nearly 150,000 cases (Chan, Joh, & Sherman, 2013). In Europe, databases are being addressed in the UK, Germany, Belgium, Czech Republic, Estonia, Ireland or France (Leprince, Carrié, & Kapsalaki, 2017).

2 METHODOLOGY

2.1 Studied dwellings

The dwellings tested were chosen based on a representative sample of the existing housing stock in Spain by means of a non-probabilistic quota sampling scheme (Feijó-Muñoz et al., 2018). The sampling method considered relevant factors that have an impact on airtightness as control variables, namely climate zone, year of construction and typology. Airtightness tests were conducted in 401 dwellings built between 1880 and 2015 in various locations of Spain, whose owners allowed voluntarily for the performance of the test.

For sampling purposes, the **year of construction** was considered either for original dwellings or **renovated** ones. This fact was taken into account as a characterization parameter in order to be able to analyse its possible impact. The sample included 275 original dwellings (68.6%) and 126 had been fully renovated (31.4%).

According to the planned sampling scheme, 325 cases were apartments (81%) and 76 cases were single-family houses (19%). Sub **typologies** were also considered: closed city blocks of apartments (62.6%), isolated blocks of apartments (18.5%), individual houses (7.2%), row houses (11.8%), etc.

Although **building characteristics** may vary, there are some common features that could define the architectural housing stock in Spain. Massive brick construction system has been broadly extended in the country over the past century (99.3% of the sample). Lightweight construction systems are very rarely used in this area. Rolling shutters are rather extended in the country, although they often constitute a discontinuity of the envelope and therefore a typical leakage path. Only 63 (15.7%) of the dwellings tested had no rolling shutters.

Regulations in Spain did not introduce ventilation control in dwellings until 2006 with the implementation of the Technical Building Code (CTE) DB HS3 (Ministerio de Fomento del Gobierno de España, 2006). This fact explains that most of the dwellings tested were ventilated naturally (99% of the cases). Ventilation is provided by opening the outer windows and air infiltration of the building envelope. Kitchens are usually supplied with a hood (89.8% of the sample).

Regarding **heating and cooling**, the presence of these systems was not uniform, since dwellings were located in different climate zones with different needs. A broad majority of the tested dwellings (85.5%) had a heating system whereas only nearly half of them (44.1%) had refrigeration.

The **size** of the dwellings also covered a wide range. Floor area ranged from 20.59 m^2 to 332.15 m^2. Table 1 summarizes the dimensions of the dwellings tested and its distribution.

Table 1: Dimensions of the tested dwellings

Parameter	Minimum	Maximum	Mean	Standard deviation	Ranges	n	% of the total
Floor area (m^2)	20.59	332.15	93.52	48.73	0-49	40	10
					50-99	239	59.6
					100-149	85	21.2
					150-199	17	4.2
					200-249	13	3.2
					250-299	4	1.0
					300-350	3	0.7
Volume (m^3)	51.48	952.13	240.96	130.80	0-99	20	5.0
					100-199	165	41.1
					200-299	131	32.7
					300-399	47	11.7
					400-499	19	4.7
					500-599	6	1.5
					600-699	6	1.5
					700-799	5	1.2
					800-899	2	0.0
					900-1000	2	0.5
Envelope area (m^2)	107.34	988.17	293.17	116.92	0-99	0	0.0
					100-199	55	13.7
					200-299	202	50.4
					300-399	88	21.9
					400-499	34	8.5
					500-599	13	3.2
					600-699	5	1.2
					700-799	1	0.2
					800-899	1	0.2
					900-1000	2	0.5
Compactness (m^{-1})	0.67	2.32	1.29	0.20	0-0.49	0	0.0
					0.5-0.99	36	9.0
					1-1.49	323	80.5
					1.5-2	37	9.2

2.2 Measurement methods

For the purpose of the study, the airtightness level of the tested cases was measured with the extended technique Blower Door test, according to EN 13829 (AENOR, 2000). Both pressurization and depressurization tests were carried out within the internal volume of the deliberately conditioned space of the dwelling. Two different protocols were followed in order to obtain both the airtightness behaviour of the building in use (Method A) and the building envelope (Method B) (AENOR, 2000). Pertinent preparations of the building were performed accordingly. An automated test was performed with 10 measurement points for each test in the range 11-65 Pa. The infiltration curve is calculated as follows (Equation 1):

$$V_{env} = C_{env}(\Delta p^n) \qquad (1)$$

where:
V_{env}: air flow rate through the envelope of the dwelling (m^3/h)
C_{env}: air flow coefficient ($m^3/(h \cdot Pa^n)$)
Δp: induced pressure difference (Pa)
n: pressure exponent

The correct calibration of the equipment was ensured to maintain accuracy specifications of 1% of reading, or 0.15 Pa. The parameters obtained from the power law that allow the comparison of results in different buildings are listed in Table 2:

Table 2: Parameters obtained from the power law equation.

Parameter		Equation	Unit
V_{50}	air flow rate at 50 Pa	$C_{env}(50)^n$	m^3/h
n_{50}	air change rate at 50 Pa (ACH_{50})	V_{50}/V	h^{-1}
w_{50}	specific leakage rate at 50 Pa	V_{50}/A_E	$m^3/h{\cdot}m^2$
q_{50}	air permeability rate at 50 Pa	V_{50}/A_F	$m^3/h{\cdot}m^2$

where:
V (m^3): internal volume. Volume of air inside the measured building, calculated by multiplying the net floor area by the ceiling height. The volume of the furniture is not subtracted.
A_E (m^2): envelope area. Total area of walls, floors and ceilings bordering the internal volume subject to the test.
A_F (m^2): net floor area. Total floor area of all floors belonging to the internal volume subject to the test.

The tested dwellings were widely characterized so that results could be compared and further analysis performed. A software tool was developed in order to retain the information in a uniform and systematic way, standardizing assessment criteria among technicians. Its extended use could constitute the establishment of a national air leakage database. The methodology followed in this study was further detailed by Feijó-Muñoz (Feijó-Muñoz et al., 2018).

3 RESULTS

Firstly, the distribution of the air change rate (h^{-1}) and the air permeability rate at 50 Pa ($m^3/h{\cdot}m^2$) results were analysed (Table 3). Histograms of the distribution can be seen in Figure 1. The range of the measured n_{50} values was large, from 1.19 to 39.42 h^{-1}, as well as the q_{50} values, from 0.96 to 29.92 $m^3/h{\cdot}m^2$. The data set constitutes a large sample and thus a small number of outliers was expected. Some of the values obtained were outliers, although they have not been considered as experimental errors, since they correspond to really leaky cases. Therefore, outliers have not been excluded from the data set.

Normality of the data was analysed with Kolmogorov-Smirnov normality test using the extended statistics tool IBM SPSS Statistics (Table 3). The null hypothesis of normality H_0 was rejected both for n_{50} and q_{50}, given the obtained *p-values* with a significance level applied for the analysis $\alpha = 0.05$ (5%). That indicates non-normal distribution of the data.

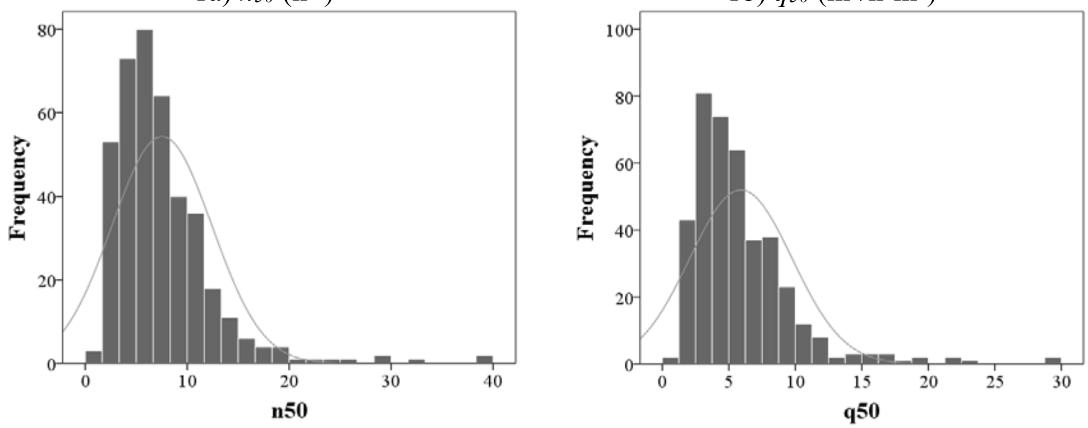
Table 3: Normality test results

Parameter	n	mean	median	sd	skewness	kurtosis	Kolmogorov-Smirnov test	
							Statistics	p-value
n_{50} (h^{-1})	401	7.52	6.39	4.91	2.62	11.25	0.13	0.00*
q_{50} ($m^3/h{\cdot}m^2$)	401	5.91	5.00	3.85	2.41	9.14	0.13	0.00*

n: number of dwellings tested.
sd: standard deviation.
*: significant results are marked with this sign.

Figure 1: Histograms of the distribution of the air permeability results of the tested dwellings.

1a) n_{50} (h^{-1}) 1b) q_{50} ($m^3/h \cdot m^2$)



The impact of different parameters on airtightness has been analysed. Given the non-normality distribution of the sample, non-parametric tests were performed to study if there was a statistically significant relation between the obtained n_{50} values and different properties of the dwellings. Results were analysed according to construction period, climate zone, typology, retrofitting state, heating system, refrigerating system, construction technology and position of the rolling shutters. Kruskal-Wallis test was performed in order to statistically verify the independence of the variables. Table 4 shows the permeability values for each variable and the significant results found.

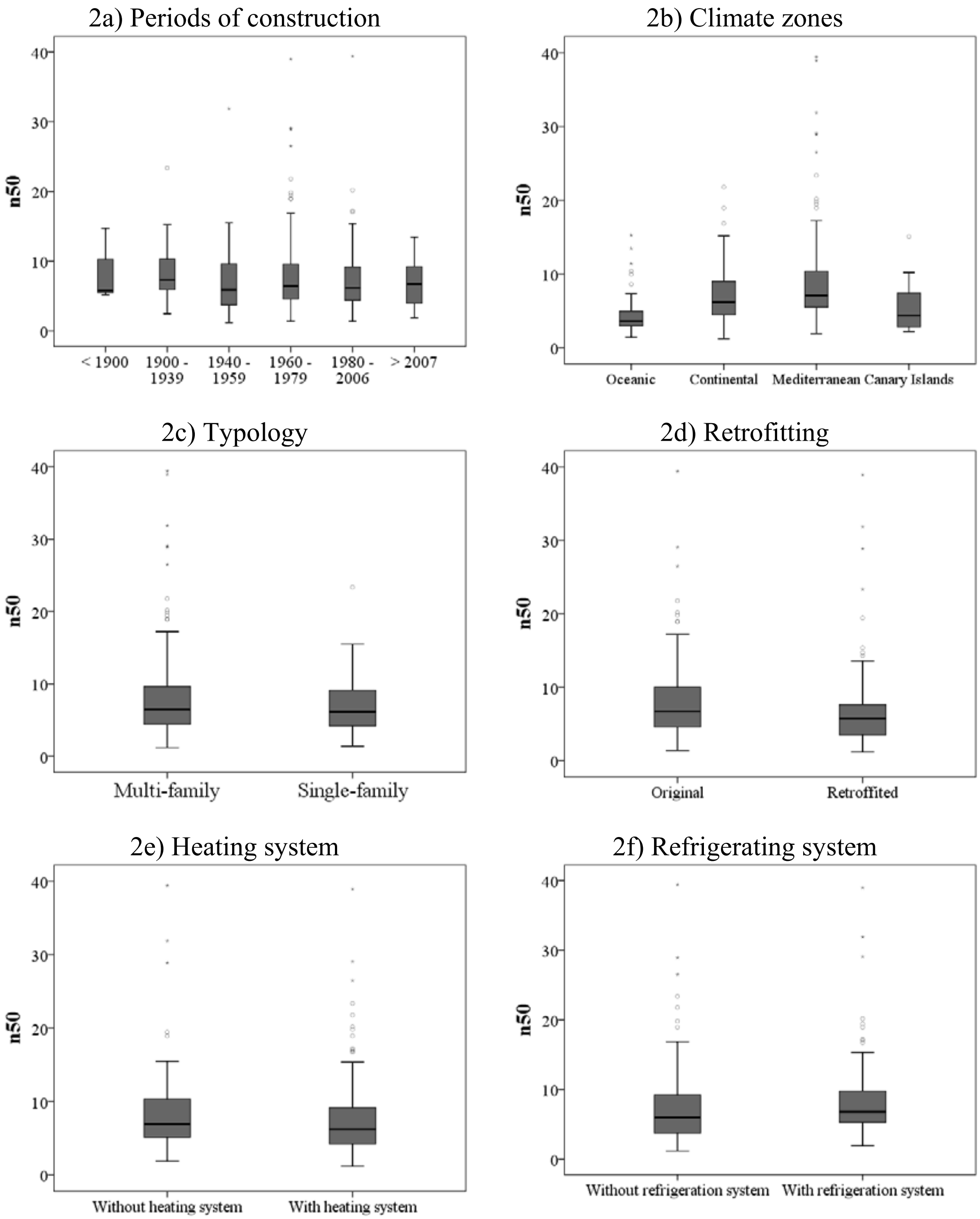
Figure 2 is a set of boxplots of the air change rate at 50 Pa of the dwellings for the parameters analysed.

Table 4: n_{50} results (h^{-1}) of the tested dwellings according to different parameters and Kruskal-Wallis test values.

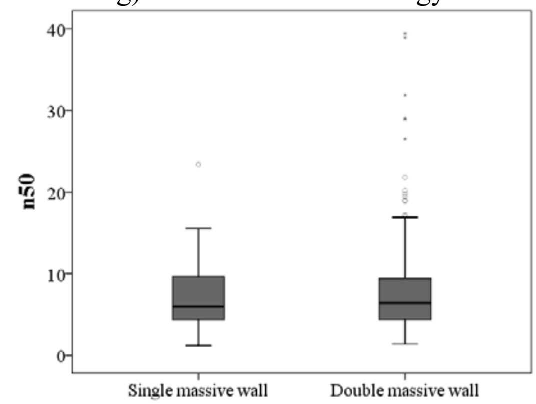
Variable	Category	n	mean	median	sd	min	max	Chi-square	Sig.
Period of construction	<1900	3	8.58	5.83	5.32	5.19	14.71	3.05	0.69
	1900-1939	22	8.42	7.29	4.62	2.47	23.38		
	1940-1959	36	7.30	5.91	5.48	1.19	31.88		
	1960-1979	148	7.93	6.47	5.58	1.41	38.96		
	1980-2006	158	7.19	6.19	4.42	1.39	39.42		
	>2007	34	6.85	6.70	3.19	1.90	13.46		
Climate zone	Oceanic	47	4.64	3.56	3.06	1.41	15.26	51.84	0.00*
	Continental	129	6.98	6.20	3.58	1.19	21.80		
	Mediterranean	209	8.66	7.05	5.63	1.90	39.42		
	Canary Islands	16	5.43	4.38	3.57	2.18	15.07		
Typology	Multi-family	325	7.66	6.50	5.13	1.19	39.42	0.56	0.46
	Single-Family	76	6.92	6.17	3.78	1.39	23.38		
Retrofitting	Original	275	7.83	6.75	4.61	1.39	39.42	10.09	0.00*
	Retrofitted	126	6.87	5.79	5.45	1.19	38.96		
Heating system	Heating	343	7.25	6.21	4.40	1.19	38.96	3.50	0.06
	No heating	58	9.16	6.92	7.05	1.90	39.42		
Refrigerating system	Refrigeration	177	8.08	6.80	4.89	1.93	38.96	9.75	0.00*
	No refrigeration	224	7.09	6.00	4.89	1.19	39.42		
Construction technology	Single massive wall	57	7.25	5.99	4.20	1.19	23.38	0.08	0.77
	Double massive wall	344	7.57	6.40	5.02	1.39	39.42		
Rolling shutters position	Non-integrated shutters	19	7.96	8.08	2.43	3.86	13.58	13.96	0.00*
	Exterior shutters	296	7.46	6.31	4.60	1.19	38.96		
	Interior shutters	23	7.70	3.56	10.15	1.41	39.42		

	No shutters	63	7.64	6.76	4.06	2.18	23.38

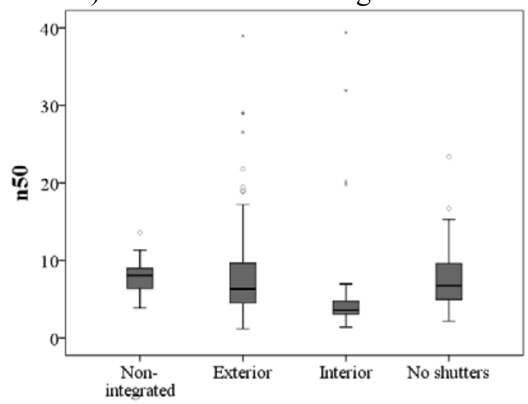
Figure 2: Airtightness of the tested dwellings.



2g) Construction technology



2h) Position of the rolling shutters



As can be deduced from the data obtained, there is not a statistical significant relation between airtightness and the period of construction of the dwellings (*p-value* = 0.69). It is relevant, though, that there is just a slight trend of improvement of the mean and median values of the air change rate over the years. Newer buildings obtained better airtightness values than the old ones but only within a tight range, even though construction technology and regulations have had a great development. As an example, dwellings built after 2007 have a mean value of n_{50} = 6.85 h^{-1} whereas the ones belonging to the period 1940-1959 have a mean air change rate of 7.30 h^{-1}, although the sample size of both periods is limited. Nevertheless, an improvement can be seen between the periods with a larger sample: 1960-1979 and 1980-2006. The air change rate varies from a mean value of 7.93 to 7.19 h^{-1}. The implementation of Spanish regulations in 1979 (Ministerio de Fomento del Gobierno de España, 1979) concerning the energy performance of buildings could be an important aspect to explain this fact.

Regarding climate zone, a statistical relationship with the air change rate was found (*p-value* = 0.00). Dwellings in the Mediterranean area are the leakiest with a mean of 8.66 h^{-1} whereas the ones located in the Oceanic area are the most airtight with a mean o n_{50}= 4.64 h^{-1}. However, this result should be verified with a larger sample size for the Oceanic zone and the Canary Islands. It is relevant also the fact that dwellings in the Mediterranean area are leakier than the ones located in the Continental area (n_{50} = 6.98 h^{-1}). This fact could be derived from the extreme temperature conditions found in the Continental area, which differs with the mild climate found in the Mediterranean part of the country.

Multi-family and single-family buildings were analysed. The relationship between the air change rate at a pressure difference of 50 Pa and typology was not significant (*p-value* = 0.46).

Retrofitting of the dwellings was also found to be statistically relevant for airtightness (*p-value* = 0.00). The sample size for both situations is large enough to draw conclusions. An improvement on the air change rate was found for retrofitted dwellings (n_{50} = 6.87 versus 7.83 h^{-1} corresponding to the original ones). However, this improvement could be greater if airtightness was considered and specific measures taken during the retrofitting process, even though Spanish current regulations do not establish certain permeability rates limits.

As for the conditioning systems provided for each case, different conclusions were drawn from heating and refrigerating systems. The presence of a refrigerating system was found to be significant regarding airtightness, whereas for heating it was not. Dwellings with refrigerating system were leakier (n_{50} = 8.08 h^{-1}) than the cases without it (n_{50} = 7.09 h^{-1}). The performance and efficiency of these systems is affected by the presence of infiltrations. This result could be explained given the fact that refrigerating system can be found mainly in locations with a mild climate.

Additionally, as it has already said before, construction systems in Spain have not experimented a large development during the past century. An analysis has been carried out in order to determine if the fact that the envelope was single massive or double had an impact on airtightness. No statistical relationship was found.

Finally, the impact of the positions of rolling shutters was analysed. The shutters were classified into four categories. One of the categories included dwellings without rolling shutters, although other shadowing systems could be found. The most usual system is the integration of the window and rolling shutter into the interior side of the envelope in such way that it rolls through the outside of the window. In the Oceanic area of the country, specifically in A Coruña, located in the north of the country by the Atlantic Ocean, an unusual system was found, with shutters rolling through the inside. Lastly, non-integrated rolling shutters, a solution employed in the case of windows that originally had no shutters, were considered. A statistically significant relationship (*p-value* = 0.00) between the position of the shutters and the airtightness level was found.

4 CONCLUSIONS

Preliminary airtightness results of residential buildings in Spain are shown. 401 buildings constitute this database at the moment, which has been created with the aim of setting the basis of a national and further developed one, completed by constructors and public or private agents. It has been designed together with an application that allows the storage of unified information, including test results and a whole characterization of the dwellings.

The sample size was designed by means of a non-probabilistic quota sampling scheme considering the climate zone, year of construction and typology. Nevertheless, a larger sample should be considered in order to draw more accurate conclusions. The mean air change rate of the whole database is 7.52 h^{-1} and the mean air permeability rate at 50 Pa is 5.91 $m^3/h \cdot m^2$. A great potential for energy savings through the improvement of construction elements can be derived from the results.

An analysis was performed in order to statistically verify the independence of different variables. Climate zone, retrofitting, refrigerating system and the position of the shutters were found to be in relation with the air change rate of the dwellings tested. On the other hand, no significance was found related to the period of construction, typology, heating system or construction technology.

Further conclusions will be derived from a deeper analysis of the data and the increase of the number of cases tested.

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