Airtightness predictive model from measured data of residential buildings in Spain

Irene Poza-Casado[*1], Pilar Rodríguez-del-Tío[2], Miguel Fernández-Temprano[2], Miguel Ángel Padilla-Marcos[1], and Alberto Meiss[1]

1 GIR Arquitectura & Energía, Dpto. Construcciones Arquitectónicas, Ingeniería del Terreno y Mecánica de los Medios Continuos y Teoría de Estructuras, Universidad de Valladolid. E.T.S. de Arquitectura
Avenida Salamanca, 18
47014 Valladolid (Spain)

2 Dpto. Estadística e Investigación Operativa, E. de Ingenierías Industriales - Sede Doctor Mergelina
Paseo Prado de la Magdalena 3-5
47011 Valladolid (Spain)
**Corresponding author: irene.poza@uva.es*
Presenting author: Irene Poza-Casado

ABSTRACT

The need for airtightness control is a reality given its impact on buildings' energy use and IAQ. For the past few years, this fact has resulted in energy performance regulations being established in many countries in Europe and North America. However, compliance proof is not always required, and on-site testing is often avoided. In this sense, predictive models have become useful in the decision-making process and to estimate input values in energy performance simulation tools. In Spain, maximum envelope permeability values were introduced recently, but pressurization tests rarely undergo. The most common approach to prove compliance is by means of reference values, which were proved to be inaccurate. This paper presents a predictive model for airtightness, which offers an alternative procedure for airtightness estimation. The model was developed from an airtightness database which included a representative sample of the residential building stock in Spain. A General Linear Model was considered to assess significant variables related to the climate zone, the age of the building, typology, building state, construction system, and dimensions. As a result, a predictive model that explains 42.9% of the variability of the response is presented, containing 12 main effects and 2 interactions. Overall, even if some limitations were identified, the relevance of the model proposed is warranted from the statistical point of view by the significance of the coefficients and the validity of its residual analysis.

KEYWORDS

predictive model; airtightness; blowerdoor; dwellings; database; statistical analysis

1 INTRODUCTION

The evaluation of airtightness is crucial for determining the energy performance of buildings and setting priorities for retrofitting strategies since airtightness is the main building characteristic that affects air infiltration (Dick 1950; Shaw 1907; Sherman and Chan 2004). This entails not only measuring airtightness but also detecting sources of leakage and the variables that affect overall performance.

When large datasets are available, statistical relationships among the variables can be determined and tools to analytically estimate the airtightness level from building characteristics can be developed. Predictive models are helpful to consider airtightness in energy performance (EP) simulation tools with the aim of controlling costs and time in the decision-making process before building construction or retrofitting actions.

The interest in approaches to analytically quantify airtightness has grown significantly (Bramiana, Entrop, and Halman 2016; Chan, Joh, and Sherman 2013; Khemet and Richman 2018, 2021; Krstić et al. 2014; Mcwilliams and Jung 2006; Pan 2010) despite the fact that airtightness estimation cannot substitute on-site testing (Relander, Holøs, and Thue 2012). The aforementioned models were created using built stocks with regionally distinct construction typologies, features, and configurations. This seems to be a shortcoming that prevents airtightness predictive models from being easily reproducible or exported to different contexts. This is also the scenario in Spain since previous predictive models (Fernández-Ag. era et al. 2016, 2019; Ibanez-Puy and Alonso 2019; Montoya et al. 2010) focused on specific regions and typologies.

1.1 Context in Spain

Spain and other Mediterranean countries with mild climates have only recently raised awareness for airtightness control. This can be explained given the traditional role of air infiltration as a source of air renewal in dwellings without controlled ventilation systems. However, the scenario has changed for the past few years, and the need for energy-efficient buildings led to mandatory controlled ventilation systems and airtightness control.

In 2019, regulations (CTE) introduced for the first time whole envelope airtightness limits depending on the volume-envelope area ratio of the dwelling (Ministerio de Fomento. Gobierno de España 2019). This requirement is only applicable for new and retrofitted dwellings for private use with a floor area greater than 120 m^2. To prove compliance, pressurization tests can be performed, but reference values can also be used. The airtightness result obtained by either method is then introduced in the official EP calculation tool LIDER/CALENER (HULC) in order to verify the requirements established by regulations.

In reality, designers and practitioners typically prefer the analytical approach, and tests rarely undergo. Therefore, accurate estimation turns crucial. In this sense, a comparison of the results obtained from the analytical approach were compared to values obtained from pressurization tests performed in a representative sample of existing dwellings (382 observations). The model suitability was evaluated by means of a correlation analysis (Poza-Casado et al. 2022). A lack of linear association between the values of the CTE model and the test values was found concluding that the analytical approach is unsuitable to estimate the airtightness of existing dwellings.

Even though on-site testing is the only reliable method to determine airtightness, a precise estimate is key to address accurate energy performance calculation, as well as to set priorities and choose strategies for building design and renovation of existing buildings.

The authors developed a predictive model from representative experimental data to estimate the level of airtightness of the built stock in Spain (Poza-Casado et al. 2022). This approach is applicable at a national level and aims at understanding the factors that most impact airtightness in dwellings. This paper presents an adjusted model based on it, which introduces new significant variables and improves the variability of the response.

2 METHODS

2.1 Sample and airtightness testing

For the development of the model proposed, the INFILES national airtightness database (Feijó-Muñoz et al. 2019) was used. The database included existing dwellings, which were considered representative of the national residential built stock. Each case was tested and fully characterised including identification information, configuration, construction of the envelope, and building systems. The airtightness of the cases assessed was measured by means of fan pressurisation tests, commonly known as blower-door tests, according to the International Standard ISO 9972 (ISO 2015).

2.2 Statistical model development

A General Linear Model (GLM) was considered as in Equation (1). In this way, categorical and quantitative variables with significant influence on the response variable were included. Both the main effects of the explanatory variables and first-order interactions among them were assessed.

$$Y = \beta_0 + \sum_{i=1}^{p} \beta_i X_i + \sum_{i<j} \tau_{ij}(X_i X_j) + \varepsilon \quad (1)$$

where: Y is the response variable to be predicted, X_i with i=1,…,p are the explanatory variables, β_i are the main effects of the explanatory variables on the response, τ_{ij} are the first-order interactions among variables X_i and X_j, and ε are the random independent homoscedastic normal perturbations. For the qualitative explanatory variables, the usual decomposition in dummy indicator variables has been considered.

Outlier detection and elimination were performed and then a stepwise procedure was considered. This procedure starts with the model containing all variables and then an iterative procedure is performed ensuring that all variables in the final model are significant. Residual analyses were also performed at each step to check the GLM assumptions of linearity, homoscedasticity, independence and normality.

Due to the asymmetry exposed by n_{50} (Poza-Casado et al. 2022:7–8)., we considered $\log(n_{50})$ as response variable Y in model (1). As for possible explanatory variables X_i to be included in the predictive model, variables related to location, age of the building, building typology, state, building systems, and dimensions were considered. First-order interactions among these variables were also considered. Table 1 contains a list of the variables initially considered, detailing which ones had a significant impact on the response variable. These significant variables are fully described below.

Table 1: Variables considered classified according to their type and their significance in the GLM model. Variables marked with * were introduced in the improved model.

Type of variable	Variables in the final model	Variables dismissed in the final model
Location	Climate zone (CTE)	City Winter severity climate Summer severity climate Simplified climate zone
Age of the building	Period of construction	Year of construction Decades of construction Applied regulations
Type of building	Typology Number of bathrooms*	Position within the building Height Number of floors Property developer Number of rooms Layout of the floorplan
Building state	Retrofitting state	Improvement of thermal bridges Identified cracks Closed balconies Integrated balconies Kitchen refurbishment Bathroom refurbishment Improvement of the envelope
Building system	False ceiling	Envelope layer composition

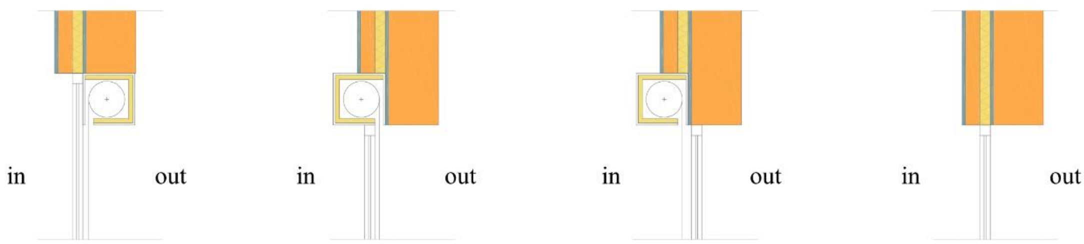
	Window permeability Window material Shutter position Heating system*	Outer cladding Insulation of the envelope Air chamber Windows opening system Double window Shutter type Partitioning system Cooling system Ventilation system Adventitious openings Ductwork Kitchen hood exhaust
Dimensions	Share of windows Share of opaque envelope	Floor area Volume Envelope area Compacity Ceiling height Share of wet rooms Windows joint length Window area Share of joint length

The relationship among variables and significance of the assessed variables on airtightness results were addressed through statistical analysis. The following variables were significant and, therefore, considered in the model proposed:

- Climate zone: climate was considered according to DB HE1 (Ministerio de Fomento. Gobierno de España 2019) regarding winter (zones A to E and α and summer severity (1-4). Climate severity combines degree-days and solar radiation in each location. From the international perspective, these zones would have the following equivalence in the Köppen-Geiger climate classification (Agencia Estatal de Meteorología (AEMET) 2011): A3 = Csa, B4 = BSk-Csa, C1 = Csb-Cfb, C2 = Csa, C3 = BSk, D2 = Csb, α3 = BSh.
- Period of construction: the age of the building is related to Energy Performance Regulations (EPR) over time. This fact was assessed by considering cases built before and after the first national regulations that established measures related to energy performance were implemented in 1980 (Ministerio de Obras Públicas y Urbanismo. Gobierno de España 1979).
- Typology: dwellings were classified as single-family or multi-family buildings given the impact that different construction systems and envelope features may entail. This variable is key in Spain, where multi-family housing prevails.
- Number of bathrooms: this variable considers the number of bathrooms of the dwelling, which are often associated with pipes and systems with an impact on the airtightness of wet rooms.
- Retrofitting estate: dwellings tested could be in their original state, or the envelope could have been retrofitted by their owners to a variable extent (windows replacement, external/internal insulation layer, etc.).
- False ceiling: the presence of this element can lead to the concealment of construction imperfections and, thus, leakages. A simplified characterisation was addressed considering dwellings with no false ceiling (FC0), dwellings with false ceiling only in corridor, kitchen and bathroom (FC1), and dwellings with false ceiling in all the rooms (FC2).
- Window permeability: the air permeability of windows was assessed according to UNE-EN 12207 (AENOR 2017) and classified as Class 0 (not tested windows), Class 1 (up to 50 $m^3/h\,m^2$), Class 2 (up to 27 $m^3/h\,m^2$), Class 3 (up to 9 $m^3/h\,m^2$), or Class 4 (up to 3 $m^3/h\,m^2$). It must be noted, though, that this information was not always available and could be just estimated from visual inspection.

- Window material: the impact of window frame material was considered (aluminium, PVC, wood, steel). The most representative material was considered when more than one type of window was found.
- Shutter position: shutters are widely used in Spain, and they have an important impact on the envelope airtightness since they constitute a discontinuity of the envelope. Rolling shutters were classified regarding their position: non-integrated shutters, external shutters, internal shutters, and no shutters, according to Figure 1. The most common solution is external shutters integrated into the inner layer of the envelope, whereas non-integrated shutters make reference to cases that originally had no shutter, and it is added constituting no additional leakages.

P.01	P.02	P.03	P.04



Non-integrated	Internal	External	No shutter

Figure 1: Shutter position classification.

- Heating system: this variable refers to the way in which the dwelling is heated, considering no heating system, heating units (e.g. radiators), underfloor heating, ducts, or other systems.
- Share of windows: it is the sum of the area of doors and windows related to the total envelope area. This parameter is closely related to A_h in the model proposed by Spanish regulations. This is a quantitative variable $[m^2]$.
- Share of opaque envelope: it is the sum of areas of the opaque thermal building envelope with heat exchange with the outdoor air related to the total envelope area of the dwelling. This parameter is closely related to A_0 in the model proposed by Spanish regulations. This is a quantitative variable $[m^2]$.

3 PREDICTIVE MODEL RESULTS

All analyses in this section: descriptive study, model estimation, variable selection and model validation, were performed with IBM SPSS software (IBM Corporation 2019).

3.1 Descriptive study

The outlier detection procedure mentioned in the previous section resulted in the elimination of 8 observations that had anomalous $\log(n_{50})$ values possibly due to measurement errors. Therefore, in the final model 392 observations are considered. Table 2 contains a descriptive study of the explanatory variables in the final model while

Table 3 gives a more detailed descriptive study of the initial response variable n_{50} and the final transformed response variable $\log(n_{50})$ and Figure 2 shows histograms of these two variables.

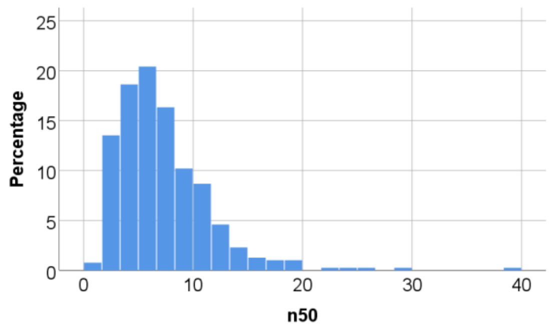
Table 2: Descriptive study for the explanatory variables in the final model. Variables marked with * were introduced in the improved model.

Variable	Value	N	%
Retrofitting state	Original	271	69.13%
	Retrofitted	121	30.87%
Climate zone	A3	33	8.42%

	B4	85	21.68%
	C1	47	11.99%
	C2	85	21.68%
	C3	112	28.57%
	D2	16	4.08%
	α3	14	3.57%
Period of construction	Before 1980	219	55.87%
	Since 1980	173	44.13%
Window permeability	Class 0 or 1	46	11.73%
	Class 2	196	50.00%
	Class 3	117	29.85%
	Class 4	33	8.42%
Window material	Steel	5	1.28%
	Aluminium	263	67.09%
	Wood	54	13.78%
	PVC	70	17.86%
Shutter position	P.01	19	4.85%
	P.02	290	73.98%
	P.03	21	5.36%
	P.04	62	15.82%
False ceiling	FC0	85	21.68%
	FC1	245	62.50%
	FC2	62	15.82%
Typology	Multifamily	317	80.87%
	Single-family	75	19.13%
Number of bathrooms*	0	3	0.76%
	1	159	40.56%
	2	166	42.35%
	3	43	10.97%
	4 or 5	21	5.36%
Heating system*	No heating	55	14.03%
	Underfloor heating	8	2.04%
	Ducts	36	9.18%
	Other systems	8	2.04%
	Heating units	285	72.70%
Share of windows	Mean		5.18
	Std. Dev.		2.04
Share of opaque envelope	Mean		25.07
	Std. Dev.		17.52

Table 3: Descriptive study for the variable n_{50} and the final transformed response variable $\log(n_{50})$.

	N	**Minimum**	**Maximum**	**Mean**	**Standard deviation**	**Lower quartile**	**Median**	**Upper quartile**
n50	392	1.1930	39.4217	7.2238	4.2981	4.3371	6.2763	9.1672
Log (n50)	392	0.18	3.67	1.8291	0.5463	1.4672	1.8368	2.2156



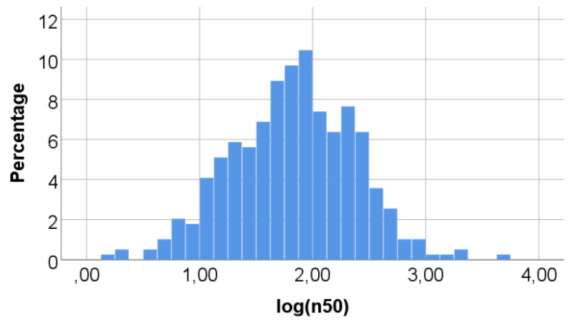


Figure 2: Histograms for the variable n_{50} and the final transformed response variable $\log(n_{50})$.

3.2 Predictive model

The improved predictive model contains 12 main effects and 2 interactions. The ANOVA table corresponding to this model is shown in Table 4. This table shows the variability of the response variable explained by each of the explanatory variables and interactions included in the model and whether this explained variability is statistically significant or not.

As a final caution, notice that we are not claiming that the variables that have been dropped in the selection procedure do not have any influence on airtightness. Their effect, as usual in multivariate statistical studies, may already be collected in the model by the variables that are already present in it.

Table 4: ANOVA table showing the variability of the response explained by each of the variables and interaction and its statistical significance. Variables marked with * were introduced in the improved model.

Source	Type III Sum of Squares	Degrees of freedom	Mean Square	F-value	p-value
Corrected model	49.997a	32	1.562	8.412	0.000
Intercept	18.359	1	18.359	98.845	0.000
Retrofitting state	1.120	1	1.120	6.030	0.015
Climate zone	9.226	6	1.538	8.279	0.000
Period of construction	2.612	1	2.612	14.063	0.000
Window permeability	4.688	3	1.563	8.412	0.000
Window material	1.985	3	0.662	3.563	0.014
Shutter position	1.841	3	0.614	3.304	0.020
False ceiling	3.172	2	1.586	8.540	0.000
Typology	1.227	1	1.227	6.606	0.011
Heating system*	1.832	4	0.458	2.465	0.045
Number of bathrooms*	2.844	4	0.711	3.828	0.005
Share of windows	2.904	1	2.904	15.634	0.000
Share of opaque envelope	0.553	1	0.553	2.976	0.085
Period of construction * Share of opaque envelope	2.541	1	2.541	13.678	0.000
Typology * Share of opaque envelope	1.112	1	1.112	5.985	0.015
Error	66.681	359	0.186		
Corrected Total	116.677	391			

a. R2 = .429 (Adjusted R2 = .378)

Table 5 contains the β_i and τ_{ij} coefficients of the equation of the final GLM model appearing in Equation (1) that can be used for predicting airtightness, together with the significance level of each coefficient. As usual in many studies, the convention used here is that p-values between 0.10 and 0.05 showed weak significance, p-values between 0.05 and 0.01 showed strong significance, and p-values less than 0.01 show very strong evidence of significance.

Table 5: Equation of the final GLM predictive model for airtightness.

Parameter	Coefficient	Parameter	Coefficient
Intercept	0.273	Shutter position. P04	0a
Retrofitting state. Original	0.137**	False ceiling. FC0	-0.313***
Retrofitting state. Retrofitted	0a	False ceiling. FC1	-0.264***
Climate zone. A3	0.346**	False ceiling. FC2	0a
Climate zone. B4	0.545***	Typology. Multifamily	0.412**
Climate zone. C1	0.273	Typology. Single-family	0a
Climate zone. C2	0.630***	Heating system. No heating	0.074
Climate zone. C3	0.053	Heating system. Underfloor heating	-0.041
Climate zone. D2	0.575***	Heating system. Ducts	0.261***
Climate zone. α3	0a	Heating system. Other systems	0.173
Period of construction. Before 1980	-0.329***	Heating system. Heating units	0a
Period of construction. Since 1980	0a	Number of bathrooms. 0	0.610**
Window permeability. Class 0 or 1	0.596***	Number of bathrooms. 1	0.347***
Window permeability. Class 2	0.322***	Number of bathrooms. 2	0.183
Window permeability. Class 3	0.255***	Number of bathrooms. 3	0.090
Window permeability. Class 4	0a	Number of bathrooms. 4 or 5	0a
Window material. Steel	0.071	Share of windows	0.045***
Window material. Aluminium	0.074	Share of opaque envelope	0.003
Window material. Wood	0.298***	Period of construction. Before 1980 * Share of opaque envelope	0.010***
Window material. PVC	0a	Period of construction. After 1980 * Share of opaque envelope	0a
Shutter position. P01	0.195*	Typology. Multifamily * Share of opaque envelope	-0.009**
Shutter position. P02	0.144**	Typology. Single-family * Share of opaque envelope	0a
Shutter position. P03	-0.123		

a. This parameter is set to 0 as it corresponds to the reference class of the variable.
* stands for p-value ≤ 0.1, ** for p-value ≤ 0.05 and *** for p-value ≤ 0.01

Figure 3 contains the residual analysis for this final GLM model. The graph shows that the main hypotheses of the model (linearity and homoscedasticity) can be assumed since no curvature or other shape is observed in the graph. Moreover, a single observation studentized residual appears outside the [-3,3] interval, which is completely compatible with the absence of significant outliers in the model.

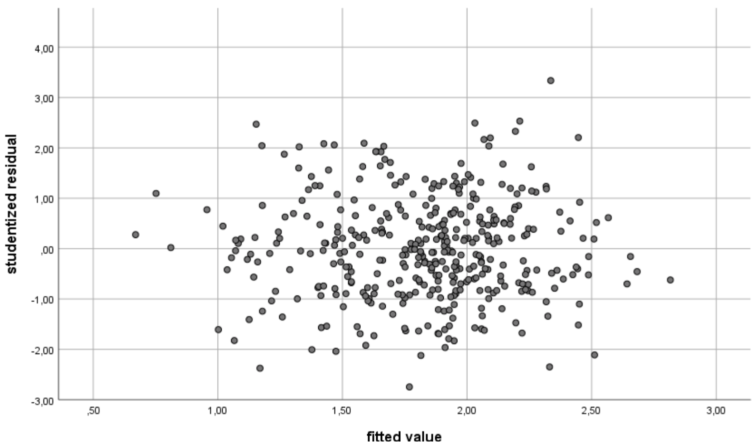


Figure 3: Residual analysis for the final GLM model proposed.

4 CONCLUSIONS

A GLM to predict the envelope airtightness was presented based on real test results obtained from a representative sample of existing dwellings in Spain. The methodology used to develop the model, although based on widespread strategies, offers added value regarding the origin of representative data, full characterization of the cases, standardised procedures, and the assessment of both quantitative and qualitative interactions.

The model allows the identification and analysis of factors with a significant impact on the level of airtightness. The variables that were found significant are in line with previously developed models: climate conditions, the age of the building, dimension-related characteristics, building systems, type of building, and conservation state. It considers, in addition, variables that refer to the singularities of the Spanish national built stock such as the effect of the position of rolling shutters, or the role of the share of the envelope to outdoors in the case of multi-family buildings. The improved model added the number of bathrooms and the heating system to obtain a better fit.

The R^2 value of this model is 0.429 so the model can explain 42.9% of the variability of the response, which slightly improves the R^2 value of the original model, which was 0.385. It should be noticed that, although this value may seem not too high, the relevance of the model is warranted by the significance of the coefficients and by the validity of its residual analysis.

In spite of identified limitations, the model is robust, and it provides valuable knowledge regarding the airtightness of dwellings and the factors that impact the most its performance. Therefore, it is intended as a useful tool although it cannot be seen in any way as a substitute of on-site testing.

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