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DOCTORATE IN ARCHITECTURE

PhD Thesis:

Airtightness performance of the building envelope of dwellings in Spain. Characterisation and energy impact of air infiltration

Presented by Irene Poza Casado for the fulfilment of the degree of Doctor by Universidad de Valladolid

Supervised by:
Jesús Feijó Muñoz
Alberto Meiss
Miguel Ángel Padilla Marcos

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SUMMARY

Only after the oil crisis in the 1970s has there been an undeniable growth in the level of interest in reducing the use of fossil fuels. In this regard, the countries of the European Union predict a sustainable, competitive and decarbonised energy system by 2050. For that purpose, it is crucial to address the energy efficiency of buildings, which are responsible for a significant percentage of energy consumption, and, therefore, greenhouse gas emissions. The potential seems obvious, considering that, according to the European Commission, 75% of the buildings in Europe are energy inefficient.

In this context, uncontrolled airflow through the building envelope, or air infiltration, is a phenomenon that involves energy loss since it needs to be conditioned at the interior comfort conditions. Air infiltration is also related to the ventilation of buildings and, thus, has an impact on indoor air quality. In this sense, a relationship is established between air infiltration, energy impact and ventilation. Since airtightness is the main characteristic of the envelope that determines air infiltration, its study is essential to understand the performance of the building envelope.

However, this issue has not been addressed in depth in most countries with temperate climates, and, specifically, in Spain, given the traditional dependence of air renewal on air infiltration. Currently, the implementation of controlled ventilation systems guarantees adequate indoor air quality in residential buildings. Therefore, air infiltration is no longer necessary as an air renewal source and, consequently, its reduction is a priority to achieve nearly zero-energy buildings (nZEB). In this sense, the airtightness characterisation of the envelope of existing buildings is essential to prioritise efforts and determine strategies for the renovation of the existing building stock according to the decarbonisation objectives which have been set at a national and international level.

To meet these needs, the general objective of this work focuses on the characterisation of the airtightness of the envelope of residential buildings in Spain, framed within the INFILES research project (BIA2015-64321-R), funded by the Ministry of Economy and Competitiveness of the Government of Spain.

As a starting point, the state of the art was addressed and the airtightness regulatory frameworks in Europe and North America were compared. Additionally, the main databases and protocols for evaluating the airtightness of the envelope were assessed. Its analysis allowed the identification of the weaknesses, threats, strengths, and opportunities of these practices. Likewise, the main keys for the development of a common outline at the international level were detailed.

The characterisation of the airtightness of the envelope of the residential building stock in Spain was carried out in a representative sample of cases that allowed the extrapolation of the information obtained. A quota sampling scheme defined by representative variables regarding the airtightness of the envelope such as the climate zone, location, year of construction, and building typology, was proposed. In short, 401 cases proportionally distributed in single-family and multi-family dwellings, built in different periods, and located in several cities, were analysed.

This sample generated a database that collects information on the complete characterisation of both construction features and the airtightness of buildings. To facilitate data management, a specific

application was developed, which enabled the sequential and standardised storage of information, whose operation could be replicable in other contexts.

The airtightness of the case studies was evaluated by means of fan pressurisation tests, according to the international standard UNE-EN 13829. In addition, a specific methodology was developed to guarantee the uniformity and reliability of the information gathered. Airtightness results were wide-ranging, which indicates the uneven performance of the buildings tested. Nevertheless, the distribution of the average values was in line with previously reported findings both in Spain and in other European countries. Different trends were identified by climate zone: the envelope of the cases located in areas with Oceanic and Continental climates was more airtight than that of the dwellings located in areas with a Mediterranean climate with a temperate cold season.

On the other hand, contrary to what might be expected, no clear trend of airtightness improvement was observed with regard to the year of construction. The different regulations regarding the energy efficiency of buildings did not lead to a significant improvement of the airtightness of the building envelope. Therefore, it seems clear that the existing residential stock in Spain remains far from the standards and practices that are already a reality in other European countries. However, the recent regulatory limitation of the global air permeability of the envelope opens a window to a change in this trend and represents an opportunity for real achievement of nZEB.

The relationship between different building characteristics and the degree of airtightness was addressed through statistical analysis. Although the limitation of the sample did not allow the development of a detailed study, a relationship was identified between the airtightness and the type of windows, the rolling-shutter system used, and the degree of renovation of the envelope. In this sense, the main leakage paths were located using infrared thermography, which allowed the identification of typical deficiencies of residential buildings in Spain. Turbulent flows through cracks located around windows and rolling shutters concentrated the main leakages. The inadequate design of the constructive solutions, as well as the careless workmanship of the joints between different elements, were pointed out as the main causes that prevent airtight envelopes, and, consequently, they pose the main challenges to face in the future.

Finally, the energy impact of air infiltration on the heating and cooling demand in the cases studied was addressed, applying a simplified model for estimating the average air change rate. The results demonstrate the high energy impact of air infiltration, which reaches values of up to 25% of the heating demand. This confirms the substantial potential for energy-saving if the air permeability of existing buildings was reduced.

The characterisation of the airtightness of the envelope of residential buildings in Spain contributed to filling the knowledge gap identified. Only in this way will future design criteria and renovation strategies of existing energy-inefficient buildings be approached in a realistic way, in accordance with the established decarbonisation targets.

RESUMEN

Desde la crisis del petróleo en los años 70, es palpable el creciente interés experimentado por la reducción del uso de la energía de origen fósil. Tanto es así, que los países de la Unión Europea auguran un sistema energético sostenible, competitivo y descarbonizado en 2050. Para ello, es de vital importancia abordar la eficiencia energética de los edificios, puesto que estos representan un importante porcentaje del consumo de energía, y, por ende, de las emisiones de efecto invernadero. El potencial parece evidente, considerando que, según la Comisión Europea, el 75% de los edificios en Europa son energéticamente ineficientes.

En este contexto, el paso de aire de un modo incontrolado a través de la envolvente, o infiltración, es un fenómeno que supone un aporte energético para reacondicionarlo conforme a las condiciones interiores de confort. La infiltración de aire también está relacionada con la ventilación de los edificios y, por lo tanto, genera una repercusión en la calidad del aire interior. En este sentido, se establece una relación entre el fenómeno de infiltración, impacto energético y ventilación. Puesto que la hermeticidad al aire es la principal característica de la envolvente que condiciona la infiltración de aire, su estudio es fundamental para comprender el comportamiento de la envolvente de los edificios.

Sin embargo, esta cuestión no se ha abordado en profundidad en la mayoría de los países con climas templados, y, concretamente, en España, dada la tradicional dependencia de la infiltración de aire en los procesos de renovación del aire interior. En la actualidad, la implementación de sistemas de ventilación controlada garantiza una adecuada calidad del aire interior en los edificios residenciales. Por lo tanto, la infiltración ya no es imprescindible como mecanismo de renovación del aire interior y, por consiguiente, es prioritaria su reducción para la consecución de edificios de consumo casi nulo. En este sentido, la caracterización de permeabilidad al aire de la envolvente de los edificios existentes es fundamental para priorizar esfuerzos y determinar estrategias para la renovación del parque construido existente conforme a los objetivos de descarbonización planteados tanto a nivel nacional como internacional.

Para dar respuesta a esta necesidad, se ha planteado el objetivo general de este trabajo, que se centra en la caracterización de la hermeticidad al aire de la envolvente de los edificios residenciales en España, al amparo del proyecto de investigación INFILES (BIA2015-64321-R), financiado por el Ministerio de Economía y Competitividad del Gobierno de España.

Como punto de partida, se ha abordado el estado de la cuestión y comparado el marco normativo de hermeticidad al aire en Europa y Norte América, así como las principales bases de datos desarrolladas y protocolos de evaluación de la permeabilidad de la envolvente. Su análisis ha permitido la identificación de las debilidades, amenazas, fortalezas y oportunidades de estas prácticas. Asimismo, se han detallado las principales claves para el desarrollo de un marco común a nivel internacional.

La caracterización de la hermeticidad al aire de la envolvente del parque residencial en España se ha llevado a cabo en una muestra representativa de casos que ha permitido extrapolar la información obtenida. Para ello, se ha planteado un esquema de muestreo por cuotas definido por variables representativas en cuanto al comportamiento de la envolvente, como la zona climática, localización, año de construcción, y tipología edificatoria. En definitiva, se han analizado 401 casos de viviendas

unifamiliares y plurifamiliares, pertenecientes a diferentes períodos de construcción, y ubicados en diferentes ciudades de manera proporcional.

Esta muestra ha generado una base de datos que recoge información completa de caracterización tanto constructiva como de hermeticidad al aire. Para facilitar el tratamiento de los datos, se ha desarrollado una aplicación específica que facilita el guardado secuencial y estandarizado de la información, cuyo funcionamiento podría ser replicable en otros contextos.

La hermeticidad al aire de los casos de estudio se ha evaluado mediante ensayos de presurización por medio de ventilador, de acuerdo con la norma internacional UNE-EN 13829. Además, se ha desarrollado una metodología específica para garantizar la uniformidad y fiabilidad de la información recogida. Se han obtenido resultados de hermeticidad al aire en un amplio rango, lo que denota el comportamiento dispar de los edificios, si bien la distribución de los valores medios está en la línea de los hallados en estudios previos tanto en España como en otros países europeos. Se han identificado distintas tendencias por zona climática: la envolvente de los casos situados en zonas con clima oceánico y continental es más hermética al aire que la de las viviendas situadas en zonas con clima mediterráneo, donde los inviernos no son extremos.

Por otro lado, contrario a lo que cabría esperar, no se ha observado una clara tendencia de mejora de la hermeticidad al aire de la envolvente en función del año de construcción. Las diferentes normativas relativas a la eficiencia energética de los edificios no han conllevado una mejora significativa frente al paso incontrolado de aire. Por lo tanto, parece claro que el parque residencial existente en España aún se encuentra lejos de los estándares y prácticas que ya son realidad en otros países europeos. No obstante, la reciente limitación normativa de la permeabilidad al aire global de la envolvente abre una ventana a un cambio en esta tendencia y supone una oportunidad hacia la consecución real de edificios de consumo casi nulo.

La relación entre diferentes características constructivas y el grado de hermeticidad al aire se ha abordado mediante análisis estadístico. Si bien la limitación de la muestra no ha permitido el desarrollo de un estudio pormenorizado, sí se ha identificado una relación entre la hermeticidad al aire y el tipo de carpintería, sistema de persiana empleado, y grado de renovación de la envolvente. En este sentido, se han localizado los principales focos de infiltración mediante termografía infrarroja, lo cual ha permitido la identificación de las discontinuidades más comunes en los edificios residenciales en España. Los focos de carácter turbulento mediante aberturas localizadas en torno a los huecos de ventanas y persianas concentran los principales pasos de caudales de infiltración. El diseño inadecuado de las soluciones constructivas, así como la descuidada ejecución de los encuentros entre diferentes elementos se han señalado como las principales causas que impiden envolventes más estancas, y, en consecuencia, suponen los principales retos a afrontar en el futuro.

Finalmente, se ha abordado el impacto energético de la infiltración de aire en la demanda de calefacción y refrigeración de los casos analizados, aplicando un modelo simplificado de estimación de la tasa media de renovación de aire. Los resultados obtenidos permiten comprobar el alto impacto energético de la infiltración de aire, que alcanza valores de hasta el 25% de la demanda de calefacción. Con ello, se confirma el considerable potencial de ahorro energético, para lo cual es necesario limitar la permeabilidad al aire de los edificios existentes.

La caracterización de la hermeticidad al aire de la envolvente de los edificios residenciales en España llevada a cabo ha contribuido al desarrollo del conocimiento en este ámbito, lo cual será fundamental para determinar futuros criterios de diseño y estrategias de renovación de los edificios existentes ineficientes energéticamente con un enfoque realista, de acuerdo con los objetivos de descarbonización establecidos.

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1 INTRODUCTION

1.1 CONTEXT AND BACKGROUND

Since the mid-1970s and the oil crisis, the need to reduce energy has led to a growing interest in the energy efficiency and performance of buildings. To this end, several international agreements have driven effort to reducing energy use and CO_2 emissions. The European Union (EU) is committed to reducing at least 55% of the greenhouse gas emissions (from 1990 levels) by 2030, and to establishing a sustainable, competitive and decarbonised energy system by 2050. This goal is crucial to the European Green Deal and aligns with the EU's Paris Agreement (2015) commitment to global climate action (United Nations, 2015).

In this sense, the building sector is critical to the EU's energy and environmental aims. At present, it is estimated that buildings are responsible for approximately 36% of the greenhouse gas emissions and that almost 50% of final energy consumption of the EU is used for heating and cooling. Moreover, around 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient (Filippidou & Jimenez Navarro, 2019).

The EU has built a legislative framework to improve the energy performance of buildings, which comprises the Energy Performance of Buildings Directive (EPBD) 2010/31/EU (European Parliament, 2010), the Energy Efficiency Directive 2012/27/EU (European Parliament, 2012), and the amend Directive 2018/844/EU (European Parliament, 2018). The EPBD covers a broad range of policies and measures to improve the existing building stock. For instance, strong long-term renovation strategies and the fact that all new buildings must be nearly zero-energy buildings (nZEB), aiming at decarbonising the national building stocks by 2050.

However, there is a low replacement rate of existing and outdated dwellings by new or renovated ones under the new energy standards. This requires action with applicable models on existing buildings. In this regard, the renovation wave strategy was presented in October 2020 as part of the European Green Deal with the objective of fostering deep renovation of buildings. Therefore, an update of the EPBD, currently under revision, will focus on the central aims while also contributing to the decarbonisation of buildings. Consequently, it seems essential to establish strategies that support the renovation of national buildings stocks, facilitating their transformation into nZEB. The reduction of heat transmission through the building envelope by the progressive improvement of the construction materials, and the increase of the insulation standards have been decisive in this regard.

However, the presence of air infiltration involves great energy impact on the overall energy performance of buildings and is often overlooked. Uncontrolled airflows through the building envelope generate a phenomenon of air mass exchange between the inside and the outside of the conditioned space, causing energy transfer with different hygrothermal conditions of air that encompass extra energy consumption. Furthermore, uncontrolled airflows caused by air infiltration reduce the operating efficiency of mechanical ventilation with heat recovery systems (Kraus & Kubečková, 2014).

The improvement of construction materials regarding heat transmission has caused, thus, a significant increase in the proportion of heat loss due to air infiltration through the building envelope

(Awbi, 2004). Therefore, advanced insulating materials have significantly solved the energy loss issue due to conduction through the building envelope, but the energy loss due to convection caused by air leakage cannot be ignored any longer. Infiltration, essentially determined by building airtightness, represent 10%–30% of the heating demand (Domínguez-Amarillo, Fernández-Agüera, Campano, & Acosta, 2019; Huang, Hanford, & Yang, 1999; Jokisalo, Kurnitski, Korpi, Kalamees, & Vinha, 2009; Jones et al., 2015; Kalamees, 2007; Meiss & Feijó-Muñoz, 2015; Simson, Rebane, Kiil, Thalfeldt, & Kurnitski, 2020; Zheng, Cooper, Gillott, & Wood, 2020).

The consequences of air infiltration are usually related to energy loss, but also to the impact on the ventilation performance and, therefore, Indoor Air Quality (IAQ) (Liddament, 1986). In the case of multi-family buildings, internal leakages might lead to the dispersion of fire gases and indoor pollutants spread, leading to an impact on the IAQ and, thus, even the health of the occupants (Sandberg, Bankvall, Sikander, Wahlgren, & Larsson, 2007).

The interdependency of airtightness, ventilation, and energy use has been demonstrated in studies on the interaction between these parameters (Sherman & Chan, 2004). As a result, the first step in reducing energy consumption and air quality issues associated with air infiltration is to understand buildings' airtightness.

In addition, leakages can cause other problems related to interstitial condensation produced by warm air exfiltration through the building envelope in cold climates, which can cause damage in construction materials and even in the structure (ASHRAE, 2021; Dorer, Tanner, & Weber, 2004; Younes, Shdid, & Bitsuamlak, 2012). Another consequence of leakages is the reduction of the performance of thermal insulation and other materials installed in the building envelope (Claesson & Hellström, 1995; Powell, Krarti, & Tuluca, 1989). Problems related to cold draughts and generally uncomfortable environments have also been reported (Liddament, 1986). Furthermore, noise and odours can penetrate the building through leakages.

Despite its numerous drawbacks, air infiltration combined with the use of openable windows, vents, and exhausts, continues to play a significant role in addressing the air renewal needs of building in a large number of countries (Liddament, 1986; Nazaroff, 2021). This is the case of Mediterranean countries, and Spain specifically, where there has been little concern regarding airtightness until recent years given its dependency on air renewal needs. Airing has traditionally been done by the manual opening of windows and doors. Infiltration, therefore, is essential in dwellings with no controlled ventilation system since it is the only continuous uncontrolled air renewal source. However, this approach results in several drawbacks:

- The opening of windows and doors depends on users' behaviour and it is not based on any objective criteria (Johnson & Long, 2005). Therefore, there is a risk of over ventilation and under ventilation;
- Infiltration depends on natural forces (temperature difference and wind), so it is not controlled nor guaranteed if certain conditions are not met;
- The level of the airtightness of the envelope is generally unknown;
- There is a lack of control of the inlet air, which does not have a filtration process.

All things considered, the issues related to the varying air change rates, poor control, and uncertain air distribution have become key factors in both building design and building renovation (Liddament, 1986). In this regard, mandatory ventilation system design came into force in Spain in 2006 to guarantee adequate IAQ in dwellings (Ministerio de Vivienda. Gobierno de España, 2006b). Either minimum ventilation performance based on CO_2 concentration or minimum airflows is required in dwellings by current building regulations (Ministerio de Fomento. Gobierno de España, 2019b). Simple flux systems are nowadays a widespread solution with pollutants and moisture exhaust in bathrooms and kitchens that force the air admission through leaks and purpose-provided openings in the living areas of dwellings.

Additionally, great efforts are being made to improve existing buildings in terms of energy efficiency, in line with European Directives. In compliance with EPBD, Spain developed the ERESEE 2020: “2020 Update of the long-term Strategy for Energy Rehabilitation in the Building Sector in Spain” (Ministerio de Transportes Movilidad y Agenda Urbana, 2020), which established a roadmap with intervention scenarios, measures and progress indicators for the renovation of the building stock, the economically profitable transformation of existing buildings into nZEB, and the decarbonisation of the sector by 2050. The objective is a 36.6% reduction of the energy use in buildings, of which it is estimated that 60% is destined for heating and hot water.

Actions towards better energy efficiency usually encompass the improvement of the thermal performance of the exterior envelope (by installing new windows, or by adding an insulation layer either on the inside or the outside of the envelope (Camino-Olea, Losa-Espina, Cabeza-Prieto, & Llorente-Álvarez, 2020; Fernández-Agüera, Domínguez-Amarillo, Alonso, & Martín-Consuegra, 2019)), and have, therefore, a direct impact on airtightness as a consequence. Those measures improve the thermal performance of buildings, but, on the other hand, they may result in air renewal decrease. In other words, if no ventilation system is implemented to provide the dilution of indoor contaminants, the IAQ may suffer (Sherman & Chan, 2004). The condensation of damp air in contact with cold envelope surfaces due to airtight envelopes and a lack of ventilation frequently cause mould.

In this context, residential buildings are the most common building use in Spain, where there are about 25.7 million dwellings (Eurostat, 2018). Around 60% (13.8 million) of the existing dwellings were built before the first energy efficiency norm came into force (Ministerio de Obras Públicas y Urbanismo. Gobierno de España, 1979), so the potential energy saving for renovation actions is huge.

All things considered, it seems clear that, in order to accomplish nZEB in line with European Directives, tight building envelopes must be encouraged, but definitely accompanied by the implementation of ventilation strategies. The major goal from a design standpoint is to reduce energy use by limiting air infiltration while guaranteeing good IAQ.

1.2 JUSTIFICATION

The airtightness of the building envelope has been broadly studied since the 1970s in northern European countries, the USA, and Canada. In recent years, weatherisation programs in the USA, and airtightness requirements in some European countries, have caused the creation of large airtightness databases, which provide valuable information to understand the performance of the building envelope and allow the evaluation of the progress of those building stocks in meeting building performance objectives. Airtightness data is mostly focused on residential buildings due to its prevalence and testing limitations in commercial buildings.

However, there is a lack of knowledge in this regard in Mediterranean countries as a result of mild climate and traditional dependency on air infiltration as an air renewal source. In addition, specific building systems and configuration precludes the option to assimilate results from other countries. Nowadays, though, the need to comply with EPBD has led to a change in the scenario, and, in order to meet energy requirements, the building envelope will necessarily tighten. Whole building airtightness requirements applicable for new or renovated dwellings bigger than 120 m^2 were recently introduced in Spain (Ministerio de Fomento. Gobierno de España, 2019a). However, systematic airtightness testing is not mandatory to prove compliance.

Airtightness tests are usually only performed to comply with voluntary energy programmes (Passivhaus, BREEAM, LEED, etc.), by constructors who wish to ensure the quality of construction, or as a diagnostic tool in case of the poor energy performance of the building or before retrofitting actions. In any case, this data is scarce, not publicly available and belong to very specific types of buildings, which are not representative of the housing stock of the country. In the field of research, some studies on airtightness in Spain have been carried out so far focused on specific building stocks (Fernández-

Agüera, Domínguez-Amarillo, Sendra, Suárez, & Oteiza, 2018; Ibanez-Puy & Alonso, 2019; Jiménez Tiberio & Branchi, 2013; Meiss & Feijó-Muñoz, 2015; Montoya, Pastor, & Planas, 2011). Although there is the general belief that new construction tends towards a better performance of the building envelope in terms of airtightness (ASHRAE, 2021), these assumptions might not be true in the context of the Spanish residential sector.

Characterising the building envelope of the existing housing stock and understanding its performance is crucial in order to prioritise the efforts towards renovation policies. Broad knowledge on the identification of the main leakage paths and their quantification to address the contribution of air infiltration to the energy load and air renewal is necessary to approach deep renovation strategies aiming at decarbonising the national building stock by 2050. This is precisely what this Thesis addresses contributing, thus, to filling the knowledge gap.

1.3 INFILES PROJECT

This Thesis is framed in the INFILES research project: "Energy impact of the permeability of residential buildings in Spain: study and characterisation of the air infiltration" (BIA2015-64321-R), funded by the Spanish Ministry of Economy and Competitiveness of the Spanish Government on its competitive call for "Excellence" and "Challenges" projects 2015.

The project was addressed towards the Spanish Strategy of Science, Technology and Innovation, as part of the challenge regarding action on climate change and efficiency on the use of resources and raw materials.

INFILES, which lasted from 2016 until 2019, was coordinated from Universidad de Valladolid by the Principal Investigator Jesús Feijó Muñoz. Other universities participated in the project: Universidade da Coruña, Universidad de Alicante, Universidad Politécnica de Cataluña, Universidad CEU San Pablo, Universidad de Málaga, Universidad del País Vasco, Universidad de las Palmas de Gran Canaria, and Universidad de Sevilla.

The main objectives of INFILES projects were:

- To characterise the residential building stock by establishing real airtightness values and infiltration rates;
- To study the main leakage paths of the building envelope;
- To establish airtightness parameters for general use, so that they are representative in building simulation and certification;
- To study the energy impact of air infiltration dependent on the level of airtightness;
- To compare the performance of the Spanish building stock with other countries;
- To propose airtightness guidelines according to other countries' frameworks.

Therefore, an extensive study was carried out in order to characterise the envelope of the existing residential stock in Spain. A rigorous and simple methodology was developed for the purposes of the project under a unified procedure and criteria, which could be easily applicable to other countries with analogous objectives. The protocol developed is available in Annex III: Testing protocol.

Airtightness tests were performed in representative dwellings through coordinated testing campaigns in order to quantify its performance related to specific building features and establish relations. The selected dwellings of the sample were located in different regions of the country with the aim of covering different climate zones and buildings (Alicante -B4-, Bilbao -C1-, A Coruña -C1-, Madrid -D3-, Sevilla -B4-, Tenerife -α3- and Valladolid -D2-). The dwellings tested constituted an airtightness repository, which could entail the origin of a national database in order to serve ultimately as a tool on the progress of the knowledge of airtightness in the country.

The main outputs of the project can be checked in Feijó-Muñoz et al. (2019), and the published papers that constitute the core of this Thesis. Additionally, the full reports obtained from all the cases studied are gathered in Annex IV: Test reports and an extract of the main airtightness results can be seen in Annex V: Test results.

In this context, the PhD candidate contributed by performing the following tasks:

- Design of the sampling method to select the case studies of the residential airtightness database;
- Experimental campaign design;
- Development of the Testing Protocol and characterisation parameters;
- Test performance of some of the pressurisation tests;
- Responsible trainer of the technicians that completed the experimental campaigns;
- Supervision of the experimental campaigns;
- Statistical analysis of the measurement results;
- Energy impact estimation;
- Diffusion of the project results attending national and international conferences and writing scientific papers listed within Annex I: Scientific dissemination;
- Co-author of the final report *Permeabilidad al aire de los edificios residenciales en España. Estudio y caracterización de sus infiltraciones* (2019), Ediciones Asimétricas. ISBN: 978-84-949522-5-8 (see Annex I: Scientific dissemination).

Furthermore, this Thesis transcended the frame of INFILES Project and carried out further research in the field of airtightness databases, whose main outputs are summarised in ***Paper 5***.

1.4 RESEARCH QUESTIONS

This Thesis aims at contributing to filling the knowledge gap regarding the performance of the building envelope in residential buildings in Spain. Therefore, the following general research question is posed:

How does the building envelope of the existing residential stock in Spain perform in terms of airtightness?

This is a broad issue that needs the understanding of different phenomena. The lack of previous representative data in Spain required the selection of a sample to characterise and draw valid conclusions.

The posed question is then answered in the published scientific papers that compose this Thesis through the following secondary questions:

How should airtightness data be managed to provide valuable and comparable information?

The study of the performance of the airtightness of the building envelope at a population scale involves the management of large datasets. Databases can offer useful information to compare building performance, to visualise trends and progress in meeting the energy performance objectives, to evaluate the effectiveness of individual measures and building design, to identify factors that impact the level of airtightness, and to provide accurate input data for building modelling. However, the approach is different depending on the context, and different setups have been established among countries, so comparing reliable information often encompasses a challenge. This question is answered in ***Paper 1*** and ***Paper 5***.

How airtight are dwellings?

Airtightness is the main building feature that conditions air infiltration, so its determination is critical to understand air infiltration processes. The evaluation of the airtightness of the building envelope is performed through airtightness measurements, which quantify its level of permeability. Airtightness data can be reduced to the quantification of the absolute size of the leakage paths in the building, determined by adding the respective individual leakage areas, a parameter that provides information regarding the relative size of the most significant leaks, or normalised measures that allow comparison among buildings. This question is answered in ***Paper 2***, ***Paper 3***, and ***Paper 4***.

Where are the main leakage paths located?

The qualitative assessment of air leakage is key to understanding the performance of the building envelope. The location of the main infiltration paths allows the identification of gaps and imperfections that can be a result of inadequate design, poor workmanship, or the deterioration of building materials over time. The assessment of the main leakage paths constitutes the first step towards the development of alternative tight building systems, and the proposal of realistic renovation strategies that enable meeting the requirements for an energy-efficient and decarbonised building stock. This question is answered in ***Paper 2*** and ***Paper 3***.

Which are the main factors that condition the airtightness of dwellings?

The analysis of a representative sample of a building stock allows the identification of different factors that condition the level of airtightness of buildings. The interrelation of different parameters may be a complex issue, but it can offer valuable information for designers and contractors in their decision-making process to seize the impact of certain choices or specific retrofitting solutions. The connection between the level of airtightness and certain building features may constitute the basis for predictive models that estimate the performance of the building envelope. This question is answered in ***Paper 2*** and ***Paper 3***.

How much energy does air infiltration lose?

The lack of airtightness leads to the presence of air infiltration under certain temperature and pressure difference conditions. Uncontrolled airflows through the building envelope make it necessary to recondition the infiltrating outdoor air to the indoor environment conditions, which involve energy loss. Quantifying the energy waste is important to estimate the potential on energy-saving through retrofitting actions and, thus, assess in a realistic way the implementation of policies and strategies both in the short and long term. This question is answered in ***Paper 3*** and ***Paper 4***.

1.5 OBJECTIVES

In line with the questions raised herein, which have driven the development of this work, several objectives are outlined. The general objective aims at answering the main research question:

To characterise the airtightness of the building envelope in existing dwellings in Spain.

Obtaining information on the performance of the building envelope of the existing residential stock is essential to identify related problems, but also opportunities to approach deep renovation strategies and policies. This will enable the responsible agents to prioritise the efforts. To reach this general objective, secondary objectives have been considered:

1. *To understand the existing information and data to be obtained for the evaluation of the airtightness of residential buildings.*

The state of the question in the current international and national contexts needs to be addressed in order to identify key knowledge gaps and needs. The assessment of previous practices and setups will set the basis for the development of the work proposed with the aim of filling the research gap.

2. *To gather, evaluate, and study international procedures and methods for the determination of the air permeability of buildings.*

Several methods to quantify the level of airtightness of buildings have been developed so far for different purposes. In this regard, the main opportunities and drawbacks will be identified in order to determine the most fitting approach to meet the objectives of this work. At a national stock level, the measurement protocols and standards used differ significantly between regions. The systematic comparison of measurement protocols will provide useful information on similarities and disparities between current practices.

3. *To identify the procedures for cataloguing airtightness phenomena.*

The airtightness characterisation at a national level involves the management of large datasets that need to be gathered in a coordinated, systematic, and efficient way, which provides ultimately valuable and accurate data analysis. Therefore, the main databases on airtightness will be explored by identifying the data available, the input scheme, their purpose, the analyses performed, and their overall structure and requirements. Furthermore, a systematical comparison of the databases will be performed, discussing their differences and gaps. In this way, their strengths and weaknesses, problems in the existing practices, as well as opportunities for future actions, will be identified.

4. *To quantify the airtightness of the building envelope of residential buildings in Spain.*

In order to evaluate de current state of the building stock, the airtightness of the building envelope will be measured using the appropriate procedures selected for that purpose. In this regard, representative dwellings of the current residential building stock, that allow inferring the results obtained to analogous populations, will be selected and systematically assessed.

5. *To analyse the current state of the building stock in terms of airtightness according to the indicators and building characteristics.*

The analysis and diagnosis of the obtained results will offer useful information in order to determine the performance of the building envelope, to make comparisons with other countries, to visualise time trends, to evaluate building design, construction practices and quality, to provide typical accurate values for building energy and air renewal estimations, and, finally, to develop clear guidelines for airtightness design and improvement in renovation actions.

6. *To identify typical leakage paths using proven and viable techniques.*

The building envelope of representative dwellings will not only be quantitatively assessed but also qualitatively evaluated. The appropriate methods will be selected in order to locate the main leakage paths and, thus, typical construction discontinuities and defects of specific building systems will be identified.

7. *To study the main factors that define the degree of air permeability of buildings.*

The statistical approach of the data gathered will enable the analysis of current building solutions and other factors that may have an impact on airtightness. Statistical tools will be useful to draw accurate conclusions and to establish relationships among building characteristics and the performance of the building envelope. This information will be valuable for design and renovation decisions.

8. *To evaluate the energy impact of air infiltration in residential buildings.*

Air infiltration is the result of the lack of airtightness of the building envelope under the action of driving forces. Understanding this phenomenon is crucial in order to determine air infiltration rates that not only provide air change, but also encompass energy impact. Its evaluation will fill a current knowledge gap that will enable the quantification of potential energy-saving and the implementation of future energy policies and strategies in a realistic way.

1.6 THESIS OUTLINE

This section gives an overview of this Thesis and its structure. First, an **Introduction** offers an overview of the **Context and background** of airtightness in Spain, the **Justification**, and the outline of the **INFILES Project**, within which this Thesis is framed. The knowledge gap found precedes the **Research questions** posed and the concordant **Objectives**.

A second section outlines the **State of the art** regarding different aspects that have been revised, which constitute the knowledge background that supported the basis for this contribution. A brief review of the existing literature that includes the knowledge of **Airtightness of the building envelope** and **Air infiltration** and its fundamentals and relationship, the most used **Airtightness measurement** methods and guidelines, and **Leakage location** procedures provide the basic context.

Furthermore, general literature focused on the estimation of the **Air infiltration rate from airtightness measurements** is presented, which is needed to estimate the **Impact of air infiltration on energy performance** and **ventilation** of dwellings. This framework justifies the existence of **Airtightness requirements** in different countries as well as **Airtightness databases** created in different countries, which constituted the references for the Spanish database developed. Previous work that was carried out from several airtightness databases that analysed the main **Factors influencing airtightness** was also reviewed.

The specific context of **Airtightness of the building envelope in Spain** was addressed including a review of the **Construction systems of the envelope**, typical **Leakage paths on the Spanish building envelope**, **Airtightness requirements in Spain**, **Ventilation strategies in Spanish dwellings**, **the Background on the study of airtightness in Spain,** and **Airtightness estimation in Spain.** This context has laid the foundations for the research developed and presented within this Thesis. It was not intended to review all the existing literature, but to offer a general overview of the state of knowledge in this research field until the most recent work developed.

The **Methods** section resumes the procedures and techniques used for the development of the work carried out. This section addresses the **Determination of the sample**, in other words, the procedures and the criteria established to determine the cases to study. It also shows the sample and distribution of the cases, as well as the **Characterisation of the dwellings** and their distribution. The methodology used to measure the airtightness of the dwellings (**Determination of the air permeability**) by means of pressurisation tests and the **Leakage location** using infrared (IR) thermal imaging are first detailed. The analytical procedures to evaluate the **Air infiltration rate estimation** from the airtightness results obtained and the Energy impact assessment are detailed. Finally, the procedures that were used for **Data analysis** of the results are presented.

The core of this Thesis is gathered in 5 **Scientific papers that support the research work,** which are referred to along the text as ***Paper 1***, ***Paper 2***, ***Paper 3***, ***Paper 4***, and ***Paper 5***. This section presents the full papers introduced by the common framework, which establishes a connection among them, and the contribution of each one to the research work carried out.

The main **Results** derived from the work are referred to, and finally, the main **Conclusions** are summarised. The partial conclusions of each of the scientific papers included in this Thesis are then contextualised in the global entity of this contribution. The research questions are then answered, relating the conclusions to the objectives set. Lastly, the main limitations found are highlighted, which trigger **Future research lines** and proposed work to be carried out.

Additional publications referenced in **Annex I: Scientific dissemination** complement the research carried out and offer further information. **Annex II: International mention** justifies the international work at Faculdade de Engenharia of Universidade do Porto in 2019 in collaboration with the Research Group CONSTRUCT - Instituto de I&D em Estruturas e Construções. LFC – Laboratory of Building Physics. The protocol developed for the purposes of INFILES project can be checked in **Annex III: Testing protocol**. All the test reports of the cases assessed are available in **Annex IV: Test**

reports. To conclude, the main outcomes of the cases tested, and further statistical analyses performed are gathered in **Annex V: Test results**.

On the other hand, it must be taken into account that given the nature of this Thesis as a compendium of scientific papers, some information might be partially reproduced in this document.

2 STATE OF THE ART

2.1 AIRTIGHTNESS OF THE BUILDING ENVELOPE

Airtightness is a "*qualitative term describing the integrity of the building envelope relative to air permeation; the resistance of the building envelope to the flow of air and entrained moisture*" ("ASHRAE Terminology," n.d.). Other authors have described airtightness as "*the ability of the envelope of the structure to resist the flow of air through it. […] Airtightness can be thought of as the resistance of an enclosure to allow air to cross its boundaries*" (Colliver, Murphy, & Sun, 1992, pp. 3–1). Therefore, airtightness is a characteristic of the building envelope that can give an idea of its construction quality.

Its importance resides in the fact that it is the main building feature that impacts air infiltration (Sherman & Chan, 2004) and, thus, measuring and characterising airtightness is key to assessing the air infiltration through the building envelope.

Air infiltration is the "*uncontrolled leakage of air into a house, that results from pressure differentials across its envelope induced by wind and inside-outside temperature*" (Shaw, 1981, p. 333). It is important not to confuse this term with ventilation, which is "*the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space*" ("ASHRAE Terminology," n.d.). In the concept of *ventilation*, it is implied that the process is intentional and controlled in contrast to uncontrolled airflows of infiltration. Both definitions are here presented since they will be key concepts along with the text. Nevertheless, this distinction is often omitted, and air infiltration can also be found referred to as ventilation because leakage contribution was traditionally essential for air renewal in naturally ventilated buildings.

Etheridge and Sandberg (1996) classified air leakage paths as adventitious openings, in contrast with purpose-provided openings. In this sense, infiltration is referred to in the scientific literature as the airflow through adventitious openings, whereas flows through purpose-provided openings are mentioned as ventilation.

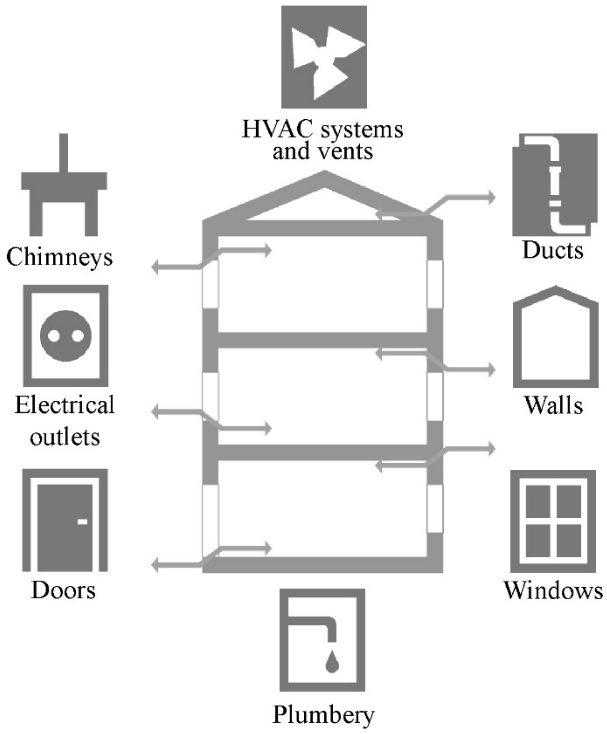
Adventitious openings are a consequence of the discontinuities or gaps among the construction elements of the envelope. They are often classified into component openings or background openings. Component openings are leakage paths located in openable components of the envelope. On the other hand, cracks in the opaque part of the envelope, connections between external wall and ceiling or floor, external wall and window or door, or external wall and penetrations in the barrier layers are considered background openings (Gullbrekken, Bunkholt, Geving, & Rüther, 2020) (**Figure *1***).

In this regard, interest concerning the distribution of the leaks within the building envelope has been stated since the early 1980s. Component leakage knowledge can be useful to estimate the whole envelope airtightness and its distribution and to make decisions regarding the design or retrofitting actions. The percentage of several component leakage areas aggregated by groups of components of a subset of houses in the USA was reported: sill and wall/ceiling (31%), HVAC-systems (15%), fireplace

(14%), pipes (13%), doors (11%), windows (10%), vents (4%), and electric outlets (2%) (Reinhold & Sonderegger, 1983).

A review of different dedicated research was gathered in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Fundamentals Handbook (ASHRAE, 2021; Dickerhoff, Grimsrud, & Lipschutz, 1982; Harrje & Born, 1982), where an estimation of the share of the main leakage paths was reported: walls (18-50%), ceiling details (3-30%), forced-air heating/cooling systems (3-28%), or windows and doors (6-22%). Sherman and Chan (2004) also summarised the origin of the main infiltration paths in different types of buildings.

Figure 1. *Typical air leakage paths in dwellings*



However, it seems reasonable to think that component air leakage may be different depending on the construction systems, which vary among countries, and its evolution over time. In this way, a growing interest in this topic has been identified in the recent literature, which encompasses updated data and valuable information. Component-weighted assessment in multi-unit residential buildings implemented in whole-building energy models proved to be useful to reduce parameter uncertainty during model calibration and to account for the variation in zone infiltration rates (Lozinsky & Touchie, 2018). Quantitative values of the components with greater impact on whole building airtightness can also be useful to address improvements in an efficient way (Hong & Kim, 2018).

Recent literature assessed real case studies of building leakage performance, obtaining a high dispersion among materials and components of the building envelope (Cardoso, Ramos, et al., 2020), whereas other authors reported comprehensive meta-analysis on laboratory and in-situ measurements (Prignon, Altomonte, Ossio, Dawans, & Moesek, 2021). These approaches are promising and offer updated information that contributes to the development and improvement of models for robust leakage prediction.

It has already been proved that accomplishing airtight envelopes is only possible if specific design principles to prevent leakages are taken into account (Dorer et al., 2004). The continuity of the air barrier between the different building elements and the sealing around supplementary construction elements and penetrations have been pointed out as key features for the airtightness performance of the envelope

(Aho, Vinha, & Korpi, 2008). Airtight solutions and specific details have been developed by several authors and commercial brands applied for different types of building systems (Aho et al., 2008; BC Housing, 2017; Jaggs & Scivyer, 2009; S. Price, Baines, & Jennings, 2020; Wahlgren & Sikander, 2010). Therefore, appropriate design and careful construction are key to achieving good performance in terms of airtightness. This involves simple geometries, avoiding penetrations through the airtight layer, simple installation, the correct choice of materials, and reliable workmanship.

Improving airtightness in existing buildings remains a challenge since leakage paths are hidden in walls and other cavities and, thus, they need to be individually identified and sealed (Bohac, Schoenbauer, & Fitzgerald, 2016). As a result, airtightness testing during the construction phase is becoming a common and recommended practice. Accessing and locating air leakages when airtight layers are still accessible allows the effective improvement of airtightness.

Another issue that has been discussed in the literature regarding airtightness is the fact that airtightness is not an invariable characteristic of the building envelope. Previous research proved some variation depending on the season of the measurement (Kim & Shaw, 1984; Persily, 1982a) and over time (Bracke, Laverge, Bossche, & Janssens, 2016). Up to 30% more leakage in winter was reported by Persily (1982a) probably due to moisture during the hot, humid season. On the contrary, other authors revealed better airtightness results in winter for very airtight dwellings, with a seasonal variation of up to 20% (Kim & Shaw, 1984), which was attributed probably to moisture content of the wall and differential thermal dilation of the material of the building envelope.

Regarding airtightness durability, some approaches focused on repeated testing campaigns of the same buildings after some years, ensuring that no intervention had been done meanwhile, whereas other approaches focused on artificial ageing. The variation of airtightness over time in experiments performed in dwellings remains unclear. A literature review (Leprince, Moujalled, & Litvak, 2017) supported by the experimental assessment of 30 detached houses (Moujalled, Leprince, Berthault, Litvak, & Hurel, 2021) concluded that the airtightness of the building envelope seems to decrease around 18% during the first year after completion, and it stabilises after this period. Chan et al. (2015b) obtained an estimate of the ageing factor that predicted a 15% increase in the Normalised Leakage (NL) over ten years. On the other hand, other studies reported the improvement of airtightness after building completion (Verbeke & Audenaert, 2020).

The mentioned review (Leprince et al., 2017) reported the lack of protocols to evaluate laboratory ageing of airtight products in a standardised way. Recent literature assessed the performance of the behaviour of specific building systems under simulated air leakage (Ge, Straube, Wang, & Fox, 2019) and sealed joints between different building components (Van Linden & Van Den Bossche, 2020).

2.2 AIR INFILTRATION

This section presents the theoretical framework of the air infiltration process, outlining the driving forces that cause this phenomenon and the nature of the airflow through air leakage paths. The knowledge of the theoretical background is fundamental to understanding air infiltration and its assessment.

Air infiltration is an entirely passive phenomenon that depends on the pressure differential across the envelope and the nature and configuration of the cracks and gaps (leakage paths) of the building envelope (Priestner & Steel, 1991). The leakage rate through the building envelope depends on (Awbi, 2004):

- The size and distribution of leakage paths or adventitious openings;
- The flow characteristics of the leakage paths;
- The pressure difference across the leakage paths.

2.2.1 Airflows through leakage paths

The airflow through a leakage path can be estimated when the characteristics listed in the previous section are known, based on the mass balance of air across the whole building envelope. In other words, a fundamental concept assumed in the process of air leakage is that the infiltration air through the building envelope displaces an equivalent mass of internal air (Liddament, 1986). The physical principles that address the infiltrating airflows are presented. Basic equations in this regard can be found in the literature, depending on the type of opening.

The airflow through large openings tends to be turbulent under natural pressures, and thus, it can be estimated using the standard orifice flow equation, as seen in Equation (1):

$$q = C_d \cdot A \cdot \sqrt{2 \cdot \Delta p/\rho} \tag{1}$$

where: q is the volume airflow rate through the opening $[m^3/s]$; C_d is the discharge coefficient of the opening $[-]$; A is the leakage area $[m^2]$; Δp is the pressure difference across the opening $[Pa]$; ρ is the density of the air $[kg/m^3]$.

This kind of openings could be assumed for purpose-provided vents and large cracks around windows. The discharge coefficient (C_d) in sharp-edge orifices can be considered independent of the Reynolds number, which defines the turbulent regime, assuming a value of 0.61.

On the other hand, essentially laminar flows dominated by the effects of viscosity are developed through narrow and deep leakage paths, for instance in mortar and joints of tight-fitting components. In these cases, the airflow rate can be calculated using the following flow equation (2) (Fox, McDonald, & Mitchell, 2020):

$$q = [B \cdot h^3/(12 \cdot \mu \cdot L)] \cdot \Delta p \tag{2}$$

where: q is the volume airflow rate through the opening $[m^3/s]$; B is the length of the crack $[m]$; h is the height of the crack $[m]$; L is the depth of the crack in the airflow direction $[m]$; μ is the absolute viscosity of the air $[Pa\ s]$, (18.13x10-6 $Pa\ s$ at 20°C); Δp is the pressure difference across the opening $[Pa]$.

However, the study of the morphology of air leakage paths in buildings is an extremely difficult issue, addressed in the existing literature. The main reason is that each adventitious opening is unique, and the developed flow is never fully turbulent not laminar. As a consequence, these equations remain theoretical. The openings' geometry in terms of shape and size can be complex and leakage paths can be even connected to other openings through cavities between the construction materials (Etheridge & Sandberg, 1996). Therefore, in practice, the interpretation of the airflow process considers a number of assumptions to simplify the models to enable a reasonable mathematical approach.

The commonly referred to as the power law (Equation (3)) is widely used to describe the relationship between the airflow rate and pressure difference for a wide range of crack geometries. Although its origin is unclear and was first found to be valid empirically, it was later provided with a theoretical basis (Sherman, 1992).

$$Q_{pr} = c_L \cdot (\Delta p_r)^n \tag{3}$$

where: Q_{pr} is the airflow rate of the opening at a reference pressure difference $[m^3/h]$; C_L is the air leakage coefficient $[m^3/(h\ Pa^n)]$; Δp_r is the reference pressure difference $[Pa]$; n is the airflow exponent $[-]$.

The coefficient n reflects the behaviour of the component and background leakages of the envelope, providing information regarding the relative size of the most significant leaks. It depends on the pressure since the nature of the cracks across the envelope might be non-uniform, and leakage distribution may vary with pressure variation. However, this dependency has been reported to be low

(Sherman & Chan, 2004) and thus n has been considered constant. Typical obtained n values are between 0.50 and 1. Values near 0.5 are usually obtained as a consequence of large leakages and short paths, causing turbulent flows within them. On the contrary, high n values close to 1 are due to a steady laminar flow through small leakages in airtight buildings (Allen, 1985).

However, it has been widely discussed in the literature the unsuitability of the power-law equation considering that it is not dimensionally homogeneous and, therefore, lacks generality (Etheridge, 1977). The exponent n is considered to depend only on the geometry of the crack, but early research (Kreith & Eisenstadt, 1957) admitted the dependency on Reynolds number as well as the geometry. Therefore, n varies for a given leakage path with the flow rate, and thus several authors advised against its use (Etheridge & Sandberg, 1996).

As an alternative, several authors supported the quadratic equation (Thomas & Dick, 1953), in which the turbulent and laminar flow components are separated, as seen in Equation (4). Therefore, it is dimensionally homogeneous and provides a more accurate assessment of the flow through a crack (Baker, Sharples, & Ward, 1987).

$$\Delta p = a \cdot Q^2 + b \cdot Q + c \tag{4}$$

where: Δp is the pressure difference across the leakage site $[Pa]$; Q is the volume airflow rate through the leakage site $[m^3/s]$; c is an optional constant representing the zero-flow pressure difference $[Pa]$; a is the coefficient representing the turbulent part of the quadratic law $[Pa\ s/m^3]$, as seen in Equation (5); b is the coefficient representing the laminar part of the quadratic law $[Pa\ s^2/m^6]$, as seen in Equation (6).

$$a = \frac{\rho \cdot B'}{2 \cdot A^2} \tag{5}$$

$$b = \frac{\mu \cdot C \cdot L}{2 \cdot A \cdot d_h^2} \tag{6}$$

where: ρ is the density of the air $[kg/m^3]$; A is the leakage area $[m^2]$; $B'$and C are constants determined by the shape of the cross-section of the opening; L is the depth of the crack in the airflow direction $[m]$; μ is the absolute viscosity of the air $[Pa\ s]$; d_h is the hydraulic diameter $[m]$, being $d_h = 4 \cdot \frac{A}{perimeter}$ (Etheridge, 2011).

Both approaches have been compared and there is no general agreement regarding the best fit. Although previous research proved that the power law could not be valid for some cases and types of cracks (Chastain, Colliver, & Winner, 1987; Honma, 1975), it seems to show enough robustness to obtain the airflow of typical openings of the building envelope. It must be noted that typical leaks in buildings are not ideal smooth circular pipes, but instead, their geometries tend to be rather rough (Walker, Wilson, & Sherman, 1998). However, as long as the power law is not used to infer specific information regarding the geometry of leaks, it has proved a good fit to quantify the airtightness of the envelope (Sherman & Chan, 2004). In addition, results showed that the extrapolation of the values obtained from pressurisation tests to the range of typical pressure conditions are valid (Walker et al., 1998).

2.2.2 Natural driving forces

Once the physical principles that address the infiltrating airflows have been revised, the forces driving the air exchange are presented. The pressure differential across the envelope can be caused either by the dynamic action of wind or by the stack effect, which is the difference in air density due to the temperature gradient between the interior and the exterior. Therefore, complex and unsteady airflow patterns are induced by the combination of wind and temperature (Priestner & Steel, 1991), or even by occupant effects (opening and closing doors) and equipment effects (vented combustion equipment, vents, etc.) (Colliver et al., 1992).

Models that address these driving forces involve a great degree of complexity given their non-linear nature and, thus, often encompass semi-empirical functions that combine wind and buoyancy generated pressure on the building envelope. Walker and Wilson (1993) reviewed the physical principles of wind and stack effect on air infiltration calculations. The stack effect volume flow rate (Q_s) and the wind effect volume flow rate (Q_W) can be obtained using Equation (3) or Equation (4) for the stack pressure difference (Δp_s) and the driving forces due to wind (Δp_w), respectively.

The stack pressure difference (Δp_s) across the building envelope caused by buoyancy, which results in the stack effect flow rate (Q_s) (**Figure *2***), varies linearly with height and can be obtained as seen in Equation (7):

$$\Delta p_s(h) = \rho_{out} \cdot g \cdot \left(h - h_{o,s}\right) \cdot \frac{\Delta T}{T_{in}} \tag{7}$$

where: $\Delta p_s(h)$ is the change in stack pressure with height caused by buoyancy $[Pa]$; ρ_{out} in the outdoor air density $[kg/m^3]$; g is the acceleration of gravity $[m/s^2]$; h is the level height $[m]$; $h_{o,s}$ is the neutral level height for stack pressure, which depends on leakage distribution $[m]$; ΔT is the indoor-outdoor temperature difference (T_{in}-T_{out}) $[K]$.

On the other hand, the driving forces due to wind (Δp_w) for windspeed v that cause the wind effect volume flow rate (Q_W) (**Figure *2***) can be obtained as seen in Equation (8):

$$\Delta p_w = \frac{\rho_{out}}{2} \cdot \left(C_p - C_{po}\right) \cdot v^2 \tag{8}$$

where: Δp_w is the wind pressure difference $[Pa]$; ρ_{out} in the outdoor air density $[kg/m^3]$; C_p is the pressure coefficient $[-]$; C_{po} is the internal pressure coefficient that balances inflows and outflows summed over all leakage sites $[-]$; v is the windspeed $[m/s]$.

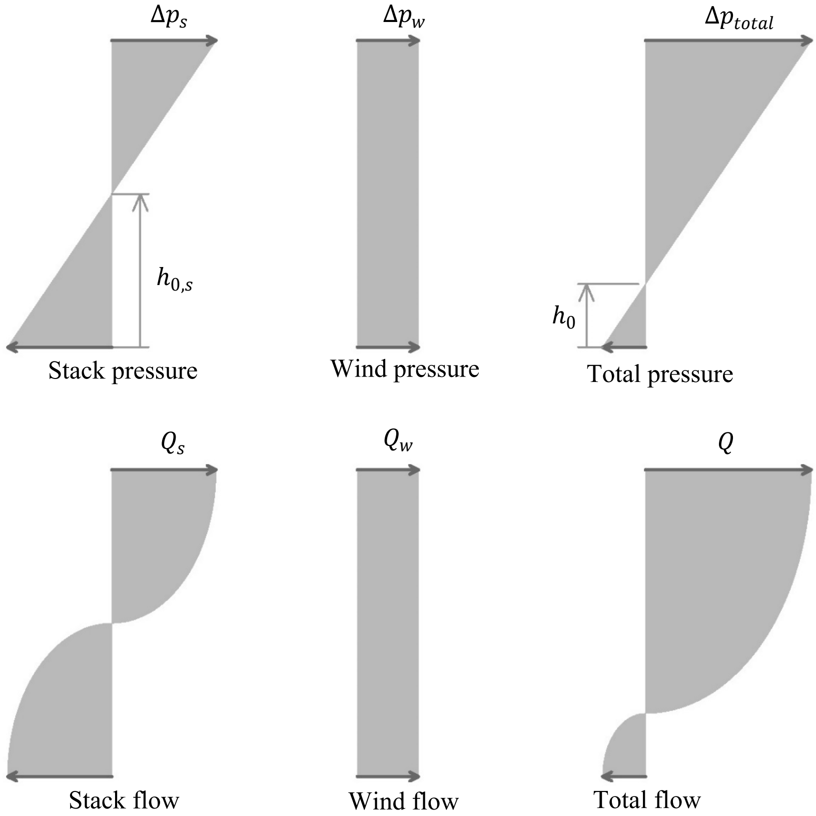
The total pressure on an air leakage path of the envelope (Δp_{total}) is the sum of the pressure due to the wind and stack effect when no mechanical ventilation is working (**Figure *2***). The way in which these forces interact has been discussed in the literature (Kronvall, 1978; Modera, Sherman, & Levin, 1983; Shaw, 1985; Sherman & Grimsrud, 1980; Walker & Wilson, 1990, 1993; Wilson & Pittman, 1983). Either way, any reasonable model should take into consideration that wind and stack effects do not influence internal building pressure in the building in the same way. Furthermore, it is important to bear in mind that the airflow conditioned by the total pressure difference at the leak will also be conditioned by the location of other leakages that impact on the equilibrium internal pressure.

To avoid using iterative models, several simple empirical expressions of the non-linear combination of forces were studied by Walker and Wilson (1993) and compared with measured air infiltration. After comparing the different models, they suggested the pressure addition used by Wilson and Pittman (1983) and Shaw (1985) to estimate wind and stack effect. The superposition model works similarly to other more complex ones, being at the same time simple, physically realistic with reasonable error. The resulting flow rate (Q) is calculated combining infiltration rates from a pressure-flow relationship considering stack (Q_s) and wind (Q_W) flowrates for a variable n model (Equation (9)):

$$Q = \left(Q_s^{1/n} + Q_w^{1/n}\right)^n \tag{9}$$

where: Q is the total volume airflow rate $[m^3/s]$; Q_s is the stack flow rate $[m^3/s]$; Q_w is the wind flow rate $[m^3/s]$; n is the airflow exponent $[-]$.

Figure 2. *Pressures and combined airflows on the envelope due to wind and stack effect*



2.3 AIRTIGHTNESS MEASUREMENT

Given the importance of air infiltration and its impact on energy performance and ventilation, it is key to understand the performance of the building envelope in this regard. However, measurement methods that directly address infiltration rates such as the tracer gas method are complex and time-consuming (Sherman, 1989), and feature also some limitations such as the lack of information regarding leakage location and the variability of the results depending on weather conditions over the year. Therefore, its use to properly represent the airtightness characteristics of a building has been questioned (Kronvall, 1980). As an alternative, airtightness assessment has been imposed because air infiltration is fundamentally determined by the airtightness of the building envelope.

The airtightness of the building envelope is difficult to assume from visual inspection, the age or the type of construction (ASHRAE, 2021), or other features. Measurement is therefore necessary, and to quantify the airtightness of the building envelope, several methods have been developed. This section describes several available techniques used to measure the airtightness of the whole building envelope, focusing on the pressurisation method. Different measurement methods were reviewed for the past 40 years (Charlesworth, 1988; Kronvall, 1980; McWilliams, 2003; Priestner & Steel, 1991; Zheng, Cooper, et al., 2020), and are briefly summarised here. Minority techniques such as infrasonic impedance and new developing techniques based on sensors (Casillas, Modera, & Pritoni, 2021; Park, Munkhbat, Song, Yoon, & Kang, 2019) were not included.

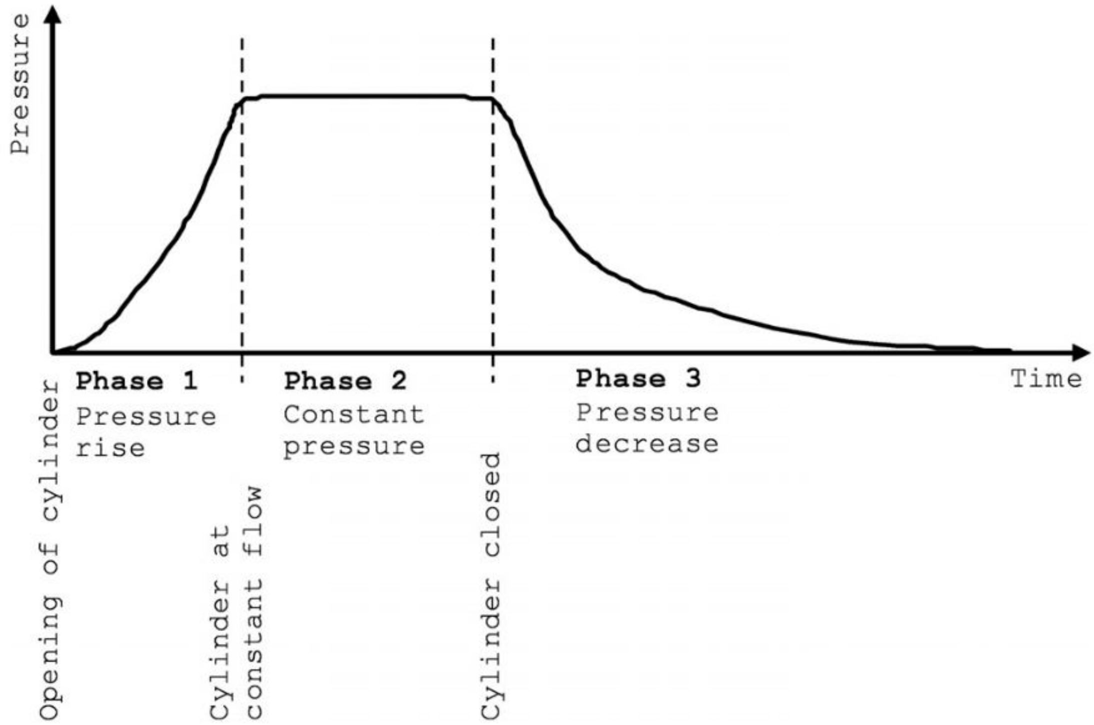
2.3.1 Decay method

This procedure was described in the literature by several authors, but its use has been mostly relegated to controlled environments such as laboratories and test chambers. In short, a pressurisation source increases the pressure inside the premises under measurement until the desired level is achieved.

The target pressure may depend on the purpose of the study or the capacity of the pressurisation equipment, for instance, at least 50 Pa (Møller, Rasmussen, & Nicolajsen, 2010), or up to 600 Pa (Gränne, 2001). The pressure increase can be generated both through an air supply duct (B. Mattsson & Claesson, 2007) or by means of a compressed air tank (Møller et al., 2010). Once a stable pressure is maintained, the supply source stops, and the lack of airtightness then causes pressure decay by air leakage through the building envelope (**Figure *3***). In this way, the leakage rate can be calculated in relation to the recorded pressure decay.

The obtained results using this method compared to the extended steady-state (DC) pressurisation method revealed some discrepancies and lack of accuracy (Møller et al., 2010). In this regard, further work should be carried out to improve the issues found.

Figure 3. *Ideal time/pressure dependency air leakage measurement by means of decay method using compressed air*

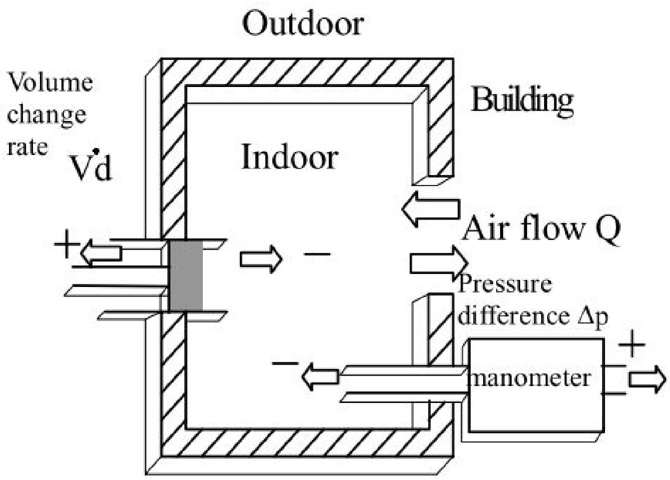


Note. From "A simplified method using compressed air to Determine Air Leakage," by E. B. Møller, T. V. Rasmussen, & A. Nicolajsen, 2010, Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference, p. 3. Copyright 2010 by ASHRAE.

2.3.2 Alternating pressurisation method

Alternating (AC) pressurisation method is based on the physical principles of fluctuating pressures using low-frequency acoustic monopoles to generate an internal pressure signal, which is analysed to obtain the leakage area of the envelope (Etheridge & Sandberg, 1996; Sherman, 1986a). Measurements are based on steady pressure, creating a sinusoidal volume change to the building by a reciprocating piston (**Figure *4***). The physical principles were first stated (Sherman, Grimsrud, & Sonderegger, 1979), and then further developed (Dewsbury, 1996; Watanabe, Kobayashi, Utsumi, & Miyagi, 1999). However, due to accuracy and interpretation issues, and reported limitations, the AC pressurisation method is not widely used at present.

Figure 4. *Leakage model of the AC pressurisation model*

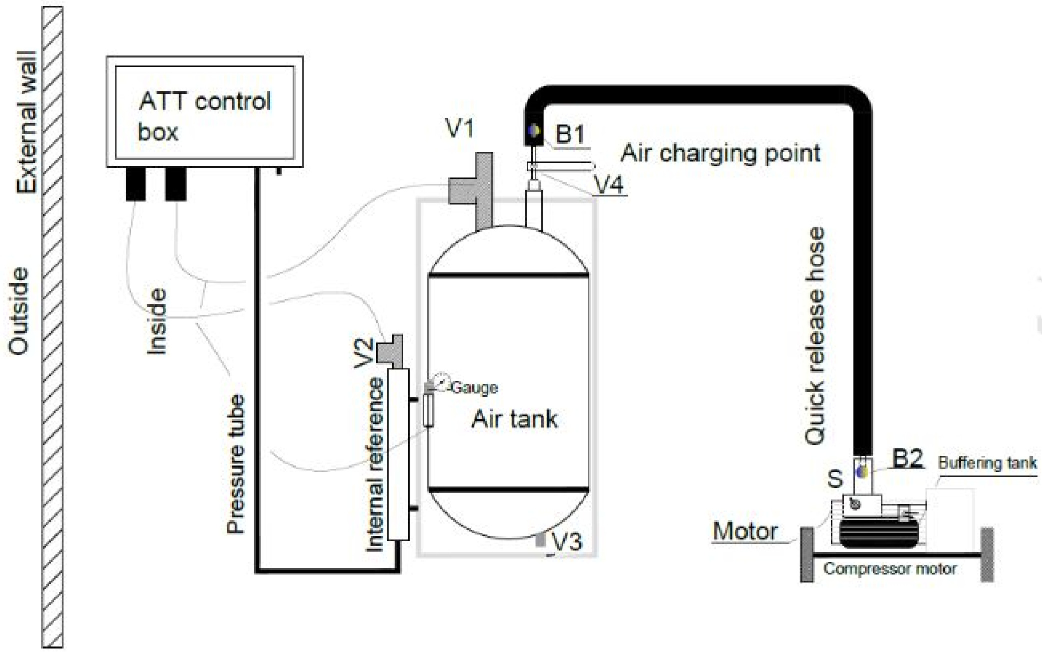


Note. From "A simplified method using compressed air to Determine Air Leakage," by Y. Watanabe, H. Kobayashi, & Y. Utsumi, 1999, *Proceedings: Building Simulation'99, Sixth International IBPSA Conference*, p. 809.

2.3.3 Pulse method

This method was developed aiming at overcoming the main drawbacks of the commonly used DC pressurisation method: measurement under unnatural conditions, time-consuming process, etc. The technique was developed based on the "quasi-steady" temporal inertia model that generates a pressure pulse inside the building by releasing a known amount of compressed air using an air tank (Carey & Etheridge, 2001; Cooper, Etheridge, & Smith, 2007). An instant pressure rise is generated, followed by a steady pressure drop. The leakage through the building envelope is then obtained from the leakage-pressure correlation, taking into account the pressure variations in the building (**Figure 5**).

Figure 5. *Schematic diagram of the pulse method*



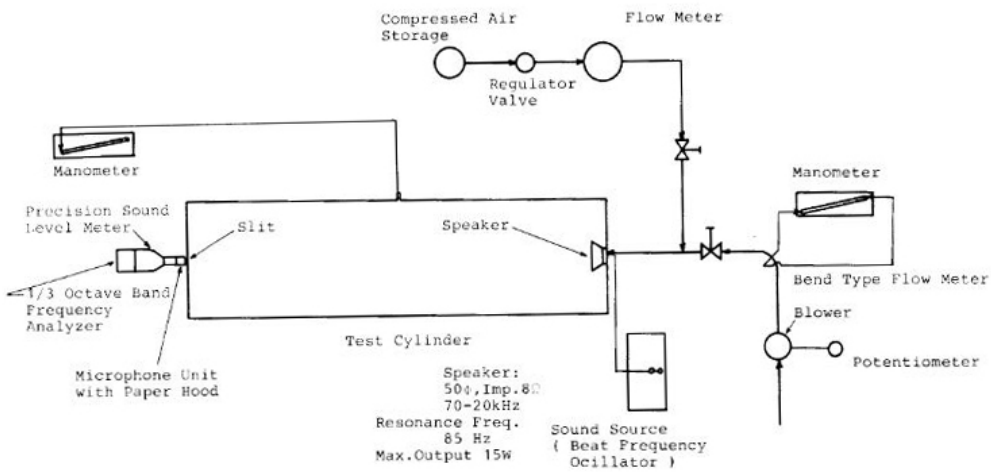
Note. From "Experimental Studies of a Pulse Pressurisation Technique for Measuring Building Airtightness," by X. Zheng, E. Cooper, Y. Zu, M. Gillott, D. Tetlow, S. Riffat, & C. J. Wood, 2019, *Future Cities and Environment,* 5(1)(10), 106269, p. 7. Copyright 2019 by the Authors. Creative Commons Attribution 4.0 International License (CC-BY 4.0).

The measurement is thus performed at similar pressures that buildings under natural conditions experience and minimises at the same time wind and stack effects given the short and dynamic operation. A first approach was developed and even patented, although at that time it was not widely used (Yuill, 1984). Recent literature numerically and experimentally validated the model, and compared results obtained with this technique and steady pressurisation method in controlled and on-site environments (Cooper et al., 2019; Zheng, Mazzon, Wallis, & Wood, 2020). However, further research is still needed to overcome identified issues regarding the measurement of highly airtight envelopes, the understanding of geometrical complexities of larger buildings, and further comparison in unsheltered environments (Zheng et al., 2019). Nonetheless, the latest findings seem promising at offering an alternative method in the near future (Cooper, Zheng, & Wood, 2020).

2.3.4 Acoustic method

Research relating sound transmission to the presence of air leakage has been present in the literature since the 1970s (Card, Sallman, Graham, & Drucker, 1978; Esdorn, 1978; Keast & Pei, 1979; Sabine, Lacher, Flynn, & Quindry, 1975) and new findings continue nowadays. It was developed with the aim of offering a cheaper, quicker, and mainly independent from weather conditions alternative to the DC pressurisation method. The method is based on the principles of sound transmission loss through cracks on the envelope to determine air infiltration. Sound waves at a known frequency are generated by a source and sound pressure level inside and outside the building is measured establishing, therefore, a relationship with air leakage paths (**Figure *6***).

Figure 6. *Simplified schematic diagram of an airtightness acoustic measurement system*



Note. From "A sonic method for building air-leakage measurements," by T. Sonoda, & F. Peterson, 1986, *Applied Energy*, 22(3), p. 208. Copyright 1986 by Elsevier Applied Science Publishers Ltd.

Early research focused on setting the basis of this method numerically (Sherman & Modera, 1988), and testing both controlled openings (Oldham, Zhao, Sharples, & Kula, 1991; Ringger & Hartmann, 1989; Sonoda & Peterson, 1986), and specific building components such as windows (Benedetto & Brosio, 1981).

More recent studies have explored this technique to measure the airtightness of building components (Hassan, 2013), and whole building leakage both under controlled environments (Kölsch, Schiricke, Schmiedt, & Hoffschmidt, 2019) and on-field tests (Iordache & Catalina, 2012; Varshney, Rosa, Shapiro, & Scott, 2013). Several setup acoustic alternatives to locate and quantify leakage areas were also explored (Raman, Chelliah, Prakash, & Muehleisen, 2014). Results obtained compared to the DC pressurisation method reported inaccuracies applying this technique to window airtightness measurement (Berardi, 2018), and other authors suggest that further research is needed to test this method under different conditions (Iordache & Zaharia, 2019) to understand the influence of each parameter, establish the error and enlarge its applicability (Catalina, Iordache, & Iordache, 2020).

2.3.5 Quantified thermography

The potential of infrared (IR) thermal imaging or thermography in the inspection of the building envelope related to energy efficiency has been highlighted (Kirimtat & Krejcar, 2018; Tejedor, Barreira, Almeida, & Casals, 2020). The later development of this method as a diagnostic tool for air leakage can be explained given its dependence on the IR thermography technology development. This technology was not commercially produced and extended until the 1980s, although early research in the field carried out in 1968 by the Cooperative Building Organisation of the Swedish Trade Unions and the Swedish National Testing Institute was reported (Pettersson & Axen, 1980).

This non-destructive technique is based on the visualisation of the infrared radiation emitted by surfaces in the infrared spectrum (0.7-100 μm) (Pettersson & Axen, 1980). In this way, uncontrolled air infiltration through discontinuities, cracks and air leakage paths can be identified by image capture since they may transport heat via additional convection losses, and these airflows affect also the temperature in the vicinity of air leaks (Vollmer & Möllmann, 2017). However, visualisation is only possible when a suitable temperature gradient through the envelope is provided.

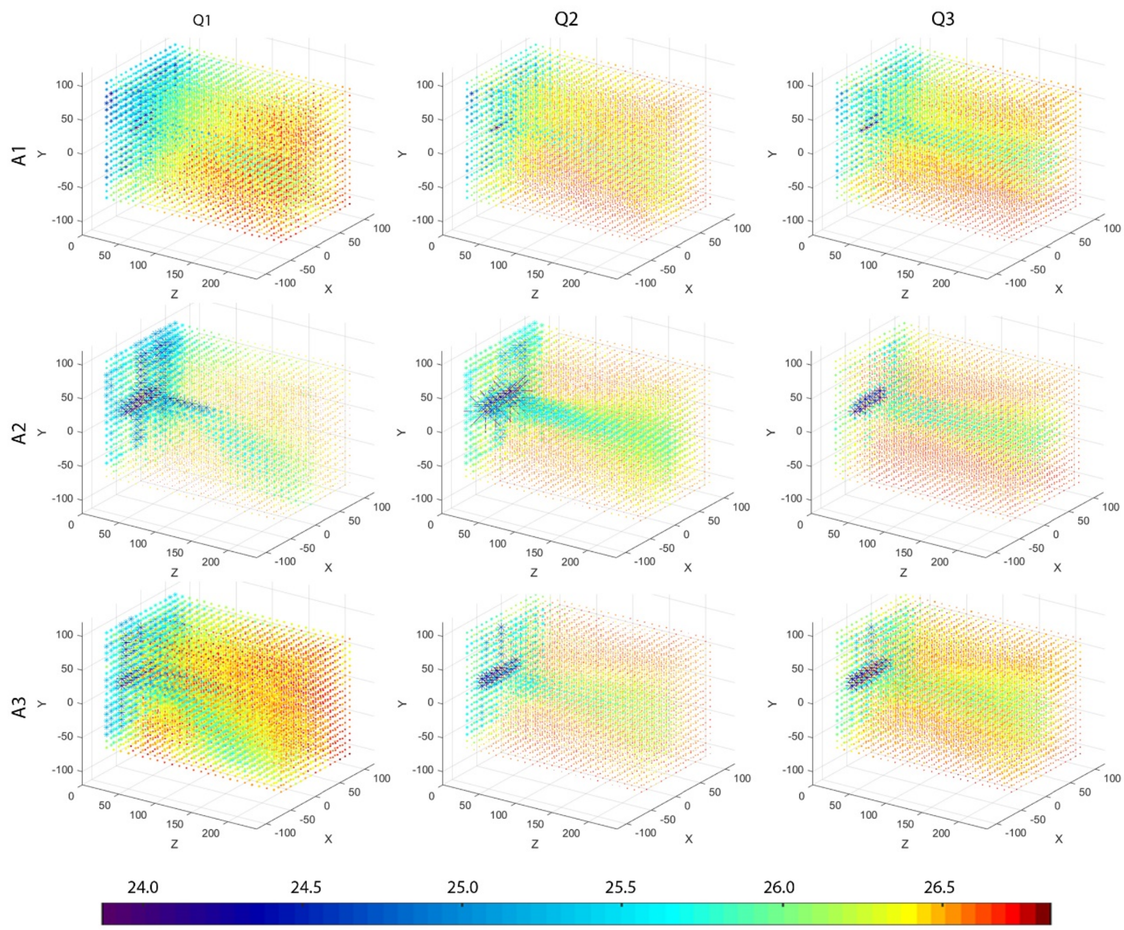
The use of this method has focused so far qualitatively on detecting infiltration paths as a diagnosis tool for characterisation, often combined with the DC pressurisation method to force the entrance of airflows through leakage paths (Eskola et al., 2015; Feijó-Muñoz et al., 2018; Gillott et al., 2016; Kalamees, 2007; Tanyer, Tavukcuoglu, & Bekboliev, 2018). Some examples of the application of IR thermography including leak detection by differential IR image were also presented (Grinzato, Vavilov, & Kauppinen, 1998).

However, quantitative IR thermography to assess leakage has not been developed until recent years. Dufour et al. (2009) used this method to dimension unintentional openings by means of experimental tests in a laboratory, combined with DC pressurisation. Another attempt towards a quantitative determination of leakages was developed, analysing influential factors for an IR thermal assessment through simulations, laboratory, and in situ measurements. However, results revealed the impossibility of deriving air infiltration flows from IR thermal imaging due to visibility issues and variation in surface temperature with air leakage dimensions (Maroy, Van Den Bossche, Steeman, & Van De Vijver, 2016; Van Den Vijver, Steeman, Carbonez, Van Den Bossche, & Vaerwyckweg, 2014). In spite of this, other authors have presented further research that focused on the quantitative study of surface temperatures using both passive and active IR thermal imaging combined with pressure differences and applying different numerical methods (Barreira, Almeida, & Moreira, 2017; Lerma, Barreira, & Almeida, 2018).

Promising results were obtained when the effective crack size and air infiltration rate were measured by means of theoretical heat transfer and fluid mechanics analyses, which were then experimentally validated (W. Liu, Zhao, & Chen, 2018). Finally, a novel approach was recently developed in a laboratory introducing IR thermal data processing and neural networks to define the infiltration airflow (Gil-Valverde et al., 2021; Royuela-del-Val, Padilla-Marcos, Meiss, Casaseca-de-la-Higuera, & Feijó-Muñoz, 2019), as shown in **Figure** *7*.

Challenges still remain regarding IR thermal imaging to quantify building leakage, mostly related to sensitivity to variations in the outdoor climate, uncertainty analysis and effective applicability for whole building airtightness evaluation. Therefore, further research is needed in order to successfully apply this technology to quantify building leakage.

Figure 7. *Three-dimensional representation of the infiltration airflow*



Note. From "Three-dimensional characterisation of air infiltration using infrared thermography," by R. Gil-Valverde, D. Tamayo-Alonso, A. Royuela-del-Val, I. Poza-Casado, A. Meiss, & M. Á. Padilla-Marcos, 2021, *Energy and Buildings*, 233, 110656, p. 7.

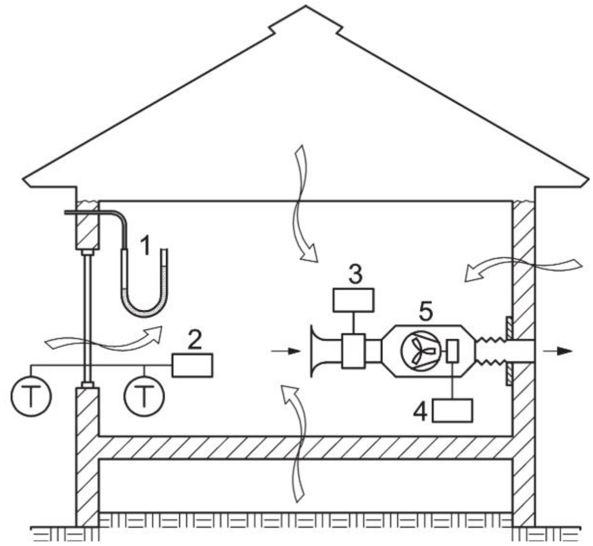
2.3.6 Steady pressurisation method

The whole-building DC pressurisation method, also known as the steady pressurisation method, fan pressurisation, or simply "blower door" test, has become the most widely used method to assess the envelope airtightness, also covered by national and international standards (Priestner & Steel, 1991). Pressurisation tests are commonly performed to measure the airtightness of the whole building or part of a building, a component of the building envelope, or a specific component in a laboratory (Liddament & Thompson, 1983).

This technology first used in Sweden in the late 1970s (Kronvall, 1980), was quickly developed and spread to the USA (Sherman, 1995), and then to other countries. Nowadays, it is the most widespread measurement method to assess whole-building airtightness. Its popularity can be explained given its convenience regarding its reasonable precision and reproducibility, and available commercial equipment.

The evaluation of the airtightness of the building envelope using this method consists of superimposing a known artificial uniform pressure difference across the envelope (usually between 20 Pa and 70 Pa) by means of a fan and measuring the generated flow rate through it (**Figure 8**). The fan is typically located in the main door and temporarily replaces the existing entrance to the building. The induced pressure difference (either negative or positive) forces the entrance or exhaust of a generated airflow through the envelope leakages. Generally speaking, the higher the flow rate required to maintain a given pressure difference, the less airtight the building (Charlesworth, 1988). Further physical principles involved during this test performance were developed by Kronvall (1980).

Figure 8. *Schematic layout of the equipment for whole-building DC pressurisation*

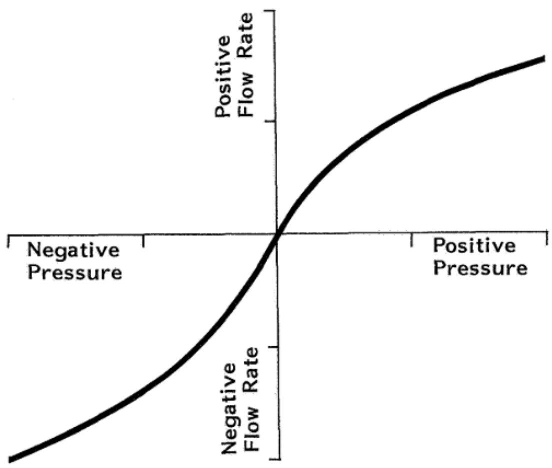


where: 1 is the pressure-measuring device; 2 is the temperature-measuring device; 3 is the airflow measuring system; 4 is the fan control; 5 is the fan.

Note. From International Standard "ISO 9972:2015 Thermal performance of buildings. Determination of air permeability of buildings. Fan pressurisation method," 2015, p. 17. Copyright 2015 by ISO 2015. All rights reserved.

Several measurements of the airflow rates over a range of pressure gradients are known as the leakage function (ASHRAE, 2021). In this scenario, a relationship between the airflow through the envelope and the pressure gradient is determined using the power law or the quadratic equation (see **Figure 9** and section "Air infiltration"). Sometimes a single point is measured, usually at a reference pressure of 50 Pa (McWilliams, 2003), and in this case, the n exponent is estimated.

Figure 9. *Air leakage function (power-law plot)*



Note. From "Air exchange rate and airtightness measurement techniques - An applications guide," by P. S. Charlesworth, 1988, *Air Infiltration and Ventilation Centre*, p. 3.11. Copyright 1988 by Oscar Faber Partnership on behalf of the International Energy Agency.

Commercial suitable equipment is available in the market to perform pressurisation tests. Fans, usually combined with a matching manometer with independent pressure channels, provide minimum flows of 4 m^3/h and maximum flows over 10,500 m^3/h. Greater airflows can be reached when combining fans or with trailer-mounted fans (90,000 m^3/h) needed for the evaluation of buildings with great volume or very leaky dwellings. The accuracy of this commercially available equipment is within the limits that international standards require.

Some of the main shortcomings that this method involves were discussed in the literature:

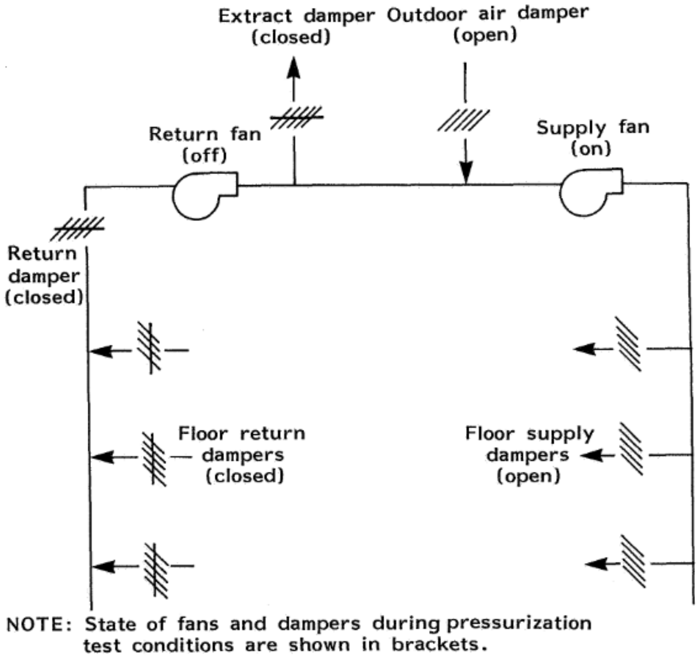
- The pressure gradient of 50 Pa is not representative of natural conditions and air infiltration cannot be directly obtained (Etheridge, 2015; McWilliams, 2003; Sherman & Chan, 2004);
- Large net fluid flows are needed (Zheng, Cooper, et al., 2020);
- Testing accuracy-related problems (see Section “Measurement uncertainties”);
- Time-consuming test and test setup (Rolfsmeier, 2019; Sirén, 1997);
- Requirement of trained agents (Leprince & Carrié, 2014);
- The whole envelope is not tested since the opening where the fan is placed is not considered on the measurement (Zheng, Mazzon, et al., 2020);
- The unreal pressure conditions on the envelope may cause the opening of additional leakage pathways (Charlesworth, 1988).

On the other hand, one of the main benefits of this method is the fact that the induced pressure gradient minimises the impact of stack and wind pressures. Weather-driven forces are thus overpowered. All things considered, the steady pressurisation method has long been accepted as a standard testing method to quantify the airtightness of the building envelope. The approach is robust and widely used in spite of its main drawbacks. It provides valuable and comparable information regarding airtightness, leakage location when combined with other methods (see section “Leakage location”) and determines leakage reduction from individual retrofits. In addition, fan pressurisation tests are widely used among practitioners and researchers, and common criteria and protocols have been established. Therefore, tests results can be easily compared with other test results and databases.

An alternative method based on the same principles using the building’s existing ventilation system for the generation of the required pressure differential has been described in the literature. This method was developed mainly for commercial buildings with big internal volumes, for which external pressurisation encompasses a drawback due to high cost and limitations in the availability of specific equipment. In this way, the mechanical ventilation supply fans create an overpressure within the building (**Figure *10***).

In this case, the airflow rate at the fans is measured and the pressure difference monitored. Several experiences revealed the importance of the accuracy of the airflow measurement, building preparation and test procedure (Szymański, Górka, & Górzeński, 2016). The main disadvantages reported were related to the accuracy of the measurement, balancing under big pressure differences (Kauppinen, Siikanen, Vähäsöytinki, & Seppänen, 2011), and the impossibility to reach a pressure difference of 50 Pa (Persily & Grot, 1986).

Figure 10. *Schematic DC pressurisation using internal fans*



2.3.6.1 Measurement results

The results of a pressurisation test can be resumed as a set of pairs of values of the airflow rate (Q) and a pressure difference (Δp) (Etheridge & Sandberg, 1996) represented in the aforementioned leakage curve (**Figure** *9*). If two sets of measurements have been obtained because pressurisation and depressurisation have been performed, results usually consider mean values, although this depends on the test purposes.

The airtightness test results can be expressed by several means. The most common ones are either related to the power-law parameters (infiltration airflow at a reference pressure (Q_{pr}), the airflow exponent (n) or the equivalent leakage area (ELA). Whereas Q_{pr} and ELA provide quantitative information regarding the airtightness of the building envelope, the airflow exponent (n) provides information regarding the relative size of the dominant leaks (Sherman & Chan, 2004).

The main air leakage metric is the airflow through the building envelope at a reference pressure (Q_{pr}). The use of the measured airflow at a pressure difference of 50 Pa has become common practice (Liddament & Thompson, 1983) because it allows minimised pressure uncertainty (wind or buoyancy effects) (Sherman & Chan, 2004) and, at the same time, it is easily reachable in dwellings with standard equipment. Nonetheless, other common reference pressures are found in the literature: 1 Pa, 4 Pa, 10 Pa, 25 Pa, and 75 Pa (Sherman & Chan, 2004). In any case, this metric is usually normalised (see section "Derived quantities").

As it has already been mentioned in Section "Air infiltration", n values are between 0.50 and 1, reflecting turbulent or laminar dominating flows respectively through leakages. Since n is part of the power law (Equation (3)), it is necessary to extrapolate measurements at different pressure regimes. However, when measurements are performed at a single pressure difference of interest (usually 50 Pa), the exponent value is not obtained and, thus, average values from large datasets are taken (normally in the vicinity of 0.66 (Orme, Liddament, & Wilson, 1994)).

The Effective Leakage Area (ELA) is a common way to define airtightness (Lawrence Berkeley National Laboratory (LBNL) Model). It is the total area of all the leakage paths of the building envelope at a given pressure difference. It is calculated considering the area of a special nozzle-shaped hole that would leak the same amount of air as the building does at a pressure of 4 Pa, which is considered representative of the pressure difference under natural conditions (Charlesworth, 1988; Colliver et al., 1992; Lozinsky & Touchie, 2020) according to Equation (10):

$$ELA = 10{,}000 \cdot Q_{pr} \cdot \left(\frac{\rho}{2 \cdot \Delta p_r}\right)^{0.5} \tag{10}$$

where: ELA is the effective leakage area $[cm^2]$; Q_{pr} is the airflow rate at a reference pressure difference $[m^3/s]$; ρ is the density of the air $[kg/m^3]$; Δp_r is the applied reference pressure difference [4 Pa].

A similar metric, the Equivalent Leakage Area ($EqLA$), was defined by Canadian researchers (Canada Model of the National Research Council), defined as the area of a sharp-edged orifice that would leak the same amount of air as the building does at a pressure of 10 Pa as in Equation (11) (The Energy Conservatory, 2012):

$$EqLA = 10{,}000 \cdot \left(\frac{Q_{pr}}{C_d}\right) \cdot \left(\frac{\rho}{2 \cdot \Delta p_r}\right)^{0.5} \tag{11}$$

where: $EqLA$ is the equivalent leakage area $[cm^2]$; Q_{pr} is the airflow rate at a reference pressure difference $[m^3/s]$; C_d is the discharge coefficient, 0.611 $[-]$; ρ is the density of the air $[kg/m^3]$; Δp_r is the applied reference pressure difference [10 Pa].

2.3.6.2 Derived quantities

The calculated airflow (Q_{pr}) is usually normalised at a reference pressure of 50 Pa by dimensional-related building characteristics for comparison and standardisation purposes (ISO, 2015):

- A_F $[m^2]$: net floor area. Total floor area of all floors belonging to the internal volume subject to the test;
- V $[m^3]$: internal volume of the deliberately conditioned space of the dwelling, calculated by multiplying the net floor area (A_F) by the clear height. Overall internal dimensions are used to calculate it. The volume of the internal walls, floors or furniture are not subtracted;
- A_E $[m^2]$: envelope area. Total area of walls, floors and ceilings bordering the internal volume subject to the test. Overall internal dimensions are used to calculate this area. No subtractions are made for the area at the junction of internal walls, floors, and ceilings with exterior walls, floors and ceilings. In the case of multi-family dwellings, the envelope area of an apartment includes the floors, walls and ceilings to adjacent apartments.

The normalisation by building envelope area (A_E) is the specific air leakage rate (q_{50}), which provides information regarding the construction quality (Equation (12)). It has been reported to be useful in buildings with parts of the envelope with different nature (exterior envelope, dividing walls, etc.) (Sherman & Chan, 2004).

$$q_{50} = \frac{Q_{50}}{A_E} \tag{12}$$

where: q_{50} is the specific leakage rate per the building envelope area at 50 Pa $[m^3/h\,m^2]$; Q_{50} is the air leakage rate at 50 Pa $[m^3/h]$; A_E is the envelope area $[m^2]$.

Normalised airflows at a reference pressure (Q_{50}) by the volume (V) of the premises under study, n_{50} as in Equation (13), is expressed in air changes at the reference pressure (as the exchange of the equivalent volume of indoor air) per hour $[h^{-1}]$. It is also commonly referred to as the air change rate at a reference pressure of 50 Pa, and it is of particular interest when referring to ventilation airflows because it can be used as an input in airflow simulation tools.

$$n_{50} = \frac{Q_{50}}{V} \tag{13}$$

where: n_{50} is the air change rate at 50 Pa $[h^{-1}]$; Q_{50} is the air leakage rate at 50 Pa $[m^3/h]$; V is the internal volume $[m^3]$.

The use of both q_{50} and n_{50} as airtightness metrics have become common practice. Although n_{50} can be considered dominant in national standards, there is a clear trend towards the spread of q_{50} as reference metric. The reason for this lies in the fact that q_{50} offers clearer information regarding the quality of the envelope, and its relation to conduction losses, which are considered in thermal simulation tools (Carrié & Rosenthal, 2008). The ambiguous definition of the volume in reference standards (ISO, 2015) and the limitation of cheating risk when using the envelope area in energy calculations have also been reported (Carrié & Wouters, 2012b). The airtightness metric should in any case be consistent with the objective of the test, and, specifically, it should be related to the EP calculation input data required.

Lastly, test airflows (Q_{50}) can also be normalised by the floor area of the dwelling (A_F), according to Equation (14). This metric is sometime used given the simplicity to access the floor area.

$$w_{50} = \frac{Q_{50}}{A_F} \tag{14}$$

where: w_{50} is the specific leakage rate per the floor area at 50 Pa $[m^3/h\,m^2]$; Q_{50} is the air leakage rate at 50 Pa $[m^3/h]$; A_F is the net floor area $[m^2]$.

Although w_{50} is not a common way to express airtightness, floor normalisation of other units such as ELA (specific effective leakage area – floor) have been widely used in airtightness measurement standards (Equation (15)):

$$ELA_F = \frac{ELA}{A_F} \tag{15}$$

where: ELA_F is the specific effective leakage area per the floor area at 50 Pa $[m^2/m^2]$; ELA is the effective leakage area $[m^2]$; A_F is the net floor area $[m^2]$.

Alternatively, the specific leakage area is also commonly normalised by the envelope area as in Equation (16):

$$ELA_E = \frac{ELA}{A_E} \tag{16}$$

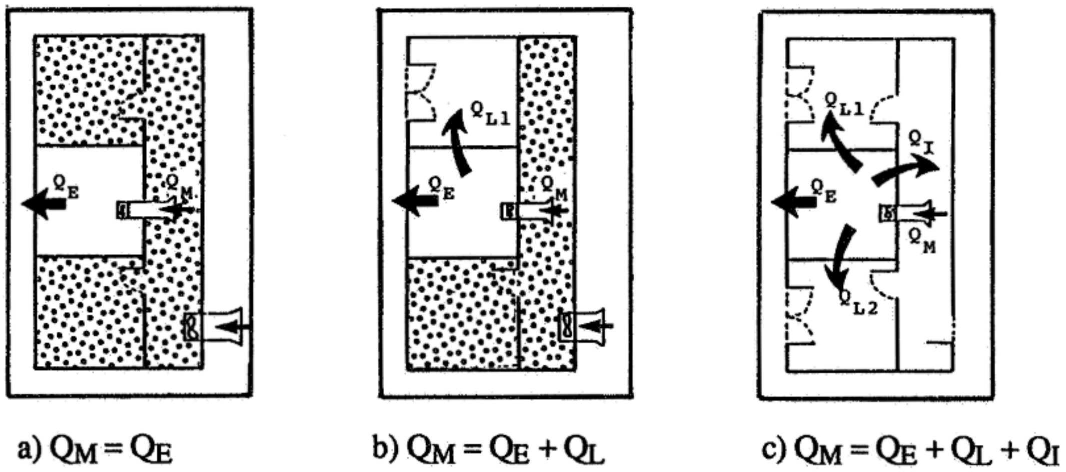
where: ELA_E is the specific effective leakage area per the building envelope area at 50 Pa $[m^2/m^2]$; ELA is the effective leakage area $[m^2]$; A_E is the envelope area $[m^2]$.

2.3.6.3 Guarded-zone measurements

Airtightness characterisation in detached houses or multi-family dwellings adds difficulty given the fact that the envelope has both external areas and partition walls that separate the dwelling under study from other dwellings, circulation areas, garages or adjacent units for other purposes (Sherman & Chan, 2004). The airtightness characterisation in multi-family dwellings can be approached both by measuring the envelope of the whole building or by performing individual units' measurements. Individual-unit tests are prevailing in the literature. However, the conventional single-zone pressurisation method does not allow to distinguish between the permeability of exterior and internal walls (Feustel, 1990).

The airtightness of specific parts of a building can be determined by means of guarded-zone tests, which consist of simultaneously pressurising the space of interest and contiguous spaces. In this sense, two or more fans are used to balance the pressure across internal partitions that will be, therefore, excluded from the measurement. When this method is used, a progressive pressure deduction method is carried out. That is, the differences between the obtained airflows from the different setups can be analysed to determine the permeability of the different envelope parts (**Figure *11***).

Figure 11. *Guarded-zone test setup in a multiroom structure*



where: Q_M is the measured airflow $[m^3/h]$; Q_E is the airflow to outside $[m^3/h]$; Q_L is the lateral airflow to a neighbouring zone $[m^3/h]$; Q_I is the airflow to the staircase $[m^3/h]$.

Note. From "The use of a guarded zone pressurisation technique to measure air flow permeabilities of a multi-zone building," by J. M. Fürbringer, C. Roecker, & C. A. Roulet, 1988, *9th AIVC Conference "Effective ventilation"*, p. 236. Copyright 1989 by Oscar Faber Partnership on behalf of the International Energy Agency.

Additional guidelines include examples, estimation of the errors, and recommendations (Etheridge & Sandberg, 1996; Hult, Dickerhoff, & Price, 2012; Hult, Sherman, & Walker, 2013; Priestner & Steel, 1991). The uncertainty estimate of this kind of test using field measurements and simulations were addressed by other authors (Herrlin & Modera, 1988; Hult & Sherman, 2014). Significant sources of uncertainty were identified, namely pressure fluctuations (4-14%), and interconnected zones not pressurised during the test (30-100%). Other studies reported a 20% variance between tests of the same component (Shaw, Magee, & Rousseau, 1991).

Guarded-zone tests can be found in the literature mostly to assess the airtightness of single units in multi-family dwellings (Kaschuba-Holtgrave, Rohr, Rolfsmeier, & Solcher, 2020; Modera, Diamond, & Brunsell, 1986; Urquhart, Richman, & Finch, 2015) and detached houses (Guyot et al., 2016). The weight of internal leakages in multi-family dwellings performing guarded-zone measurements was addressed by several authors, who obtained inter-zonal leakages to account for 12-36% of the total leakage (Levin, 1988), 27-32% (Kaschuba-Holtgrave et al., 2020), 31-58% (Shin & Jo, 2013), or even values of 60% (Modera et al., 1986). Overall, internal leakages between units by means of different methods have been reported in the literature to account for 15% to over 85% of the total air leakage (Lozinsky & Touchie, 2020). The results obtained, therefore, do not allow to establish a common trend, probably because conclusions are drawn from small, non-representative samples with different test procedures.

However, recent research reported the labour-intensive and impractical nature of the method (Lozinsky & Touchie, 2020) and suggested further research to develop a new functional quantitative method that can differentiate air leakage characteristics by surfaces (Lozinsky & Touchie, 2021). Moreover, a major limitation is the fact that there is no standard test method for guarded-zone testing and, thus, tests are usually adapted from single-zone standards. In this regard, alternative measurement methods are being developed (Fine, Gray, Tian, & Touchie, 2020; Fine, Lozinsky, & Touchie, 2021).

To conclude, it must be taken into account that the assessment of the airtightness in multi-family dwellings gains complexity and the method chosen for airtightness measurement will depend on the purpose: leakages from other conditioned units should be dismissed for energy impact analysis, whereas interzonal leakages could be of interest in terms of IAQ and pollutant transport.

2.3.6.4 Measurement uncertainties

Even though pressurisation tests have been performed for a long time, questions still arise concerning the uncertainty of measurements. This is of special awareness nowadays in a context in which airtightness requirements implementation with the focus on energy use has become a trend in European and North American countries, and pressurisation tests need to be performed to prove compliance (***Paper 5***).

Several authors reviewed the possible sources of error that can increase uncertainty when performing pressurisation tests (Bracke et al., 2016; Sherman & Palmiter, 1994) and methods to quantify uncertainties have been developed (Prignon, Dawans, Altomonte, & van Moeseke, 2019). Sherman and Palmiter (1994) mentioned three main categories that must be considered: random measurement error (precision), systematic measurement error (bias), and extrapolation errors.

Random measurement error (precision) is due to the random variability of the experimental conditions, of the instrument and the amount of data, and can be statistically estimated (Caillou, Bossche, Delmotte, Orshoven, & Vandaele, 2008). It involves mainly flow and pressure measurement error induced by wind turbulence (speed and direction variation), which may cause fluctuations in measurements (pressure variation around the building envelope). These effects were reviewed (Hsu, Zheng, Gillott, & Wood, 2019) and experimentally assessed by other authors (M. Mattsson, Sandberg, Claesson, Lindström, & Hayati, 2013).

Repeatability (successive tests carried out with the same method on identical test items under the same conditions: operator, equipment) and reproducibility assessment (successive tests performed with the same method on identical test items under changing conditions: operator, equipment) when performing pressurisation tests can also be found in the literature (Delmotte & Laverge, 2011; Murphy, Colliver, & Piercy, 1991; Persily, 1982a).

Systematic measurement error (bias) makes reference to reading variations in a fixed unknown way. It must be noted, though, that it cannot be directly known since the "true" value is a priori unknown (Caillou et al., 2008). These uncertainties are usually referred to as equipment-related errors related to non-linearities regarding, for instance, pressure range reading, hysteresis and sticking problems associated with the pressure measurement devices, or calibration errors (Sherman & Palmiter, 1994). The inhomogeneous leak distribution over the building envelope has also been referred (Caillou et al., 2008).

Steady wind and stack effect are considered systematic measurement error sources that prevent uniform pressure difference on the building envelope. Delmotte (2021) analytically assessed both phenomena through Monte Carlo simulations, whereas Hurel and Leprince (2021) offered a comprehensive overview of the published knowledge and gaps. Building airtightness measurement uncertainty due to the steady stack effect was specifically evaluated based on physical modelling and numerical simulations (Carrié, Olson, & Nelson, 2021), and other authors reported its impact experimentally (M. Mattsson et al., 2013). Uncertainties related to steady wind were approached offering an analytical expression of the error that depends on the leakage distribution and pressure coefficients (Carrié & Leprince, 2016). The effect of the wind was further studied in a model scale experiment under controlled conditions to reproduce fan pressurisation tests for different leakage distributions (Mélois et al., 2020). Due to particular conditions, stack effect and wind-related uncertainties have proven to be especially challenging when testing high buildings (Simons & Rolfsmeier, 2014).

Extrapolation errors refer to the measurement model of the physical situation (modelisation error). These uncertainties are common when flow rates at naturally occurring pressures are extrapolated from airflows at measurement pressure differences (Sherman & Palmiter, 1994). In this respect, steady wind and temperature differences were reported to cause extrapolation error due to the differential pressures on different points of the faces of the envelope that they may induce (M. Mattsson et al., 2013).

Another phenomenon that must be considered is that the nature of the pressurisation method subjects the building envelope to unnatural conditions that might temporarily impact the leakage characteristics. The pressure difference can modify the building elements and cause different performance during the pressurisation or depressurisation test. This might be the case of false ceilings, flap traps, or certain kinds of windows when they are not sealed for test purposes (Charlesworth, 1988). These elements may remain closed when there is negative pressure, and slightly open in case of overpressure (or vice versa), causing thus, a valving effect that results in leakage curves that do not overlap (Allen, 1985; Cardoso, Ramos, et al., 2020). Besides, it has been reported that significant changes in leakage characteristics with the same leakage area could be found as a result of the asymmetric geometry of some cracks in relation to the flow direction (Baker, Sharples, & Ward, 1986). This phenomenon should be taken into account, acknowledging that it could not occur under natural pressure differences.

Other recommendations have been made to reduce uncertainty when performing pressurisation tests: increased recorded period for the measurement of the pressure difference at a zero-flow rate, avoidance of windy conditions, correct location of the external pressure gauge using a T-connector (Hurel & Leprince, 2021), appropriate choice of instrumentation and proper calibration (Caillou et al., 2008), the performance of multipoint measurements (regression analysis), adequate range of measurements, improvement of the experiment design (Sherman & Palmiter, 1994), time and pressure-averaged measurements (Modera & Wilson, 1990), the performance of both pressurisation and depressurisation measurements (Walker, Sherman, Joh, & Chan, 2013). A generally made conclusion when assessing uncertainty is that airtightness measurements at high pressures ($50\ Pa$) have reasonable uncertainty, whereas airtightness predictions under natural conditions (low-pressure differences) tend to suffer from significant uncertainty (M. Mattsson et al., 2013). Therefore, the choice of an appropriate reference pressure difference is key, especially under unfavourable weather conditions.

2.3.6.5 Fan pressurisation method guidelines

There are different guidelines with regard to the DC pressurisation method, although the main inputs can be considered equivalent. The most widely used protocols in North American are the standards of the American Society for Testing and Materials, ASTM E779 (ASTM, 2019) and ASTM E1186 (ASTM, 2017), and the standards of the Canadian General Standards Board (CGSB) in Canada, CGSB 149.10 (Canadian General Standards Board, 2019). In Europe, the International Standard ISO 9972 (ISO, 2015), or its European translation EN ISO 9972, is dominant and commonly sets the basis for specific measurement requirements for different countries. These standards include measures to reduce measurement uncertainty such as wind and stack effect limitation, or minimum accuracy requirement of the pressure and temperature measurement devices. Further related information related to this issue can be found in ***Paper 5***.

2.4 LEAKAGE LOCATION

The blower door technique is used to quantify the leakage of a building, but this test does not provide information regarding leakage location. In this way, several methods can be used: smoke detection, anemometers, or IR thermography, often combined with depressurisation, are the most widely used, but other methods such as the soap bubble method, hand inspection, or helium-filled balloons have also been reported (Pickering, Cucchiara, Gonzales, & McAtee, 1987).

The measurement of the air velocity caused by air infiltration through leakage paths by means of hot-wire anemometers is a common practice. This method is based on the cooling effect of air on a heated wire, which is used as a measure of air velocity (Pettersson & Axen, 1980). It must be noted, however, that a certain pressure difference across the construction, naturally driven or generated by DC pressurisation, is needed. This method is easy to approach, but other methods such as IR thermography have been imposed given the time-consuming process of air velocity measurement.

Smoke detection is also widely used combined with DC pressurisation to locate air leakage paths. A smoke piston is used to visualise the infiltrating airflows, providing information concerning the direction of the airflow and leakage paths. This method is also time-consuming and usually, there are limitations with regard to the location of the smoke source. For instance, better visualisation of infiltrating air is produced during depressurisation, but access to the exterior wall of the envelope is not always possible in multi-family buildings or tall buildings without balconies. Moreover, tracer smoke can cause issues regarding indoor air contamination and discomfort for the users.

In this context, IR thermography has become the most widely used method to qualitatively assess air leakage, as reported by Kronvall (1980). When the outer environment is colder than the inner volume of the space under study, the colder external air entering the room through the leakages cools down the warm inner surface adjacent to the leakages, and, in this way, leakage paths can be thermally identified. Pettersson and Axen (1980) extensively described the principles and the applicability of IR thermal imaging to evaluate the thermal insulation and airtightness of the building envelope. The authors presented a series of guidelines concerning aspects that should be considered for successful IR thermography assessment under natural conditions:

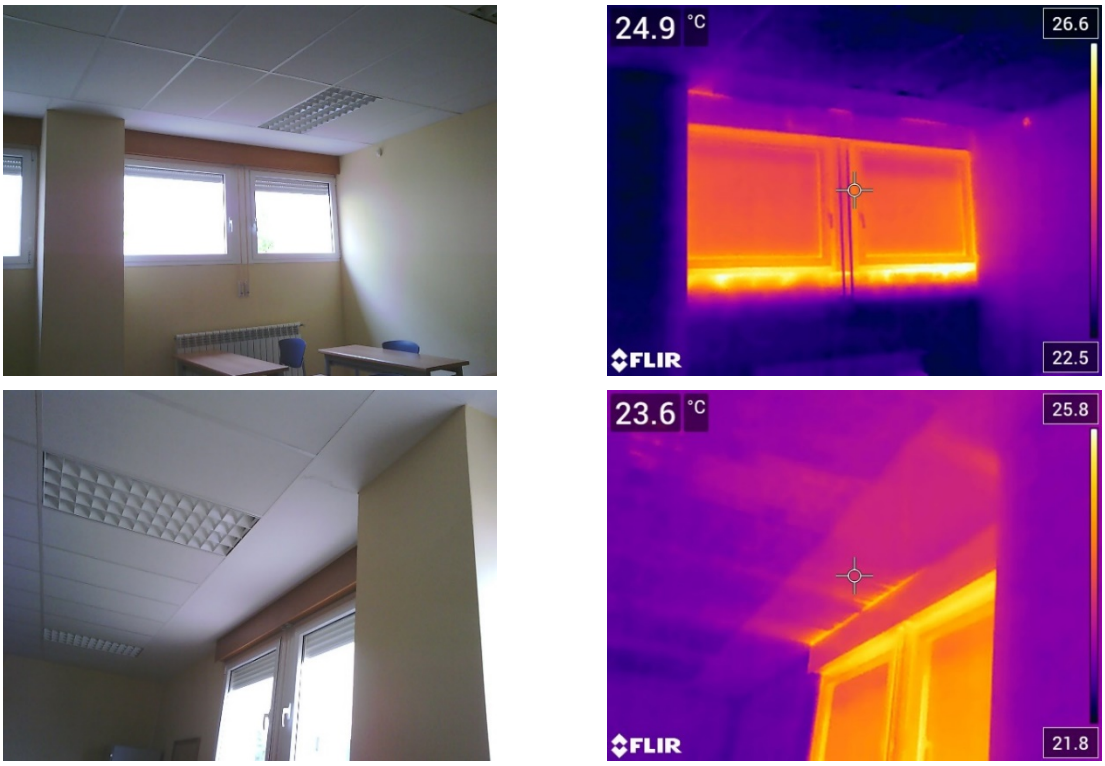
- Pressure drop across the building envelope of around 5 Pa. The pressure inside the building must be lower than the pressure outside;
- Wind and cloud conditions including precipitation during the test;
- Orientation and near environment characterisation;
- At least $5°C$ temperature difference across the envelope. Temperature determination indoors and outdoors during the measurement. Determination of the maximum and minimum air temperature 24 hours before the measurement;
- Sunshine conditions over 12 hours before the measurement;
- Location of leakage points from the inside of the building;
- Determination of the emissivity (ε-value) of the surface materials);
- Air movement and thermal radiation assessment indoors;
- Characterisation of warm radiators and pipes on the envelope, which should be turned off when possible.

The combined use of IR thermography and DC pressurisation tests is extended practice to locate leakage paths for airtightness assessment, guaranteeing a certain pressure difference across the building envelope (Eskola et al., 2015; Feijó-Muñoz et al., 2018; Gillott et al., 2016; Tanyer et al., 2018). In this way, as long as there is enough temperature difference between the indoor environment and outdoors, leakage paths can be also identified when the indoor temperature is lower than outdoors, as is shown in **Figure *12***.

One typical reported problem is that leaks often occur close to building elements that cause thermal bridges, so it is important not to confuse them with leakage paths (Charlesworth, 1988). In this way, one recommended practice is to perform image subtraction, comparing natural pressure and depressurisation of the building images (Kalamees, 2007). This method offers valuable information and is considered a good practice. Further recommendations and guidelines were presented (Vollmer & Möllmann, 2017).

Overall, IR thermal imaging combined with DC pressurisation seems the most effective method to locate leakages. However, the related seasonal limitations represent the main drawback when performing measurements out of the cold season, so other methods like the mentioned air velocity measurement and smoke detection are to be used when minimal environmental conditions are not met.

Figure 12. *Leakage location using IR thermal imaging during depressurisation stage*



Note. From "Impact of Air Infiltration on IAQ and Ventilation Efficiency in Higher Educational Classrooms in Spain," by I. Poza-Casado, R. Gil-Valverde, A. Meiss, & M. Á. Padilla-Marcos, 2021, Sustainability, 13(12), 6875, p. 10. Copyright 2021 by the Authors. Creative Commons Attribution 4.0 International License (CC-BY 4.0).

2.5 Air infiltration rate from airtightness measurements

Although airtightness is the main building factor that determines air infiltration, it must be taken into account that both concepts refer to different realities. While airtightness is a characteristic of the building envelope, air infiltration is a naturally driven process, which consists of the entrance of outdoor air under normal operating conditions through leakages of the building envelope. Seasonal average infiltration rates are key to estimate the energy impact caused by the lack of airtightness of the envelope, as well as to understand the contribution of leakages to the outdoor air renewal of a building, which is critical for maintaining adequate IAQ (Jones, Persily, & Sherman, 2016).

Pressurisation tests measure the airtightness of the building envelope regardless of the weather conditions and results are often expressed at a reference pressure difference of 50 Pa. Pressurisation measurements, thus, do not provide actual airflow information during normal building operation (McWilliams, 2003). However, test results are often used to infer the air infiltration rate (ISO, 2015; Sherman, 1995).

Addressing leakage estimation is not easy because it is dependent on weather-driven forces (indoor-outdoor temperature gradient and wind speed), which involves non-linearities and, thus, it is not the result of the average instantaneous values. Furthermore, the interaction of these driving forces with the ventilation system and other leakage paths should be also considered. Wind pressures, which are the main source of unsteadiness, are not easy to assess given that they depend on many factors, are unpredictable, and are not easily measurable (Etheridge & Sandberg, 1996). This is why simplifications are made and wind is considered to be steady for averaging periods. Infiltration rates are thus time-averaged or stated for some given condition (Colliver et al., 1992). As a result, air infiltration is usually estimated as an equivalent constant rate using a simple linear relationship.

Early modelling work compared pressurisation test results with tracer-gas measurements (Caffey, 1979). In this sense, the first attempt to relate airtightness and air infiltration is the well-known “rule of thumb”, also known as Sherman’s ratio, or the Kronvall-Persily (K-P) rule, which estimates the annual air change rate under natural conditions (ACH_{K-P}) from the air change rate at a pressure difference of 50 Pa (n_{50}) obtained from the pressurisation test as in Equation (17):

$$ACH_{K-P} = \frac{n_{50}}{20} \tag{17}$$

where: ACH_{K-P} is the annual air change rate defined by the rule of thumb [h^{-1}]; n_{50} is air change rate at 50 Pa [h^{-1}].

The origin of this relationship in the late 1970s was attributed to Kronvall and Persily due to their related previous work (Kronvall, 1978; Persily, 1982b). However, the issue is still unclear because only references to it have been published ever since, so the enigma remains unsolved (Jones et al., 2016; Sherman, 1987).

Sherman and Grimsrud (1980) soon proposed the orifice flow model, which aimed at measuring air infiltration from pressurisation tests for specific weather-driven forces. In this way, the proposed model estimated air infiltration from measurable parameters, namely, the leakage area of the building (obtained from the pressurisation test), the geometry of the structure, the temperature gradient between the interior and the exterior (which determines the stack effect), the terrain class of the structure, and the wind speed. The leaks caused by wind, stack effect, and mechanical ventilation were calculated separately and then combined by quadratic superposition.

Sherman and Grimsrud’s model that is referred to as the LBNL infiltration model was compared to measurement infiltration data in order to determine its accuracy and precision (Modera et al., 1983; Sherman & Modera, 1986). Concurrently, other approaches were proposed (Reeves, Mcbride, & Sepsy, 1979; Shaw, 1981; Warren & Webb, 1980). However, these models have a good fit only for buildings with certain characteristics of leakage distribution, wind pressure and internal partitioning (ASHRAE, 2021).

The LBNL model derived in the annual infiltration model proposed by Sherman (1987) assuming a typical single-story dwelling. An empirical correction factor k scaled according to building and environmental conditions variations: local climate, air leakage path size, dwelling height and shielding was considered (Equation (18)).

$$ACH = \frac{n_{50}}{k} \tag{18}$$

where: ACH is the average annual air change rate [h^{-1}]; n_{50} is the air change rate at 50 Pa [h^{-1}]; k is the leakage infiltration ratio [$-$].

The leakage infiltration ratio (k) is a non-dimensional constant that depends on coefficients related to the characteristics of the building and site, as seen in Equation (19).

$$k = C_f \cdot cf_1 \cdot cf_2 \cdot cf_3 \tag{19}$$

where: C_f is the climatic factor, calculated in the model from hourly climate data for more than 200 points in the US and Canada. Its value is in the range of $15 - 30$; cf_1 is the height correction factor of the building, applicable to buildings in which the tested spaces are on 1 floor (cf_1 = 1) up to 3 floors (cf_1 = 0.7); cf_2 is the site shielding correction factor, for well-shielded cases (cf_2 = 1.2), (cf_2 = 1) or exposed dwellings (cf_2 = 0.9); cf_3 is the leakiness correction factor, dependent on the value of the leakage exponent n. Buildings with small cracks, a typical situation of typical tighter buildings are given a correction factor cf_3 = 1.4, whereas leakier buildings with large holes have a correction factor cf_3 = 0.7.

It must be noted that the model represents a simplification of a non-constant and complex reality (Chan, Price, Sohn, & Gadgil, 2003). Although it cannot provide accurate estimates of building air change rates, it is considered valid for the estimation of infiltration rates from pressurisation tests (Jones et al., 2016). The correction factor k was recently calculated for nZEB depending on the shielding of the dwelling for Mediterranean cities and cities located in northern Europe (Guillén-Lambea, Rodríguez-Soria, & Marín, 2019).

Walker and Wilson (1990) developed the Alberta Infiltration Model (AIM-2), with some significant assumptions from other existing models. They considered wind and stack effect separately and then superposed. The model was compared to other existing ones and results revealed a good fit and assumable error, being local wind shelter and leakage distribution the major sources of uncertainty.

Alternative models (Walton, 1989) and improvement suggestions for the existing ones (Palmiter, Bond, & Sherman, 1991) have been developed over time. Orme and Leksmono (2002) and other authors (Breen et al., 2014) made comprehensive reviews of a number of developed models, including their input data and areas of application: single-zone simplified models like the aforementioned ones such as the CEN simplified calculation procedure on EN 16798-7: 2017 (CEN, 2017), Air Infiltration Development Algorithm (AIDA) (Liddament, 1989), CIBSE "inverse sizing" model (Irving, Ford, & Etheridge, 2005), DOMVENT (Jones et al., 2015), and multi-zone network models: AIOLOS (Allard & Santamouris, 1998), BREEZE (Orme & Leksmono, 2002), COMIS (Allard et al., 1990), or CONTAMW (Walton & Dols, 2005).

Physically-based modelling approaches consider the physics theory of building airflow to predict cumulative distribution functions of mean infiltration rates. Therefore, more rigorous predictions of infiltration rates are obtained. Their complexity, though, might result impractical in some policy contexts, or to save time when a large number of cases need to be analysed and the computational time is an issue (Orme & Leksmono, 2002). Other examples of accurate dynamic methods (Alessandrini, Ribéron, & Da Silva, 2019) do not involve great difficulties and, thus, their use is encouraged. In practice, simplified models are applied still nowadays by building codes around the world or even for policy decision-making. However, significant limitations have been reported (Jones et al., 2016) since simplified models do not consider the interaction with other systems are not accurate when estimating the energy demand of individual dwellings. Thus, simplified models should be used only as quick rules-of-thumb to make infiltration rates estimations.

2.6 IMPACT OF AIR INFILTRATION ON ENERGY PERFORMANCE

The uncontrolled entrance of outdoor air into a building requires the reconditioning of the infiltrated air to adjust it to interior comfort conditions. The energy required to raise the temperature of outdoor air to the indoor environment's temperature is the sensible component, whereas the energy associated with the net loss of humidity from the space is the latent component (ASHRAE, 2021). The amount of energy required depends on the enthalpy difference between the exfiltrated and infiltrated air.

Numerous studies that estimated the energy impact of air infiltration have been carried out so far in northern Europe. In regions with a moderately cold climate (2,500 degree-days), the energy impact of air infiltration on the heating demand was estimated at around 10 $kWh/m^2\ y$ (Carrié & Wouters, 2013). Other studies revealed that the lack of airtightness of the building envelope can increase the heating demand from 5 to 20 $kWh/m^2\ y$ in countries with temperate climates (Spiekman, 2010).

The estimation of the energy impact of infiltration is a complex issue, given that it depends on the air infiltration rate calculation (see Section "Air infiltration rate from airtightness measurements"). The driving forces that cause air infiltration depend on the wind and the stack effect caused by a temperature gradient, and therefore, the relationship is non-linear (de Gids, 1981; Jackman, 1974; Sherman, 1995). Different calculation models have been developed so far with varying degrees of complexity and reliability. The more simplified models assume a uniform distribution of leakage paths and constant average leaks over time.

The instantaneous passage of cold outside air into the building generates a thermal load, which is a function of the rate at which the air enters and the temperature gradient between the indoor and the outdoor environment (Equation (20)). The latent component of the thermal load can be considered negligible (Jackman, 1974).

$$E_{inf} = q_m \cdot c_p \cdot \Delta T \tag{20}$$

where: E_{inf} is the infiltration heat loss $[W]$; q_m is the mass flow rate of infiltration $[kg/s]$; c_p is the specific heat of air $[kJ/kg\ K]$; ΔT is the indoor-outdoor temperature gradient $[K]$.

Which in terms of volumetric flow can be expressed as in Equation (21).

$$E_{inf} = \rho \cdot Q \cdot c_p \cdot \Delta T \tag{21}$$

where: E_{inf} is the infiltration heat loss $[W]$; ρ is the density of air $[kg/m^3]$; Q is the total infiltration $[m^3/h]$; C_p is the specific heat of air $[Wh/kg\ K]$; ΔT is the indoor-outdoor temperature gradient $[K]$.

The associated instantaneous load due to conduction losses is calculated according to Equation (22):

$$E_{conduction} = \lambda \cdot \Delta T \tag{22}$$

where: $E_{conduction}$ is the conductive heat loss $[W]$; λ is the envelope conductivity $[W/K]$; ΔT is the indoor-outdoor temperature gradient $[K]$.

Therefore, the total heating load of the envelope as a result of the transmission heat loss and the heat loss associated with air infiltration can be obtained by combining both effects (Equation (23)).

$$E_{heat} = (\lambda + \rho \cdot Q \cdot c_p) \cdot \Delta T \tag{23}$$

where: E_{heat} is the heating load $[W]$; λ is the envelope conductivity $[W/K]$; ρ is the density of air $[kg/m^3]$; Q is the total infiltration $[m^3/h]$; c_p is the specific heat of air $[Wh/kg\ K]$; ΔT is the indoor-outdoor temperature gradient $[K]$.

Jackman (1974) studied design values of wind speed and outdoor air temperature to be used in the calculation of infiltration rates and the resulting heat loss. He proposed a method to calculate the impact of air infiltration from tabulated values of the infiltration rate, exposure, orientation, and environmental conditions, which was developed for a specific site in the UK. De Gids (1981) also proposed a calculation method for a reference house from wind pressures, air temperatures, airtightness, and exposure based on a previous model developed for ventilation and infiltration in buildings (de Gids, 1978).

Heating degree-days (HDD) are often used to determine the severity of the climate in terms of the heating requirements of the building. HDD are calculated from the sum of the differences between the base temperature and each hourly average temperature during the heating season, known as the number of heating degree-hours, and then divided by 24 (Orme, 1998). Its use allows infiltration losses to be estimated, by quantifying the average temperature rise needed for the indoor environment throughout the heating season. Therefore, if the concept of HDD is applied to the model, the seasonal or annual heating load can be estimated as in Equation (24).

$$E_{heat} = 24 \cdot \left(\lambda + \rho \cdot Q \cdot \ c_p\right) \cdot HDD \tag{24}$$

where: E_{heat} is the heating load $[W]$; λ is the envelope conductivity $[W/K]$; ρ is the density of air $[kg/m^3]$; Q is the total infiltration $[m^3/h]$; c_p is the specific heat of air $[Wh/kg\ K]$; HDD is the Heating Degree-Days $[°C - day]$.

This widespread simplified model assumes a constant infiltration rate and fails at considering weather-driven forces. In this regard, Sherman (1986b) developed the Heating Infiltration- Degree Day ($HIDD$) simplified method to assesses the infiltration-related climate. The statistic $HIDD$ was designed with the aim of overcoming the inaccuracies inherent in using standard degree-days for the non-linear infiltration process. It was defined as in Equation (25).

$$HIDD = \frac{1}{24} \sum_{hours} \frac{s}{s_0} \cdot \left(T_{base}^{h} - T_{out}\right) \tag{25}$$

where: $HIDD$ are the Heating Infiltration Degree-Days $[°C]$; s is the specific infiltration $[m^3/h\ cm^2]$; s_0 is the average specific infiltration $[m^3/h\ cm^2]$; T_{base}^{h} is the base temperature during the heating season $[°C]$; T_{out} is the outdoor temperature $[°C]$.

In this way, Sherman (1986b) explained the role of the specific infiltration (s) as a weighting factor in the definition of $HIDD$, so that periods of high infiltration are weighted more heavily than low infiltration periods. The total annual load due to conduction and air infiltration can be, therefore, accurately calculated according to Equation (26).

$$E_{heat} = 24 \cdot \ \left(\lambda \cdot HDD + \rho \cdot Q \cdot \ c_p \cdot HIDD\right) \tag{26}$$

where: E_{heat} is the heating load $[W]$; λ is the envelope conductivity $[W/K]$; HDD is the Heating Degree-Days $[°C - day]$; ρ is the density of air $[kg/m^3]$; Q is the total infiltration $[m^3/h]$; c_p is the specific heat of air $[Wh/kg\ K]$; $HIDD$ are the Heating Infiltration Degree-Days $[°C - day]$.

On the other hand, the associated concept of cooling degree-days is not as broadly accepted as that of heating degree-days due to the latent heat component associated with the humidity changes that are often necessary when cooling (Orme, 1998), although Sherman proposed an approach based on enthalpy differences (Sherman, 1986b).

Most calculation methods for building energy consumption, like the one developed by Sherman (1986b) calculate the heating load of the envelope as a result of the transmission heat loss and the heat loss associated with air infiltration, assuming that the thermal interaction of air leakage and heat conduction in leakage paths can be ignored (Janssens, 2003). This phenomenon, known as “infiltration heat recovery”, involves a reduction of the actual building heat loss, which can be considered negligible only when air leakage is mainly concentrated (cracks surrounding doors and windows, for instance). However, diffuse leakage of air through a wall shifts the temperature distribution of the wall (Anderlind, 1985). Therefore, the conventional addition of transmission and infiltration heat losses might lead to the overestimation of building heat loss (Anderlind, 1985) from 10 to 95% (Buchanan & Sherman, 1998).

Infiltration heat recovery was first accounted for by using a reduction factor (R). If the air leakage is totally diffuse, then R is almost zero. On the other hand, R approaches 1 for a purely concentrated flow (Anderlind, 1985). In reality, infiltration is a combination of concentrated and diffuse flows, and, thus, R usually adopts an intermediate value based on the flow distribution (Younes et al., 2012).

Another dimensionless correction was introduced to consider the magnitude of the effect of infiltration heat recovery: the infiltration heat recovery effectiveness ($IHRE$), which was introduced in the calculation as a weighting factor of the infiltration heat loss (Claridge & Bhattacharyya, 1990). As a result, Equation (24) could be rewritten as Equation (27).

$$E_{heat} = \left(\lambda + (1 - \varepsilon) \cdot \rho \cdot Q \cdot c_p\right) \cdot \Delta T \qquad (27)$$

where: E_{heat} is the heating load $[W]$; λ is the envelope conductivity $[W/K]$; ε is the infiltration heat recovery effectiveness ($IHRE$) $[-]$; ρ is the density of air $[kg/m^3]$; Q is the total infiltration $[m^3/h]$; c_p is the specific heat of air $[Wh/kg\ K]$; ΔT is the indoor-outdoor temperature gradient $[K]$.

Additionally, the effect of solar radiation was studied by Liu (1992), who assessed the combined impact and interaction among conduction, infiltration, and solar radiation in walls. Although several experimental and theoretical studies have been carried out to understand the effect of infiltration heat recovery (Buchanan & Sherman, 1998; Janssens, 2003; M. Liu, 1992), still further research is required to get a better knowledge of its performance for different leakage geometries and typical building components that supports the numerical analysis of infiltration heat recovery. This is essential given its consequences on the heating and cooling needs of a building and, therefore, the sizing of the required systems and a more realistic approach regarding airtightness limitation.

Nowadays, whole-building simulation tools are broadly used to estimate the energy performance of buildings. Infiltration is considered within the air mass balance accounting for zone air thermal mass and direct convective heat gains. Usual inputs for infiltration include the effective leakage area per zone and the estimated distribution of the leakage area over each wall (D. B. Crawley, Hand, Kummert, & Griffith, 2008; Tian, Han, Zuo, & Sohn, 2018).

Theoretical models to predict infiltration rates and the associated heat loss at a population scale have been developed for the past few years with an application on policy making decisions (Jones et al., 2015; Logue, Turner, Walker, & Singer, 2016; Pallin, Stockdale, Boudereaux, & Beuchler, 2017).

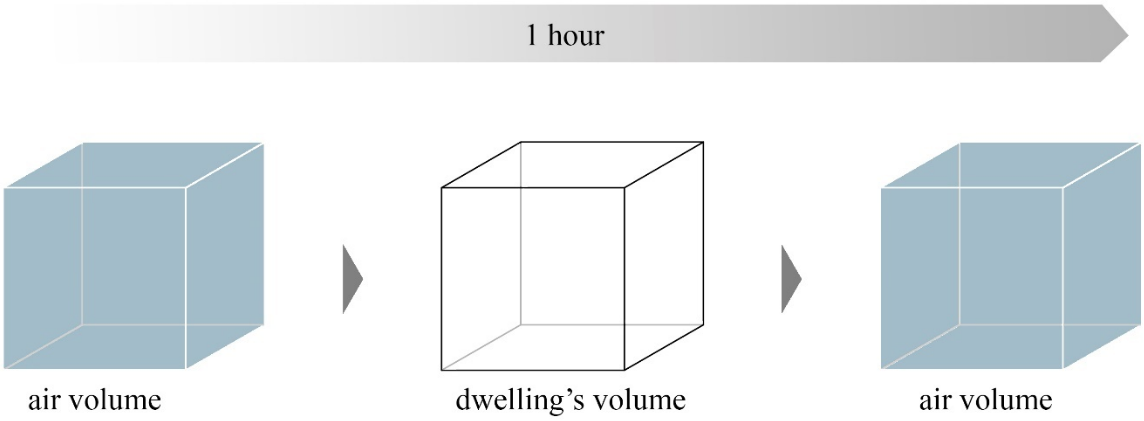
2.7 IMPACT OF AIR INFILTRATION ON VENTILATION

Ventilation strategies imply an intentional and controlled process, and are based on the adequate design of buildings and their systems for the supply and distribution of renewal airflows (Padilla-Marcos, 2015). In this regard, the air supply is differentiated from the exhaust air, which is considered of poorer quality. The supply of fresh air into the indoor environment can be carried out through building purpose-provided openings as a result of pressure difference caused by the action of wind and buoyancy (natural ventilation), mechanically driven with fans (mechanical ventilation), or as a combination of both (hybrid ventilation) (Etheridge, 2015; Niachou, Santamouris, & Georgakis, 2007).

Therefore, air infiltration is an uncontrolled and naturally driven process that contributes to the air renewal of indoor environments. The airflow rate caused by air infiltration is often related to the volume of the building or a part of it. In this way, the air change rate concept can be defined as "*the volumetric rate at which air enters (or leaves) a space divided by the volume of the space*" (Priestner & Steel, 1991, p. I.9) (**Figure *13***). When it is referred to a period of one hour, this value is known as the air changes per hour (ACH). In other words, it expresses the number of times that the equivalent volume of air of the space passes through the leakage paths of the building envelope for one hour.

However, it is important to note that the air change rate does not have a direct relation with the air renewal. The indoor air actual renewal and, thus, contaminants removal, depends on the air change efficiency of the interior space (Liddament, 1993; Sutcliffe, 1990). "*Effective ventilation is defined as the steady-state ventilation that would yield the same average pollutant concentration over some time period as the actual time varying ventilation would in that same time period*" (Turner, Sherman, & Walker, 2012, pp. 1125–1126). In this regard, air leakage provides little control over the pattern of air movement within buildings (Liddament, 1986), partly because leakage paths are not uniformly distributed on the envelope (Bossaer, Demeester, Wouters, Vandermarke, & Vangroenweghe, 1998).

Figure 13. *Schematic representation of the air change rate (one air change per hour)*



In naturally ventilated buildings, ventilation needs are addressed by the use of controlled openable windows and vents or purpose-provided openings (Liddament, 1986). When the air supply is done by means of windows operated by the users, this process is called airing, which is supplemented by infiltrating airflows. In this case, the air change rate depends on the airtightness of the building envelope, weather conditions (indoor-outdoor temperature gradient and wind speed) and also on the users' behaviour related to window opening, induced exhaust and the use of heating and cooling systems (Nazaroff, 2021). Therefore, air infiltration plays a key role since it is the only air renewal source that does not depend on the users.

On the contrary, mechanical ventilation systems offer a controlled air supply within the indoor environment. In this case, the presence of uncontrolled airflows through the building envelope may lead to the oversizing of the ventilation system and thus, cause its bad performance.

While over-estimating the contribution of air infiltration can result in poor IAQ and pollutant exposure, ignoring infiltration can result in excess air renewal and subsequent energy waste (Turner et al., 2012). In this regard, the analysis of a large airtightness dataset of new dwellings in the UK revealed that the ventilation strategy was not coupled with the airtightness of the building envelope (J. Crawley, Wingfield, & Elwell, 2019). This might lead to IAQ issues in naturally ventilated homes, and excessive energy demand in dwellings with mechanical ventilation with heat recovery. Therefore, an accurate understanding of air infiltration is important when designing the ventilation system of a building (Cardoso, Pereira, Ramos, & Almeida, 2020).

However, predicting the contribution of air infiltration is complex and, as a result, leakage measurements should be performed to accurately estimate its contribution to air renewal (Etheridge & Sandberg, 1996) in naturally ventilated buildings, or its interference with mechanical ventilation systems (Liddament, 1986).

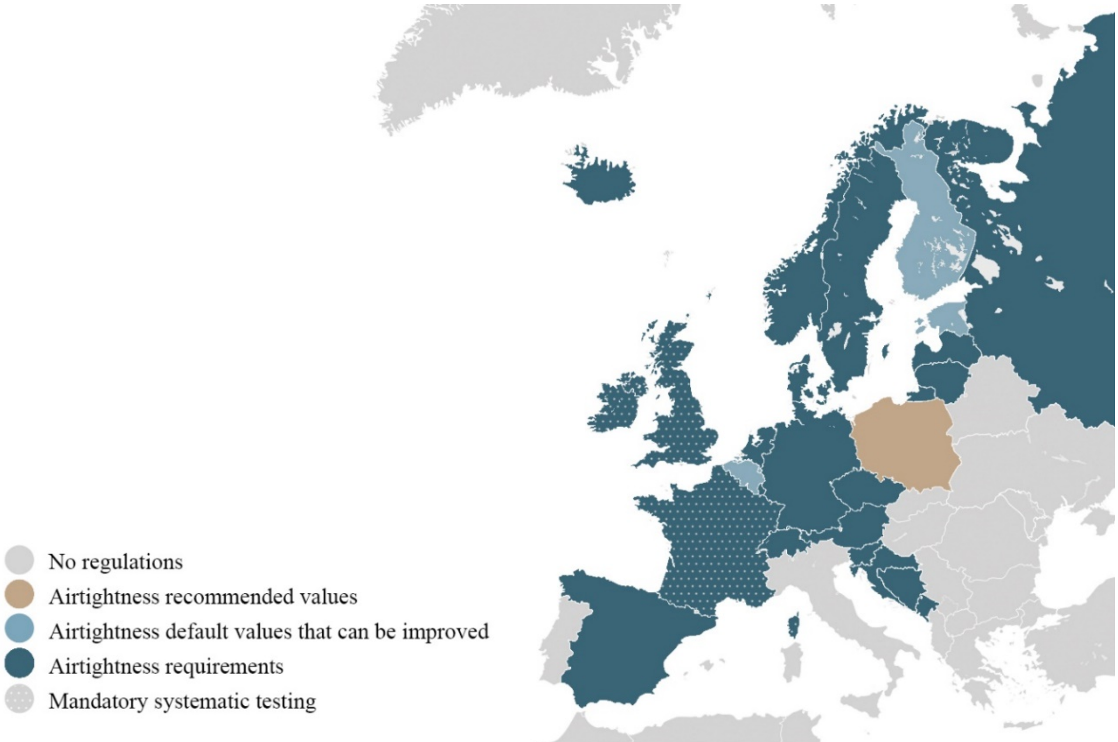
Procedures to estimate the extent to which infiltration contributes toward air renewal needs have been approached in the literature (Turner et al., 2012; Yuill, 1991). The issue is complex because infiltration depends on building airtightness and weather-induced pressure differences, so it is a non-linear phenomenon. What is more, varying air infiltration rates will result in different levels of contaminant dilution and, hence, effective air renewal. Accordingly, Turner et al. (2012) used the principles of effective ventilation to calculate the impact of weather-driven infiltration on indoor pollution dilution for different climates in North America.

2.8 AIRTIGHTNESS REQUIREMENTS

Since the 1970s oil crisis, there has been a growing interest in building physics, indoor climate, and energy efficiency in buildings (Wouters, 2000). The European Strategy for Sustainable Development, as well as the Paris Agreement, reached after the United Nations Climate Change Conference in 2015 (United Nations Framework Convention on Climate Change (UNFCC), 2016), promoted political awareness and established contemporary criteria of energy saving and efficiency and the reduction of emissions, especially from buildings (Feijó-Muñoz, Pardal, et al., 2019). This has led to the need to define joint strategies aimed at achieving solutions to the high energy consumption related to building development. In this regard, energy policies that limit the energy use of buildings have been established. For the last few years, the focus on European countries has become the implementation of nZEB, whose framework is set in the Energy Performance of Building Directive (EPBD) (European Parliament, 2018).

In this context, air infiltration control with airtight envelopes is key to avoiding a significant impact on the energy demand of dwellings (Younes et al., 2012). Consequently, many countries have incorporated limitations in their regulations regarding the airtightness of the envelope (Leprince et al., 2017) since the beginning of the 2000s. However, EPBD does not establish specific requirements or a standard procedure to determine the energy balance (Guillén-Lambea et al., 2019), so discrepancies exist among countries in the regulation on the control of air leakage: some regulations set limitations on the whole building permeability (e.g., the UK, France), whereas others just set recommendations (e.g., Poland), default values (e.g., Belgium, Finland) or even no consideration at all (e.g., Greece, Hungary) (**Figure *14***). In addition, other voluntary standards such as Passivhaus certification introduce strict minimum airtightness performance (Passive House Institute, 2016).

Figure 14. *Airtightness regulatory context in Europe*



Note. From "Residential buildings airtightness frameworks: A review on the main databases and setups in Europe and North America," by I. Poza-Casado, V. E. M. Cardoso, R. M. S. F. Almeida, A. Meiss, N. M. M. Ramos, & M. Á. Padilla-Marcos, 2020, *Building and Environment*, 183, 107221, p. 4. Copyright 2020 by Elsevier Ltd. All rights reserved.

The focus is also different regarding the criteria to determine airtightness limitations (Poza-Casado et al., 2020), which can depend on:

- Integrated ventilation system type (natural, hybrid, mechanical and, in some cases, considering heat recovery), e.g., Germany (BGBI, 2014);
- Dwelling typology (single-family or multi-family buildings), e.g., France (Ministère d'Etat de l'écologie de l'énergie du développement durable et de la mer, 2010);
- New or retrofitted dwelling, e.g., Switzerland (Assemblée générale de l'EnDK, 2018);
- Energy performance label, e.g., Lithuania (Lietuvos Respublikos Aplinkos Ministro, 2016);
- Climate zone, e.g., USA (ICC - International Code Council, 2017);
- Ratios between different geometric properties, e.g., Denmark (Ministry of Transport, 2018);
- Prescriptive path on air barrier detailing, e.g., Canada (National Research Council Canada, 2015).

Regardless of the measurement metric, DC pressurisation tests are the widespread method used to assess the airtightness of dwellings and prove compliance with regulations. Measurement protocols, therefore, need to be objective and reproducible (Sherman, 1995) (see Section "Fan pressurisation method guidelines"). However, only a few countries and specific energy labels require systematic on-site testing so far. In most countries, in contrast, airtightness is just estimated based on building characteristics and DC pressurisation tests are only performed as random checks.

However, in Mediterranean countries with milder climates, whole building airtightness has still not been the focus from a regulatory point of view. Air renewal has traditionally been done in a natural and manually controlled way, so infiltration has been part of the air supply.

Despite the uneven guideline adoption by the different member states, since the EPBD requires the compliance of new buildings to be nZEB, changes on airtightness limits are expected in the building energy codes of European countries in the near future. More information on airtightness requirements in the international context can be found in ***Paper 5***.

2.9 AIRTIGHTNESS DATABASES

Airtightness databases constitute knowledge sources of great relevance. In recent years, the gaining concern for the airtightness of the building envelope, the spread of regulatory frameworks and corresponding stricter requirements in many countries, and the need to demonstrate compliance with those requirements have favoured the creation of airtightness databases. Representative airtightness databases of a building stock can be of interest for several purposes (Poza-Casado et al., 2020):

- Demonstrate the compliance with regulations when they are mandatory (Charrier, Bailly, & Carrié, 2015);
- Provide more accurate and reliable input data for buildings energy and air change estimations of future construction and weatherised buildings (Han, Srebric, & Enache-Pommer, 2015);
- Gather information for modelling and designing (Montoya, Pastor, Carrié, Guyot, & Planas, 2010);
- Evaluate which factors are the most important for airtightness (Prignon & Van Moeseke, 2017);
- Evaluate building design, construction practices and quality (Feijó-Muñoz, González-Lezcano, Poza-Casado, Padilla-Marcos, & Meiss, 2019);
- Develop clear guidelines for airtightness best practices (BC Housing, 2017);
- Evaluate the effectiveness of individual measures in improving airtightness (Gillott et al., 2016);
- Visualise time trends (Bracke et al., 2016);
- Evaluate the progress of the building stock in meeting building energy performance objectives (Erhorn-Kluttig, Erhorn, Lahmidi, & Anderson, 2009);
- Compare the building performance with other countries (Papaglastra, Leivada, Sfakianaki, Carrié, & Santamouris, 2008).

An early and ground-breaking airtightness database was developed by the Air Infiltration and Ventilation Centre (AIVC) with the aim of gathering numerical data for design purposes and model validation (Orme et al., 1994). Whole building airtightness measurements in over 2,700 buildings in 10 countries were included, as well as data on component air leakage and a wind pressure evaluation. However, this database was not subjected to ongoing data updates, so it cannot be considered anymore representative for the current building stock.

In recent years, some airtightness databases with a large number of cases were developed in several countries as a result of mandatory systematic on-site testing (e.g., the UK, France, Ireland), or very unfavourable default values on the Energy Performance of Buildings (EPB) calculations where the only way to improve them is by introducing the actual airtightness values obtained from measurements (e.g., Belgium) (Laverge, Delghust, Bossche, & Janssens, 2014).

A comprehensive review of the most important existing databases in Europe and North America containing detailed information, main inputs, comparison, identified challenges, and successful approaches was addressed in ***Paper 5***.

2.10 FACTORS INFLUENCING AIRTIGHTNESS

Whole-building airtightness databases are sources of valuable knowledge. One of their most important application is the determination of the main factors that have an impact on airtightness through their analysis in order to provide aid in the decision-making process (Prignon & Van Moeseke, 2017), both for the design of new buildings and the evaluation of retrofitting actions (Orme, 1994).

Some authors reviewed this issue and provided an overview of the conclusions drawn from different databases and their comparison (Prignon & Van Moeseke, 2017; Sherman & Chan, 2004). A general overview of the results obtained from the analysis of different airtightness databases and the impact of some building characteristics is also gathered in ***Paper 5***.

Prignon and Van Moeseke (2017) analysed data from 14 datasets from different countries and classified the main factors influencing airtightness according to their significance. In spite of the inconsistencies found, they identified common trends in the data. The number of stories, building method, envelope structure, ventilation system, the design target and supervision seem to have an impact on airtightness. However, interactions among the factors and the influence of supervision and workmanship add difficulties for the analysis. Overall, issues regarding differing metrics for data presentation, parameters definition and statistical approach were highlighted (Prignon & Van Moeseke, 2017).

Sherman and Chan (2004) reviewed the main factors influencing airtightness from different databases from the USA, Canada, Sweden, the UK, Belgium, and New Zealand with regard to year of construction, building geometry and climate. The year of construction seems to be an influencing factor in the datasets analysed. However, this might not be the case in milder-climate countries and countries with no airtightness regulations. Building geometry was concluded to be related to the envelope complexity, and thus, potential leakage paths. To conclude, a clear relationship was found considering climate as an influencing factor on the airtightness performance of the envelope due to the energy-associated implications.

Results obtained from the analysis of the AIVC airtightness database (Orme et al., 1994) from measurements of over 2,700 buildings in 10 countries revealed the influence of the type of construction and building age (also with the particular influence of standards) among other factors.

Weatherisation-assistance programs and residential energy efficiency programs in the USA incentivised the construction of one of the most important airtightness databases. Chan et al. (2013) analysed data from 134,000 single-family dwellings and found year built and climate as the most influencing variables on airtightness.

The study of 900,000 cases in Canada built between the late 1700s and 2016 (almost a sample of 12% of the single-family housing stock in the country) revealed key variables such as building geometry, building materials, building age, or local climate (Khemet & Richman, 2018).

The French airtightness database currently being developed as a result of mandatory measurement for new buildings identified the main material of the building, the thermal insulation technique and the type of ventilation system as influential factors. The sample was made of around 219,000 cases from residential buildings built since 2010, and, thus, the sample is only representative of new dwellings (Mélois, Moujalled, Guyot, & Leprince, 2019).

Related analyses have been performed from other recent airtightness databases quickly developed for the past few years such as the one settled in the UK by ATTMA since 2015. Results and trends from 250,000 pressurisation tests were reported (Cope, 2017; Love et al., 2017), pointing out with concern the clear relationship between design targets and test results, which questions data quality. This reliability issue seems to have been solved by the quality framework for building airtightness testing in the Flemish region of Belgium (Strycker, Gelder, & Leprince, 2018). Although a comprehensive analysis of the factors influencing airtightness has still not been published so far to the author's knowledge regarding both UK and Belgium databases, Cope (2021) recently pointed out the impact of construction material on the airtightness performance of buildings.

Other conclusions drawn from more limited samples can be found in the literature, mostly focusing on new single-family dwellings in Belgium (Laverge et al., 2014), in the Czech Republic (Böhm et al., 2021), in the UK (Pan, 2010), and in the Netherlands (Bramiana, Entrop, & Halman, 2016), including also multi-family dwellings in Finland (Vinha et al., 2015), in Russia (Armstrong, Dirks, Klevgard, Northwest, & Saum, 1996) and Estonia (Hallik & Kalamees, 2019). Other samples focused on low-energy dwellings in the Czech Republic (Kraus & Charvátová, 2016), and in cases belonging from different periods (Sfakianaki et al., 2008; Sinnott & Dyer, 2012).

Overall, although discrepancies have been found, common trends can be identified through the analysis of different datasets. Among others, the year of construction, building geometry-related factors, materials used, type of construction and climate are repeated influencing factors found in the literature. The contradictions among different studies might be due to the fact that conclusions can only be applied to cases with the same characteristics of the sample since construction practices vary considerably among regions. In any case, the conclusions drawn from the evaluation of airtightness databases depend on many factors, namely, the size of the sample, its representativeness, the kind of data gathered, its quality, etc.

2.10.1 Development of predictive models

Airtightness prediction has been present in the literature for the past 30 years. However, the tightening of building regulations has strongly increased the interest in estimation tools to predict airtightness. Predictive models are useful to model the infiltration phenomenon and to control costs and time on the decision-making process before the construction of buildings. However, airtightness estimation cannot be seen in any way as a replacement for measurement (Relander, Holøs, & Thue, 2012). In line with the influencing factors obtained from the analysis of large datasets, several empirical models have been developed from them, establishing statistical relationships between the variables.

In the USA, a model to predict the leakage of single-family dwellings was developed from more than 100,000 measurements applying statistical regression techniques. The model was designed with age, climate zone, floor area, height of the house, participation in an energy efficiency program, presence of floor leakage, and occupant income as input data (Mcwilliams & Jung, 2006). Improvement could be performed if the database was complemented with more representative cases.

Univariate analyses and multiple linear regression based on measurement results of the aforementioned dataset in Canada (Khemet & Richman, 2018) were used to develop a predictive airtightness model. The proposed model used 8 variables and was able to predict 48% of the normalised leakage. The same authors then combined whole building measurements and component testing results to develop a specific model for light-framed detached residential buildings (Khemet & Richman, 2020).

A novel approach was implemented by Krstić et al. (2014), who proposed the development of a predictive model by applying neural networks. The model was subsequently validated (Krstić, Otković, Kosinski, & Wójcik, 2016) obtaining consistent results for a sample of buildings with similar construction technology. The method is promising and could be further applied to other datasets.

Prignon and Van Moeseke (2017) reviewed existing models, classifying them into different types: theoretical models, empirical models, building characteristic models, and single-component models. Empirical models were found accurate only when they are used to predict leakage of other buildings close to the sample. The authors found existing models unreliable and concluded that none of the existing ones can be used as an effective design tool. One of the main challenges that hinder consistent models is the thoroughness of workmanship and supervision, which are difficult parameters to consider in predictive models (Prignon & Van Moeseke, 2017; Relander et al., 2012).

2.11 AIRTIGHTNESS OF THE BUILDING ENVELOPE IN SPAIN

The airtightness of buildings has not been traditionally a real concern in the Spanish building sector. The fact that air infiltration constituted a complementary air renewal source in dwellings with no controlled ventilation systems, has made it necessary to allow a continuous uncontrolled air inlet that contributed to the air renewal of indoor spaces. The scenario in recent times is changing, though. The strategies oriented towards the achievement of nZEB inevitably involve air infiltration control and, therefore, airtight buildings with mechanical ventilation systems that guarantee adequate IAQ.

2.11.1 Construction systems of the envelope

The residential building stock in Spain is dominated by dwellings built over the last half-century, whose construction followed common defined patterns across the country. The socioeconomic circumstances during this period influenced the evolution of the buildings' construction trends and led to a progressive generalisation of formal and constructive solutions, which were repeated frequently. Unlike other countries, multi-family dwellings represent more than 70% of the residential stock (Instituto Nacional de Estadística, 2016). A detailed overview regarding the main construction systems widely used over the past century and trends in the Continental and the Mediterranean climate zones of Spain can be found in ***Paper 2*** and ***Paper 3***. An extract is included here.

Traditionally, the building envelope had both structural and protection functions. In this regard, the envelope was mainly based on load-bearing walls made of a single layer of variable thickness (always greater or equal to 24 cm) made of ceramic bricks of different qualities, or other materials. However, during the past century, façade systems evolved as a consequence of the industrialisation of metal structures and the introduction of reinforced concrete (Monjo Carrió, 2005). This development was gradual and, during the first years of the 20th century, the use of mixed solutions with an internal framework and massive load-bearing walls with one layer was still common in some cities (Ros García, 2005).

Openings were frequently single-pane windows with wooden swing frame. When the metalwork window appeared, its use was restricted to the main façade, placing the wooden windows in the courtyards' facades (Valencian Institute of Building, 2011). Traditionally, the protection and solar control function was solved with folding blinds or traditional exterior wooden rolling shutters (Martí, Araujo, & Araujo, 2015).

After the Spanish Civil War (1933-1936), numerous cities received a growing migratory flow from the countryside (Meiss, del Caz Enjuto, & Álvaro Tordesillas, 2013). There was an important demand for housing that private developers could not cope with, largely due to the period of autarchy that the country was going through and the important restrictions on steel, cement and the transport of materials to construction sites (Kurtz, Monzón, & López-Mesa, 2015). The State became the main housing developer (Meiss et al., 2013), which favoured traditional constructive techniques. Quick, simple and repetitive solutions were employed (Ros García, 2005). A widespread façade solution during the 1940s was exposed brick of different thicknesses ranging from 11.5 to 36 cm (Kurtz et al., 2015). In most cases, the façade worked as a load-bearing wall with an internally reinforced concrete structure.

The regulations applied to public housing construction had a decisive influence. From 1940 onwards, the hygrothermal behaviour of the enclosure was considered, establishing minimum quality requirements (Ros García, 2005). In large cities, the construction of low-cost housing in satellite neighbourhoods was frequently carried out with load-bearing walls perpendicular to the façade.

During the period 1956-1961, the largest number of public housing was built in Spain. These were unitary operations with similar typological and constructive characteristics throughout Spain with slight adaptations to different climates (Rubio del Val, 2011). In this sense, innumerable deficiencies affecting public constructions can be found (Fernández Sánchez, 1991). The construction of these neighbourhoods was based on solutions of maximum simplicity, although some attention was paid to health standards and environmental comfort issues (Ros García, 2005).

A new standard in 1954 featured the use of cavity walls, regulating the double layer system with national scope (Ros García, 2005). From this moment, it can be said that the façade abandoned its structural function, giving way to the use of grid structures, which allowed the façade to be thinner and lighter (Kurtz et al., 2015; Zaparaín, 2016). Single 24 cm-brick wall was used especially as an outer layer, cladded with a simple hollow layer with continuous plaster interior finish and, sometimes, insulating material in the cavity between them (Monjo Carrió, 2005). The development of new insulating materials offered by the industry (foams and glass fibres, wood sawdust, cellular glass, etc.) allowed the cavity wall system to be economically competitive.

Single pane windows with aluminium sliding frame were also introduced (Valencian Institute of Building, 2011), and it is from the decade of the 1950s when the use of the rolling shutters in the inner layer of the envelope was generalised.

Around 1955 and 1960, a singular type of façade became very popular, fitting the enclosure between the slabs and beams of the main structure, reducing its thickness to the maximum. They assumed the function of pure enclosure of the exterior walls, with insulating material in most cases (Ros García, 2005). This solution was extended in Spain until the 1980s (Monjo Carrió, 2005; Zaparaín, 2016).

In the following decades, there was a gradual entry of private development and the State initiative ended up assuming a mere subsidiary function from 1963 (Meiss et al., 2013).

In the 1970s, façades were definitively lightened, already mostly cavity walls, executing the external layer with 11.5 cm brick in an almost exclusive way (Monjo Carrió, 2005); even replacing the perforated brick with the cheapest alternative: 11.5 cm-hollow-brick wall covered and painted (Valencian Institute of Building, 2011). During these years, the great growth of tourism in the Mediterranean coast required a large number of dwellings in a short period of time, which resulted in buildings with poor construction quality in these areas. Therefore, the absence of thermal insulation of the envelope was typical, as well as construction defects due to an accelerated urban expansion.

With the entry into force of the Standard NBE-CT-79 (Ministerio de Obras Públicas y Urbanismo. Gobierno de España, 1979), thermal insulation was placed into the air chambers, already in a generalised way (Valencian Institute of Building, 2011). One common solution was a double layer of double hollow brick, with 3-4 cm of thermal insulation on some occasions and an air chamber with interior finishing made of continuous plaster. The envelope was finally continuous, setting back the line of pillars towards the interior. Another remarkable aspect is the fact that ventilated facade systems began to be introduced in these years. With regard to windows, aluminium or polyvinyl chloride (PVC) became common materials, with simple or double glazing. Rolling shutters were built integrated into the enclosure, although from the 1990s, compact rolling shutters were introduced.

From 2006, new dwellings have to comply with the CTE Regulations (Ministerio de Vivienda. Gobierno de España, 2006c), paying special attention to its performance concerning energy saving and protection against noise. Although construction techniques have evolved, it can be said that conventional solutions still prevail. A catalogue of constructive elements (Ministerio de Fomento. Gobierno de España, 2011) collects information on the characteristics of generic constructive solutions related to the basic requirements of the CTE.

A widespread envelope solution consists of two brick layers: a thicker one at the outside and a thinner one at the interior, with an intermediate air chamber. The insulation layer has gradually increased its thickness as regulations tightened the energy requirements. The interior finish is usually a continuous plastering layer or commonly lightweight plasterboard systems. On the outside, the coating can be quite diverse: monolayer coatings, discontinuous coatings with natural stone or ceramic cladding, concrete panels, ventilated façades, external thermal insulation systems, etc. In the case of windows, nowadays aluminium with thermal bridge break and PVC prevail, with double or even triple glazing. Windows usually integrate compact rolling shutters with insulation.

2.11.2 Leakage paths on the Spanish building envelope

In line with the previous section, there are several reasons that explain the performance in terms of the airtightness of the envelope of Spanish buildings constructed over the past century. The accelerated urban expansion during some periods, the reluctance towards dry construction systems, the lack of concern, and the large-scale speculative practices in the construction sector lead to the incorrect design and execution of the envelope with innumerable deficiencies.

Specifically, the main hygrothermal problem of the most used façade solutions was the interruption of the external layer of the massive wall and the insulating material in the joint with the horizontal structure or the pillars. There were no movement joints between structural components and facades, which caused numerous cracks and fissures in the brick walls (Valencian Institute of Building, 2011). Thermal bridges and interstitial condensation and leaks problems appeared in the joints between brick and mortar, and cracks (Monjo Carrió, 2005). Double-brick envelopes with an air chamber between the inner and the outer layer constitute common leakage paths. The outdoor air can enter this cavity through any discontinuity of the outer layer, and penetrate the interior through junctions, electrical fittings, etc. (Allen, 1985). In this regard, the use of lightweight plasterboard systems in the last decades encompassed the same problems.

It is also important to mention a common practice in multi-family dwellings whose users' needs required more space, or simply to increase the property's value. To do so, non-conditioned service spaces adjacent to kitchens and terraces were in many cases integrated into the conditioned space of the house through its closure with carpentry. Inadequate and careless execution of these interventions contributed to its poor thermal performance and the introduction of unwanted leakage paths.

Several authors have reported a great share of the total permeability to windows in Mediterranean countries (Almeida, Ramos, & Pereira, 2017; d'Ambrosio Alfano, Dell'Isola, Ficco, & Tassini, 2012; Fernández-Agüera, Domínguez-Amarillo, Sendra, & Suárez, 2016; Sfakianaki et al., 2008). The approach to window airtightness remains a challenge even nowadays with restrictive regulations that require airtight windows. Standards focus only on the window itself, but the air leakage from the joint window-wall and wall assemblies, which has been reported to be precisely dominant (Russell, Sherman, & Rudd, 2007; Van Den Bossche, Huyghe, Moens, Janssens, & Depaepe, 2012), is not considered. This highlights the importance of joint detailed design and workmanship.

Another problematic point of the envelope is related to rolling shutters, which constitute discontinuities of the envelope and, therefore, significant air leakage paths. Only in the last decades has this solution been to a certain extent improved with integrated shutters in windows with insulation.

Overall, it can be said that the evolution of construction systems has generally not led to the improvement of the airtightness of the envelope in the country. In contrast to what might be expected, more extensive adventitious openings and overall air infiltration were identified in recent buildings than in traditional construction.

2.11.3 Airtightness requirements in Spain

As already mentioned in Section "Construction systems of the envelope", in Spain, concerns about the energy use of buildings were for the first time reflected on the EP regulation Spanish Construction Basic Norm NBE-CT-79 (Ministerio de Obras Públicas y Urbanismo. Gobierno de España, 1979), which introduced requirements on the thermal conditions of buildings. The general trend involved the increase of the thermal insulation, achieving an improvement of the energy performance of buildings.

However, there was no awareness about airtightness, so the relative impact of air infiltration on the global energy performance of buildings increased. In 2006, the Basic Document of the Spanish Technical Building Code (CTE) for the Energy Saving in Buildings (DB HE1) (Ministerio de Vivienda. Gobierno de España, 2006a) introduced airtightness requirements for the first time and limited the permeability of doors and windows. Maximum permeability values (q_{100}) were established for new and retrofitted buildings expressed at a reference pressure of 100 Pa. The requirements set 50 and 27 $m^3/h\,m^2$ as the maximum allowed permeability for doors and windows, depending on the winter severity for the Spanish climate zone where the building was located.

In December 2019, a new update of DB HE1 (Ministerio de Fomento. Gobierno de España, 2019a) came into force, with encouraging novelties. The construction solutions and workmanship of the building envelope must guarantee adequate airtightness performance. Specifically, this norm promotes special attention to joints and discontinuities on the thermal envelope.

Minimum airtightness requirements for windows and doors for new and retrofitted buildings, which were already mandatory, toughened. Stricter limit values for the air permeability (q_{100}) are given regarding the winter climate zone where the building is located according to **Table *1***.

Table 1. *Permeability limit values for doors and windows of the thermal building envelope*

	Climate zone for winter conditions					
	α	A	B	C	D	E
q_{100}	≤ 27	≤ 27	≤ 27	≤ 9	≤ 9	≤ 9

Note. According to UNE-EN 12207 (AENOR, 2017), the permeability limit values correspond to Class 2 (≤ 27 $m^3/h\,m^2$) and Class 3 (≤ 9 $m^3/h\,m^2$). If a window has a rolling shutter, its permeability value should also include it. Climate zones A, B, C, D and E refer to Continental Spain. Zone α refers to the Canary Islands.

Regarding whole envelope airtightness, requirements were introduced for the first time at a national level. This requirement is only applicable for new and retrofitted dwellings for private use with a floor area greater than 120 m^2. The requirement proposes limit airtightness values with regard to the compacity of the dwelling, using the air change rate at 50 Pa (n_{50}) as the reference metric, as shown in **Table *2***.

Table 2. *Permeability limit values in relation to compacity*

Compacity V/A_{ET} $[m^3/m^2]$	n_{50} $[h^{-1}]$
$V/A_{ET} \leq 2$	6
$V/A_{ET} \geq 4$	3

where: n_{50} is the air change rate at 50 Pa $[h^{-1}]$; V is the internal volume of a building or part of a building $[m^3]$; A_{ET} is the sum of areas of the thermal building envelope with heat exchange with the outdoor air. Therefore, internal partitions and the envelope area in contact with other adjacent spaces or buildings are excluded $[m^2]$. *Note*. The limit permeability values for intermediate compacity values can be obtained by interpolation.

There are two options to prove compliance with airtightness requirements. On the one hand, a pressurisation test can be performed according to Method 2 described on UNE-EN ISO 9972 (AENOR, 2019). This Spanish version of the international standard ISO 9972 (ISO, 2015) includes no further guidelines.

On the other hand, an estimation of n_{50} can be done by means of reference values provided by the norm (Equation (28)).

$$n_{50} = 0.629 \cdot \frac{C_0 \cdot A_0 + C_h \cdot A_h}{V} \tag{28}$$

where: n_{50} is the air change rate at 50 Pa $[h^{-1}]$; V is the internal volume of a building or part of a building $[m^3]$; C_0 is the airflow coefficient of the opaque part of the thermal envelope at a reference pressure of 100 Pa $[m^3/h\,m^2]$. Reference values are assigned depending on the type of building. For new or existing buildings with improved airtightness, C_0 is 16 $m^3/h\,m^2$, whereas for existing buildings a value of 29 $m^3/h\,m^2$ is assumed; A_0 is the sum of areas of the opaque thermal building envelope with heat exchange with the outdoor air. Therefore, internal partitions and the envelope area in contact with other adjacent spaces or buildings are excluded $[m^2]$; C_h is the permeability of doors and windows on the thermal building envelope at a reference pressure of 100 Pa $[m^3/h\,m^2]$, according to laboratory testing results provided by the manufacturer; A_h is the sum of the area of the doors and windows of the thermal building envelope $[m^2]$.

Then, the EP Calculation is performed by using the official unified tool LIDER/CALENER (HULC), or other tools which use the same calculation method, in order to verify the requirements established by regulations. In this tool, the airtightness of the envelope can be either introduced by means of a default value obtained from Equation (28), or the air change rate at 50 Pa (n_{50}) procured from the pressurisation test result according to Method 2.

Having stated what the norm establishes, it is important to note that some inconsistencies have been identified. For instance, some contradictions were found regarding the envelope area definition (A_{ET} and A_0), where it is not clear whether the envelope in contact with the ground should be included or not. Perhaps this case should be treated accordingly depending on the construction solution, considering possible ventilated or non-ventilated air chambers in walls and slabs, or direct contact with the ground.

One aspect that may cause concerns is the different criteria chosen for the limit establishment, which is climate zone for windows and doors, whereas it is compacity for global airtightness, prioritising building design criteria rather than environmental conditions, which will impact on the energy demand. Another contentious issue is the fact that limiting windows and doors' airtightness might seem redundant since they are part of the building envelope. This could be justified, though, if minimum quality is sought because airtightness test performance is not mandatory. The given values for the airflow coefficient of the opaque part of the thermal envelope (C_0) are somehow striking since the opaque part of the envelope has higher permeability values than the required ones for doors and windows. Finally, it must be taken into account that the estimation of n_{50} by means of reference values cannot be comparable to pressurisation test results because reference pressure values and building dimensions are considered differently.

Overall, this first approach to introducing whole minimum building airtightness requirements, although not too stringent, can be seen as a way to raise awareness and positive progress towards energy-efficient buildings. However, some refinement would be advisable in its definition: pressurisation tests should be encouraged as a diagnosis tool and to obtain real performance values, the estimation method with reference values should be revised, and limit criteria should be unified. A trend towards more demanding limits and mandatory compliance for buildings of any kind and size at least for the most extreme climate zones is expected.

2.11.4 Ventilation strategies in Spanish dwellings

Window airing and natural ventilation are the traditional methods used to supply fresh air into dwellings in Mediterranean countries. Single-sided or cross airflows through the exterior envelope and light shafts are usually only promoted by the occasional opening of windows when users consider it necessary, so they can highly influence the air renewal patterns (Ramos et al., 2015). This manual control of the openings is even more limited during the cold or hot season in areas with severe climate conditions (Fernández-Agüera, Domínguez-Amarillo, Alonso, et al., 2019; Johnson & Long, 2005) since it causes a considerable drop in the dwelling's hygrothermal conditions and uncomfortable airflows. To favour the natural ventilation process, the installation of orientable glass slats in kitchens and bathrooms was a common practice in the Mediterranean area until the end of the 20th century, which constituted continuous air renewal sources. Another strategy was the installation of natural air exhaust in bathrooms and kitchens by means of vertical ducts based on stack effect, implemented by the NBE-CT-79 (Ministerio de Obras Públicas y Urbanismo. Gobierno de España, 1979).

The main drawback of natural ventilation is its inherent problem of air change rate control because it depends on random phenomena. In the context of window airing as a sole air renewal strategy, air infiltration through cracks and other unintentional openings in the building envelope, even unfiltered and uncontrolled, is the only mechanism that can provide the continuous renewal of the indoor air (d'Ambrosio Alfano et al., 2012). However, air infiltration is the least predictable and reliable option resulting in draughts, health, and comfort problems derived from poorly mixed internal air (Limb, 1994). Thus, maintaining acceptable IAQ remains a challenge.

Even though window airing and natural ventilation have been traditionally used and accepted in mild climates, previous research revealed that air infiltration was not enough to maintain adequate IAQ in low-income and social housing in Spain with no active ventilation system (Fernández-Agüera, Domínguez-Amarillo, Alonso, et al., 2019; Serrano-Jimenez, Lizana, Molina-Huelva, & Barrios-Padura, 2020). This problem worsens nowadays when retrofitting actions are carried out in order to improve the energy performance of buildings and the envelope tightens as a result, at the expense of decreased air renewal (Salehi, Torres, & Ramos, 2017). Thus, minimum ventilation must in these cases be guaranteed to promote adequate IAQ.

In 2006, the Spanish building regulations "HS 3: Indoor Air Quality," (Ministerio de Vivienda. Gobierno de España, 2006b) implemented mandatory mechanical or hybrid ventilation systems and minimum ventilation airflows with the aim of improving IAQ in dwellings. It must be noted that this standard establishes requirements only in terms of indoor air quality, and the performance of each individual solution regarding its energy use is not within its scope.

In 2017, current guidelines, which determine ventilation airflows in dwellings, came into force. Two calculation procedures were established, whose choice is at the discretion of the designer (Ministerio de Fomento. Gobierno de España, 2017).

On the one hand, a performance-based approach based on CO_2 concentration was defined. In this case, given design conditions are established based on CO_2 generation per occupant, number of occupants within the dwelling, and occupancy patterns, so that mean annual CO_2 concentration does not exceed maximum given concentration. The dilution procedure according to UNE-EN 16798-1 (AENOR, 2020) may be used, obtaining airflow rates around 10 l/s per person.

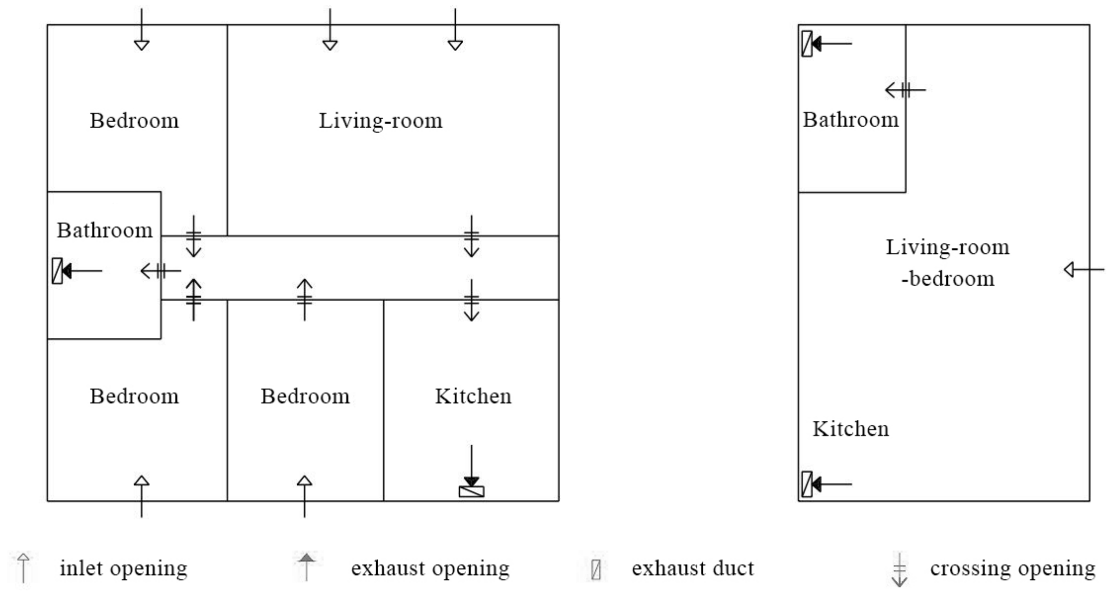
On the other hand, a prescriptive method was defined by establishing minimum ventilation airflows based on constant ventilation, according to the type and number of rooms. In this calculation, the highest global value between intake and exhaust airflows must be used in order to obtain a balanced system. **Table *3*** shows minimum ventilation airflows according to the document on its last version (Ministerio de Fomento. Gobierno de España, 2019b).

Table 3. *Minimum ventilation airflows for a constant airflow ventilation system design*

	Minimum airflow Q_v $[l/s]$				
	Dry rooms			Wet rooms	
Type of dwelling	Main bedroom	Other bedrooms	Living rooms	Total minimum	Room minimum
0 or 1 bedroom	8	-	6	12	6
2 bedrooms	8	4	8	24	7
3 or more bedrooms	8	4	10	33	8

Airflows circulate from dry rooms (e.g., living rooms, bedrooms, offices) to wet rooms (e.g., bathrooms and kitchens) through controllable apertures strategically placed classified as inlet, crossing, and exhaust openings (**Figure *15***). Allowed inlet openings are micro ventilation mechanisms, fixed openings, or even leaky windows (class 1 according to UNE-EN 12207 (AENOR, 2017)). The equivalent leakage area can be considered as part of the ventilation opening area. In this way, using technical specifications tables or minimum values of airtightness established for each type of window, the required admission areas can be adjusted. In practice, however, the lack of knowledge regarding airtightness involves that leakage paths are not measured and therefore, the envelope is assumed as ideally airtight.

Figure 15. *Ventilation systems examples in two dwellings*



Note. Adapted from “Código técnico de la Edificación (CTE). Documento básico HS 3: Calidad del aire interior (in Spanish),” by Ministerio de Fomento del Gobierno de España, 2019, p. 63.

A comparison of the ventilation airflows determined by Spanish regulations and the ones set in other countries is not easy given that they are not harmonised and their different approaches and theoretical background for their determination (Brelih & Seppänen, 2011; Kunkel, Kontonasiou, Arcipowska, Mariottini, & Atanasiu, 2015). In any case, base ventilation rates required for removing and diluting human bio-effluents as the only source of indoor air pollution have been reported to range between 4 and 15 l/s per person (AENOR, 2020; Carrer et al., 2018, 2015; Seppanen, Fisk, & Mendell, 1999). In this scenario, air infiltration caused by the lack of airtightness of the building envelope could encompass a complementary air renewal source, although this does not appear to be a satisfactory solution to overcome inadequate air renewal provisions (Carrié & Wouters, 2012a).

A widespread ventilation solution in Spain given its simplicity is the design of mechanical exhaust and inlet of fresh air through direct openings in the envelope promoted by the under-pressure generated.

In this kind of system, heat recovery is usually not performed and, therefore, energy-saving is low. In this regard, more energy-efficient solutions should be encouraged in line with the need to reduce the energy demand of buildings. Although a higher initial investment is needed, airtight buildings with balanced ventilation systems with heat recovery systems could represent an efficient alternative to achieve both adequate IAQ and energy control. Nevertheless, fan power systems are key when assessing the profitability of the system and its performance could be compromised depending on the climate zone (Laverge, 2013). The choice concerning ventilation system design, thus, should take into account climate characteristics, dwelling configuration, investment, and maintenance cost.

2.11.5 Background on the study of airtightness in Spain

Knowledge regarding building airtightness in Spain is still scarce, probably due to the lack of awareness on this issue. Airtightness has been widely addressed in the literature at an international level since the 1970s. However, in Spain, the performance of the building envelope regarding air infiltration has not been the focus and little attention has been paid until a decade ago.

The specific characteristics of the residential building stock in the country (e.g., building typologies, construction systems, climate conditions) allows the assimilation of conclusions reached in other countries only for particular samples. Overall, though, it is necessary to address the characterisation of the airtightness of the building envelope in representative samples of the building stock in Spain in order to understand its performance and particularities.

In this respect, Montoya et al. (2011) performed air infiltration tests in 27 single-family Catalan dwellings. This study established a first empirical characterisation of the air change rates of dwellings, which contributed to the fulfilment of the knowledge gap in the country.

Some early approaches assessed the impact of air infiltration and retrofitting actions on the energy performance of social housing in Southern Spain (Fernández-Agüera, Suárez, & Heiselberg, 2011) and specific protocols for airtightness measurement and modelling in multi-family dwellings in these areas were developed (Fernández-Agüera et al., 2016; Fernández-Agüera, Sendra, & Domínguez-Amarillo, 2011).

On the other hand, in Northern Spain, a broad study on 120 recently built apartments was conducted (Jiménez Tiberio & Branchi, 2013) to determine the level of airtightness in residential buildings and to establish the determining factors that have an impact on it, which were related to design, construction systems windows, and workmanship.

Additionally, in Northern and central Spain, Meiss and Feijó-Muñoz (2013) developed a procedure for the evaluation of the impact of air infiltration on the energy consumption of dwellings, which was complemented by the analysis of 13 cases in multi-family dwellings built under different energy regulations that determined periods for analysis (Meiss & Feijó-Muñoz, 2015). The lack of airtightness was estimated to represent between 11.3 and 13.0% of the energy demand in winter in retrofitted existing buildings constructed before 1979, 21.9 and 27.0% in buildings constructed between 1979 and 2006, and between 10.5 and 27.4% in buildings built after 2006.

Research has intensified for the past two years, and a growing interest in the topic is undeniable. The recent literature has focused on three main aspects: airtightness characterisation, the impact of airtightness on energy needs, and its impact on thermal comfort and IAQ.

Taking into account this classification, some research with the aim of characterising representative dwellings and quantifying their level of airtightness were identified. In this regard, a sample of multi-family dwellings in Southern Spain built in different periods was characterised in terms of airtightness (Fernández-Agüera, Domínguez-Amarillo, & Campano, 2019). Main leakage paths were identified, and no evidence of leakage between apartments was found.

The comprehensive research that incentivised this Thesis, the INFILES Project, was the first approach that involved a global characterisation of a representative sample of characterised dwellings that covered the entire country. The main outcomes can be checked on ***Paper 1***, ***Paper 2***, ***Paper 3***, and also (Feijó-Muñoz, Meiss, et al., 2019; Poza-Casado, Meiss, Padilla-Marcos, & Feijó-Muñoz, 2017, 2018).

The impact of airtightness on energy needs features the second aforementioned topic of interest. Great energy impact on the wintertime energy demand was revealed due to the lack of airtightness in 53 low-income dwellings (Domínguez-Amarillo et al., 2019). ***Paper 4*** and (Poza-Casado, Meiss, Padilla-Marcos, & Feijó-Muñoz, 2019a, 2019b) show an estimation of the energy impact of uncontrolled airflows through the envelope on the heating and cooling demand in residential buildings in Spain, confirming in this way a great potential for energy saving if airtightness was improved.

Other authors focused on the energy impact of airtightness in low-energy buildings (Guillén-Lambea et al., 2019) and dwellings built under the Passivhaus standard (Echarri-Iribarren, Sotos-Solano, Espinosa-Fernández, & Prado-Govea, 2019). Guillén-Lambea et al. (2019) estimated the potential heating and cooling energy demand for different levels of infiltration rates in different cities by means of simulation, and questioned the n_{50} fixed value required by the Passivhaus standard since the associated energy impact depends on the climate conditions of the location of the building.

Finally, the impact of airtightness on thermal comfort and IAQ in dwellings has recently been addressed in vulnerable scenarios without any controlled ventilation system such as low-income housing (Fernández-Agüera, Domínguez-Amarillo, Alonso, et al., 2019) and social housing with elderly occupants (Serrano-Jimenez et al., 2020). In those scenarios, air renewal is done naturally by the manual opening of windows, and naturally driven air infiltration.

Several social housing units in Madrid and Seville built in the period 1940-1980 were analysed to determine the degree of airtightness and its impact on IAQ (Fernández-Agüera, Domínguez-Amarillo, Alonso, et al., 2019). High CO_2 concentration levels and night-time peaks revealed poor IAQ, and condensation risk was also identified. Therefore, infiltration was found to be insufficient to maintain healthy conditions within the dwellings. This scenario was aggravated by the fact that common retrofits for such buildings encompass airtight windows installation and envelope sealing with no implementation of controlled ventilation systems. Findings in the same line were reached by Serrano-Jiménez et al. (Serrano-Jimenez et al., 2020).

The recent introduction of whole building airtightness requirements in Spain (see Section "Airtightness requirements in Spain") and the growing awareness of energy use and IAQ seem to indicate that the interest in this issue will spread, and future research lines will rise.

2.11.6 Airtightness estimation in Spain

The lack of airtightness data in Spain has been the main reason that explains the absence of analysis and development of predictive models to estimate leakage from building characteristics in the country until recent years. The results obtained from the airtightness characterisation of some studies of specific building stocks have led to the development of predictive models aimed at estimating the airtightness of buildings with assimilable characteristics to the ones that constituted the sample of the tested dwellings.

Montoya et al. (2010) developed a leakage model to predict air leakage of single-family dwellings in Catalonia by means of a multiple linear regression technique. The model was based on data from 251 dwellings in France from 1983 onwards and established the structure type, floor area, age of the building, the number of stories and the insulation type as the most significant variables. Then, air infiltration airflows were estimated through simulation. The approach is interesting, but it lacked validation and additional experimental data from Catalonia to verify its applicability in a different building stock than the sample source.

An algorithm was developed by Ibáñez-Puy and Alonso (2019) to predict the airtightness of new and retrofitted dwellings. 150 multi-family dwellings in different cities with different climate areas, envelope solutions and construction systems constituted the database. Clear impact of window perimeter and rolling-shutter length, and the composition of the outer layer was found. However, the authors revealed that the most important factor was workmanship, which is a variable that adds difficulties for its integration in a model. The approach seems promising, although no validation was found, and the cases chosen for the sample were not specified.

Two additional models were found in the literature to estimate airtightness in low-income multifamily buildings in a Mediterranean region (Fernández-Agüera, Domínguez-Amarillo, Sendra, & Suarez, 2019) both for new and existing buildings. The model considered 159 representative samples and was based on building characteristics such as winter severity, envelope exposure, presence of a bathroom window and envelope type. Cluster analysis and multiple linear regression were performed to develop the mentioned mathematical models.

Therefore, the background regarding building characteristics that have an impact on airtightness and the development of empirical estimation tools carried out so far have experienced great development recently. Predictive models have been found to be useful to evaluate design at an early stage, and also the impact of potential improvements and retrofitting actions before assuming any investment (Ibanez-Puy & Alonso, 2019). Nevertheless, existing Spanish databases focused on specific building stocks with particular characteristics and typologies. To fill this knowledge gap, a new database was built under the INFILES Project (BIA2015-64321-R), which considered the first representative sample of the whole building stock in terms of climate zone, building typology and year of construction. The main outcomes regarding the characteristics that have an impact on airtightness can be found in ***Paper 2*** and (Poza-Casado et al., 2018).

3 METHODS

3.1 DETERMINATION OF THE SAMPLE

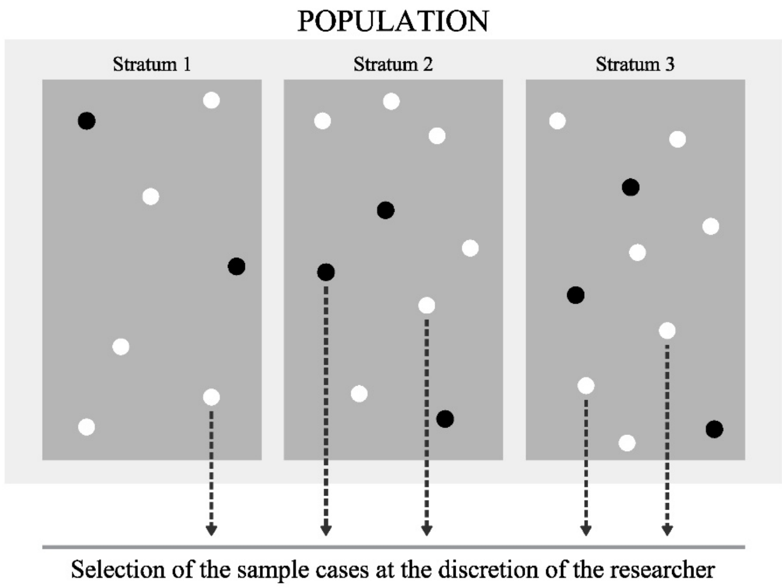
A large number of existing dwellings in Spain and the great variability in its nature and characteristics made it necessary to limit the cases to be studied. A sampling method was carried out with the aim of establishing a representative sample to characterise the existing Spanish residential stock in terms of airtightness in the most reliable way.

3.1.1 Sampling method

The methodology used to design the sample of cases to perform the characterisation of the dwellings in terms of airtightness was detailed in ***Paper 1***.

From a theoretical point of view, the best way to estimate a relevant statistical distribution of the cases is by selecting a simple random sample of dwellings (P. N. Price, Shehabi, Chan, & Gadgil, 2006). However, this approach was considered impractical and unfeasible given the nature of the study that required access to the dwellings to perform pressurisation tests. Taking into account the objectives and characteristics of the research, a more realistic approach was considered, proposing a non-probabilistic quota sampling scheme (**Figure *16***). This sampling method reproduces the population on a smaller scale based on a considered sample size according to some characteristics or control variables. In this way, the heterogeneity and proportionality of the selected cases were ensured.

Figure 16. *Example of a non-probabilistic quota sampling scheme*



In this way, the Spanish residential stock was partitioned into non-overlapping proportional groups called strata (**Figure *17***). Specific measures were established to avoid the possible bias in the sample when the cases were selected in very specific environments. The number of samples per stratum was determined according to Equation (29):

$$S_i = S \cdot \frac{N_i}{N} \tag{29}$$

where:
S_i is sample size of stratum i
S is the sample size
N_i is the population size of stratum i
N is the population size

Figure 17. *Stratification process for the quota sampling scheme*

Thus, the size of the sample was determined. The number of tests to be performed was established considering:

- the purpose of the study, resources availability and temporal framework;
- the accepted level of confidence and error;
- the homogeneity interval. The more heterogeneous the population is, the bigger the sample size needs to be.

Since the kind of sampling used had a probabilistic structure and the Spanish residential stock is statistically considered an infinite population, Equation (30) was used to obtain the sample size:

$$S = \frac{Z^2 \cdot \sigma^2}{e^2} \tag{30}$$

where: S is the sample size; Z is the critical value which depends on the confidence interval; σ is the population standard deviation; e is the margin of error.

The value of Z is given by the Gaussian distribution, depending on the confidence interval accepted. The most frequent values are Z = 1.645, Z = 1.96 and Z = 2.575, for confidence levels of 90%, 95% and 99%, respectively. The value of the variance in terms of the airtightness of the envelope in Spain was unknown because there was no representative data in this regard before the test campaign was carried out. Values obtained in a previous study performed in Italy were taken as a reference, by proximity, constructive and climatic analogy (d'Ambrosio Alfano, Dell'Isola, Ficco, Palella, & Riccio, 2016). A variance of 17.584 was obtained by the results of the evaluation of 20 cases of several typologies and years of construction.

In this way, the sample size of the dwellings to be tested was determined. Taking into account that a higher level of confidence or a minor admissible error significantly increased the sample size and that the number of cases to be analysed was conditioned by the limits of the study, a confidence level of 95% and an error of ± 0.4 were considered acceptable, resulting in a sample size of 423 cases. This figure was finally reduced to 411 due to numerical rounding in the stratification process when the number of cases for each category was proportionally determined.

It is necessary to note, however, that the real error is unknown in this case because of the nature of the sampling method. The error and the confidence level were only estimations because the values used in the equation are only valid for probabilistic sampling, whose model was adopted given its comprehensible structure.

3.1.2 Parameters considered

A decisive aspect was the selection of relevant control variables to be used for the construction of the quotas in the stratification model, trying to avoid the omission of relevant ones. To this end, a review of the literature that related airtightness and different characteristics in residential buildings was assessed (Poza-Casado et al., 2017), as shown in **Table 4**.

***Table 4**. Parameters considered in previous characterisation studies.*

Parameter	(Sfakianaki et al., 2008)	(P. N. Price et al., 2006)	(Orme et al., 1994)	(Mcwilliams & Jung, 2006)	(Sherman, 2006)	(Chan, Joh, & Sherman, 2012)	(Erinjeri, Katz, & Witriol, 2009)	(Zou, 2010)	(Montoya et al., 2010)	(Pan, 2010)	(Krstić, Otković, & Todorovic,
Age of the building	x		x	x	x	x	x	x	x		x
Type of construction/ construction building system	x	x	x					x	x	x	x
Floor area		x		x	x	x	x		x	x	
Climate zone	x			x	x	x	x			x	
Height/number of storeys		x			x	x		x	x		
Type of foundation/floor structure			x	x		x		x			
Energy-efficiency programs				x	x	x		x			
Significant penetrations										x	
Economic status				x	x	x					
Surface area								x		x	x
Ducted air system through unconditioned space			x			x					
Ventilation type/presence of ducts				x				x			
Joinery/sealing			x								x
Retrofitting work/renovation						x		x			
Insulation position/thickness									x		x
Window frame length	x							x			
Complex floor plan			x		x						
Air barrier			x							x	
Design target										x	
Management context										x	
% transparent part of the envelope											x
Windows/glazing											x
Installation layer								x			
Heating system									x		

It was deduced that one of the variables with greater relevance was the year of construction (Alev et al., 2014; Chan et al., 2013; Montoya et al., 2010; Sinnott & Dyer, 2012). Also, characteristics of the building such as typology (Pan, 2010), type of construction (Montoya et al., 2010), type of window/glazing (Krstić et al., 2015) and window frame (Sfakianaki et al., 2008; Zou, 2010), foundation

(Chan et al., 2013), construction system (Kalamees, 2007), materials (Krstić et al., 2015; Orme et al., 1994; P. N. Price et al., 2006; Zou, 2010), floor area (Chan et al., 2013), total height (Chan et al., 2013), number of storeys (Kalamees, 2007), ventilation system (Pinto, Viegas, & de Freitas, 2011; Van Den Bossche et al., 2012), type of insulation (Montoya et al., 2010), sealing devices (Orme et al., 1994) and management type (Pan, 2010) should be considered. In addition, workmanship also seemed to be a relevant factor regarding the airtightness of the envelope (Relander, Bauwens, Roels, Thue, & Uvsløkk, 2011; Van Den Bossche et al., 2012). Several authors in the literature also considered that the climate zone is a significant variable (Chan et al., 2013; Erinjeri et al., 2009).

Once the most significant factors that have an impact on airtightness were set, the establishment of the control variables was done, considering that its distribution had to be known. In this sense, characteristics related to construction building systems could not be used as sampling parameters because statistical sources did not contemplate its actual distribution in the residential building stock. In this sense, it was assumed that if the sample reproduced the building stock with respect to the main characteristics, it would reproduce it in the same way for secondary characteristics. All things considered, the year of construction, typology and climate zone were taken as control variables given their relevance and data available.

The age of the building has an impact on airtightness in several ways. Firstly, materials and their joints deteriorate over time (Ylmén, Hansén, & Romild, 2014). An increase of 10-15% on air leakage every 10 years was estimated (Chan, Walker, & Sherman, 2015a; Mcwilliams & Jung, 2006). Secondly, construction systems are being developed and improved. However, in milder-climate countries, where there is no airtightness standard for new buildings, recent dwellings are not necessarily more airtight than older ones (Sherman & Chan, 2004) due to the lack of awareness concerning airtightness, construction systems used, and poor workmanship, among other reasons. Thirdly, the age of the building is associated with regulations, which establishes requirements and conditions the building construction systems.

Regarding the type of construction, most studies focus on the characterisation of single-family dwellings. However, in Spain multi-family buildings represent more than 70% of real estate (Dirección General de Arquitectura Vivienda y Suelo; Ministerio de Fomento. Gobierno de España, 2011), so the study had to inexorably reflect both typologies, with particular focus on multi-family dwellings.

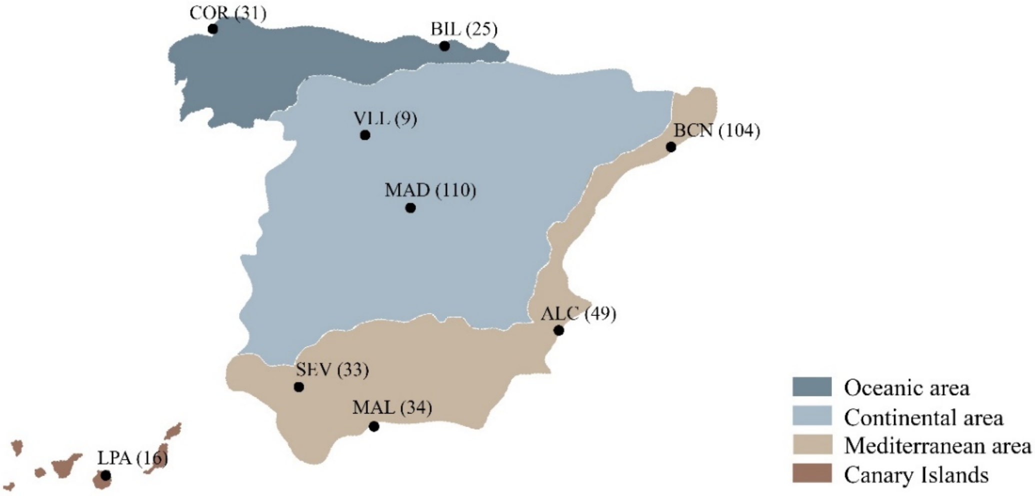
Climate zone has also an important impact on the airtightness of dwellings. Buildings in cold climates tend to be tighter due to comfort and energy impact, whereas in milder climates dwellings were found to be leakier (Mcwilliams & Jung, 2006). Moreover, climate zones not only determine weather conditions but can also establish differences in regulatory requirements or different construction systems (Chan et al., 2013).

3.1.3 Distribution of the sample

The number of cases belonging to each stratum was made proportionally, according to the statistical distribution of the residential building stock in Spain (Instituto Nacional de Estadística, 2016), obtaining a stratified representation of the population.

Considering the age of the building, 10 periods of time were determined according to statistical sources (Instituto Nacional de Estadística, 2016); typology was considered within two main categories (single-family and multi-family buildings) (Instituto Nacional de Estadística, 2016); concerning climate zone, a simplification was made, obtaining a total of four areas: Oceanic (wet climates), Continental (cold climates), Mediterranean (mild climate) and Hot desert area (Canary Islands). On each climate area, one or several cities were set as bases for the test performance taking each region as influence area (**Figure *18***). Therefore, 108 categories or strata are the result of this sampling method (**Figure *19*** and **Table *5***).

Figure 18. *Location of the participant centres, climate zones determined, and number of tests*



Note. COR: La Coruña. Universidad de la Coruña / BIL: Bilbao. Universidad del País Vasco / VLL: Valladolid. Universidad de Valladolid / MAD: Madrid. Universidad San Pablo CEU / BCN: Barcelona. Universidad Politécnica de Cataluña / ALC: Alicante. Universidad de Alicante / MAL: Málaga. Universidad de Málaga / SEV: Sevilla. Universidad de Sevilla / LPA: Las Palmas. Universidad de las Palmas de Gran Canaria.

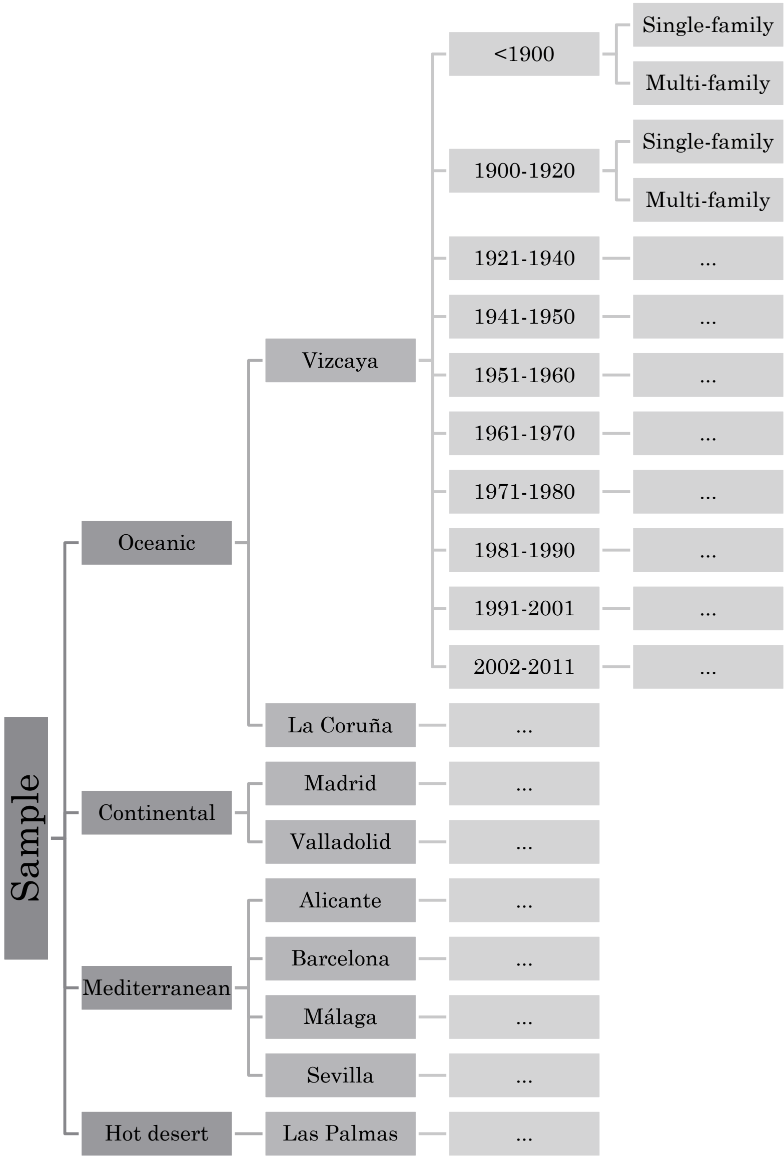
From "Methodology for the Study of the Envelope Airtightness of Residential Buildings in Spain: A Case Study," by J. Feijó-Muñoz, I. Poza-Casado, R. A. González-Lezcano, C. Pardal, V. Echarri, R. Assiego De Larriva, J. Fernández-Agüera, M. J. Dios-Viéitez, V. J. Del Campo-Díaz, M. Montesdeoca Calderín, M. Á. Padilla-Marcos, & A. Meiss, 2018, Energies, 11(4), 704, p. 5. Copyright 2018 by the Authors. Creative Commons Attribution 4.0 International License (CC-BY 4.0).

Table 5. *Sample distribution*

		Oceanic		**Continental**		**Mediterranean**				**Hot desert**
Year of construction	Type	COR	BIL	VLL	MAD	BCN	ALC	MAL	SEV	LPA
<1900	S	1	-	-	-	1	1	-	-	-
	M	-	1	-	2	3	-	-	-	-
1900-1920	S	1	-	-	-	1	-	-	-	-
	M	-	1	-	2	3	-	-	-	-
1921-1940	S	1	-	-	-	1	-	-	-	-
	M	-	1	-	3	4	-	-	-	-
1941-1950	S	1	-	-	-	1	1	-	1	-
	M	-	1	-	3	3	1	-	1	-
1951-1960	S	1	-	-	1	1	1	1	1	-
	M	1	3	-	8	7	1	1	1	1
1961-1970	S	1	-	-	1	2	1	1	2	1
	M	3	7	2	19	19	5	3	4	2
1971-1980	S	1	-	-	3	3	2	2	2	1
	M	5	5	2	23	22	8	6	5	2
1981-1990	S	1	-	-	3	3	3	2	2	1
	M	2	1	1	9	6	5	5	2	2
1991-2001	S	1	-	1	4	3	2	2	3	1
	M	3	2	1	13	10	3	4	3	2
2002-2011	S	2	-	1	3	2	3	1	3	1
	M	6	3	1	13	9	12	6	3	2
	TOTAL	**31**	**25**	**9**	**110**	**104**	**49**	**34**	**33**	**16**

where: S: single-family houses; M: multi-family dwellings.

Figure 19. *Stratification by climate zone, site, year of construction and typology*



3.2 CHARACTERISATION OF THE DWELLINGS

In order to assess the existing residential stock in Spain, the selected cases of the sample were characterised, not only in terms of airtightness but also through a whole process of data gathering. The need to capture and manage a great volume of data led to the development of a specific tool called *infilAPP* (***Paper 1***, and (Feijó-Muñoz, Meiss, et al., 2019)), which constituted the core of the database. The development of this tool involved different goals:

- To allow a simple, fast and intuitive data management;
- To automate the data gathering process;
- To facilitate a structured workflow;
- To standardise and systematise processes;
- To establish common criteria for the different agents;
- To optimise the time spent for the characterisation of each case;
- To reduce the time spent on site;

- To ease subsequent data analysis;
- To avoid the lack of data or inconsistencies through verification;

infilAPP was developed in Microsoft® Excel® using Visual Basic® programming and was set to perform the data dump to a common shared online repository. It was structured in different tabs according to the temporal process of the assessment of each case: identification of the case, required information for the test, characterisation of the dwelling, and test results and conditions (**Table *6***).

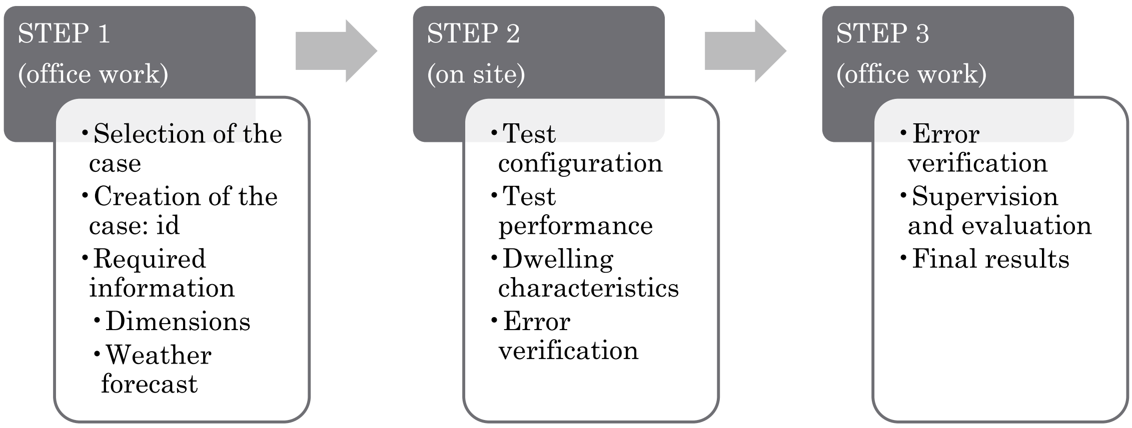
Table 6. *Overview of the parameters registered by infilAPP*

IDENTIFICATION OF THE CASE		
Participating University	Name, phone, and email address of the technicians	Name, phone, and email address of the owner
Year of construction	Cadastral reference	Bar code
Full address of the case	Planned test date	
REQUIRED INFORMATION FOR THE TEST		
Dimensions of the dwelling		
Global ceiling height	Floor area and ceiling height of each room	Presence of false ceilings
A_F $[m^2]$, automatically calculated	V $[m^3]$, automatically calculated	Vertical A_E $[m^2]$by adjacent space (exterior, heated space, unheated space, other building, other use, ground)
Horizontal A_E $[m^2]$ by adjacent space (exterior, heated space, unheated space, other use, ground)	A_E $[m^2]$, automatically calculated	Compacity $[m]$, automatically calculated
Expected weather conditions during the test		
Altitude	Temperature	Wind speed
Wind speed according to Beaufort scale	Wind exposure	Time
DWELLING CHARACTERISTICS		
Graphic information		
Floor plan	Exterior image of the building	IR thermal image
General information about the dwelling		
Typology and its position with respect to other dwellings	Property developer	Height of the building
Use of the basement	Use under the roof	Height of the dwelling
Number of rooms	Number of bathrooms	Layout of the floor plan
Dwelling state		
Retrofitting state	Refurbishment of the kitchen or bathrooms	Extension of the heated volume
Presence of closed balconies	Detected thermal bridges	Improvement of thermal bridges
Furbishing	Detected cracks or other pathologies	
Construction systems		
Class of the windows	Area of the windows	Windows joint length
Windows opening system	Presence of double window	Windows material

Presence of shutters	Type of shutters	Position of the shutter
Type of envelope	Presence of outer cladding	State of the envelope
Conditioning and ventilation systems		
Type of heating system	Individual/whole building heat generation	Heating system distribution
Type of refrigerating system	Individual/whole building refrigeration	Refrigerating system distribution
Type of ventilation	Ventilation of the kitchen	Kitchen hood extraction
Presence of ventilation grids	Ventilation in bathrooms	
Environmental conditions during the test		
Indoor air temperature	Outdoor air temperature	Mean wind speed
Gust wind speed		
TEST RESULTS		

In this regard, a workflow was established in order to optimise time, effort, and guarantee the correct development of the whole characterisation process for each case (**Figure *20***).

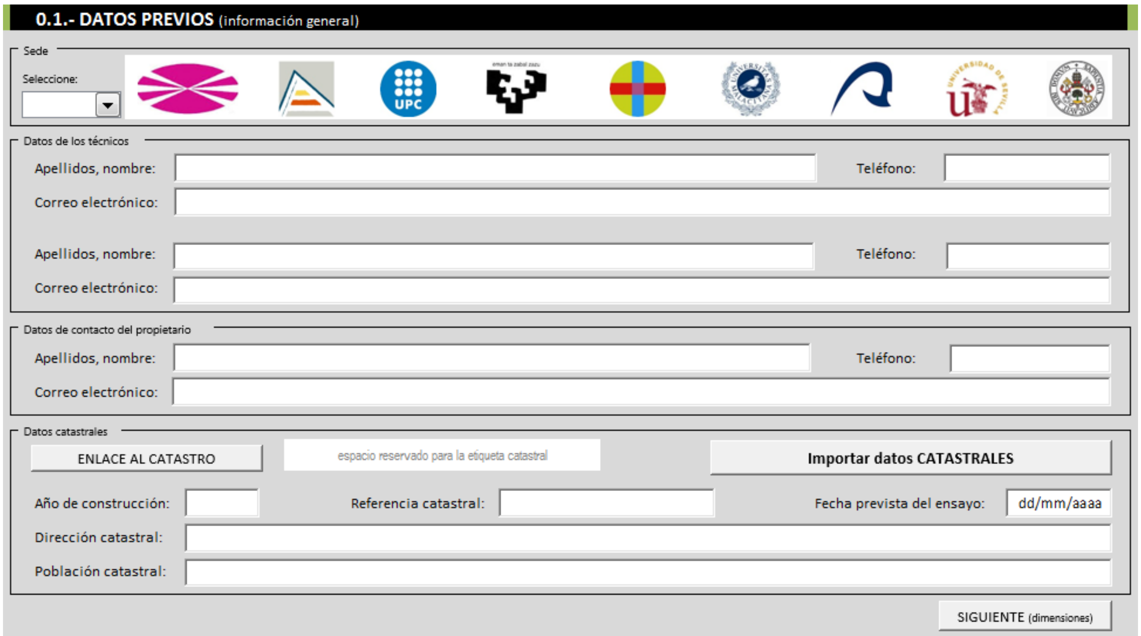
Figure 20. *Workflow for each case assessment*



3.2.1.1 Creation of the case: identification

Some data had to be completed before the test performance on site so that the minimum time within the dwelling was spent. The first stage involved creating the case files, filling all the identification information (data of the technicians and the owner, responsible university, reference number, location, and year of construction of the dwelling) (**Figure *21***). A code was automatically generated for each case, which allowed its identification and personal data protection.

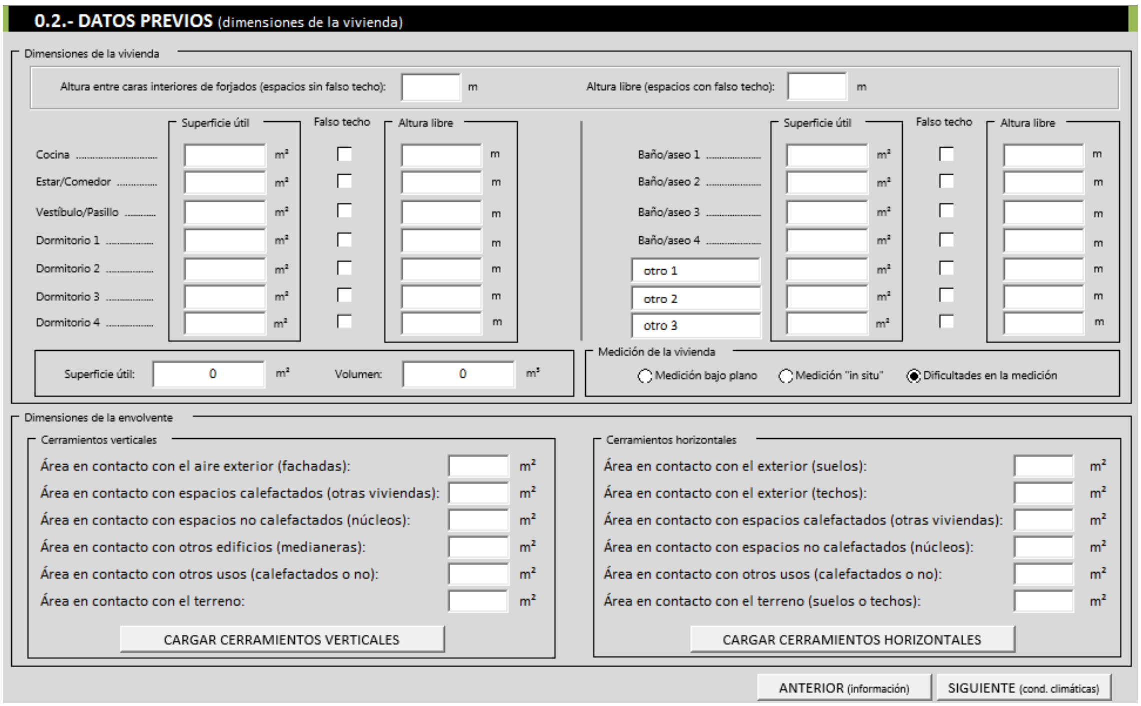
Figure 21. *infilAPP. Identification of the case*



3.2.1.2 Required information for the test

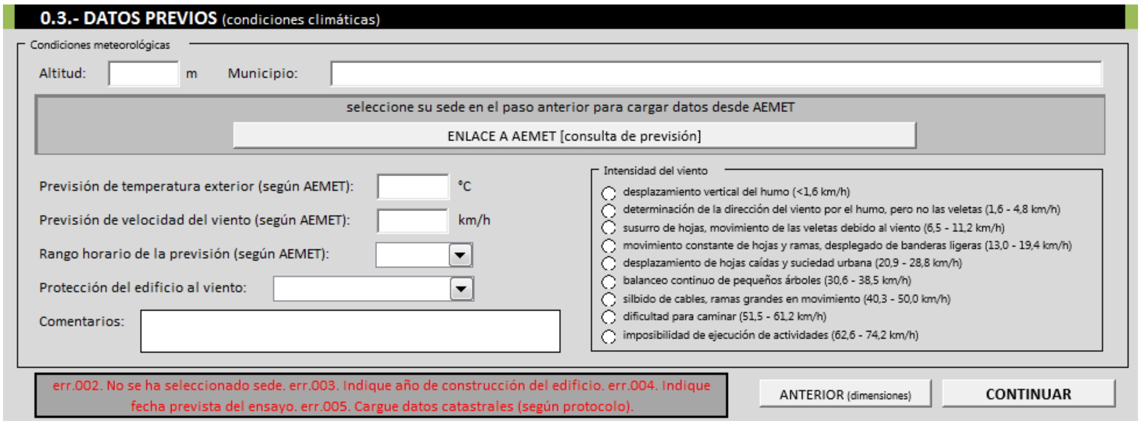
The required information for the test was gathered in another tab: itemised dimensions and weather forecast. In the event that graphical documentation of the dwelling was not available, simple floor plans were sketched on site in order to obtain the required information. The interior dimensions were introduced: floor area by room and height, and envelope area depending on the nature of the envelope (exterior, in contact with another heated space, in contact with the ground, etc.). Dimensions such as floor area (A_F), volume (V), envelope area (A_E) or compacity were automatically calculated from the partial dimensions (**Figure** *22*).

Figure 22. *infilAPP. Information required for the test: dwelling's dimensions*



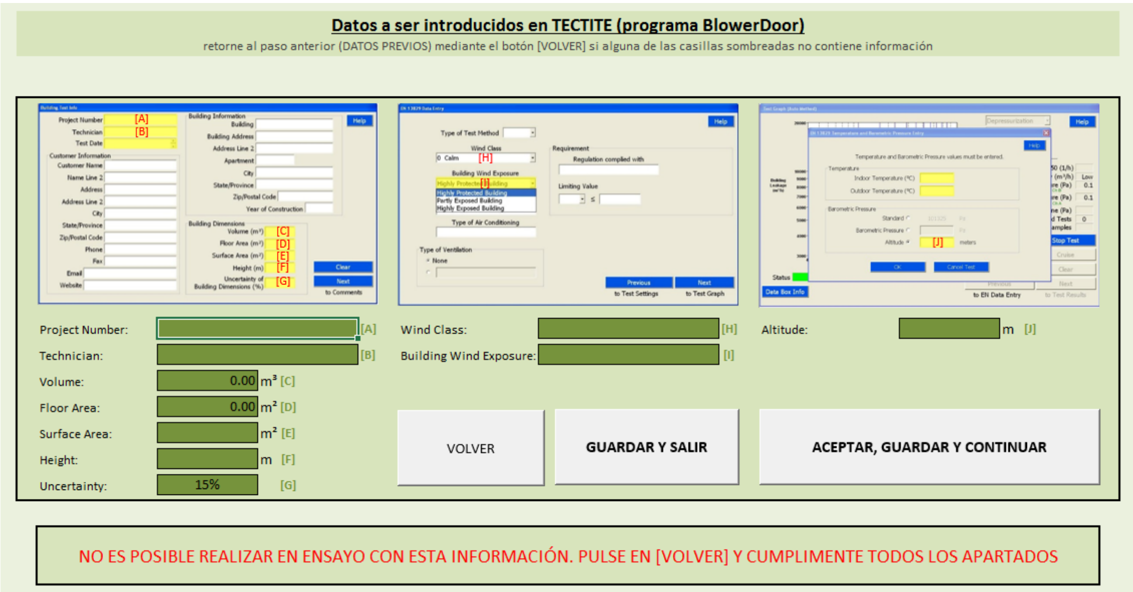
Weather conditions (temperature and wind speed) at the expected date and time of the test were also recorded before the test to ensure suitable meteorological conditions (AENOR, 2002). If the wind speed exceeded 6 m/s, the test was required to be postponed (**Figure** *23*). The shielding class of the building depends on the near environment where the dwelling is located, which impacts the pressures distribution on the envelope considered for the airtightness test purposes. The protocol developed included guidelines that specified the criteria to select the appropriate shielding class.

Figure 23. *infilAPP. Information required for the test: weather forecast*



The following tab included a summary of the introduced data needed for the test performance. It is shown as a guide to assist in the data entry process in TECTITE (**Figure** *24*).

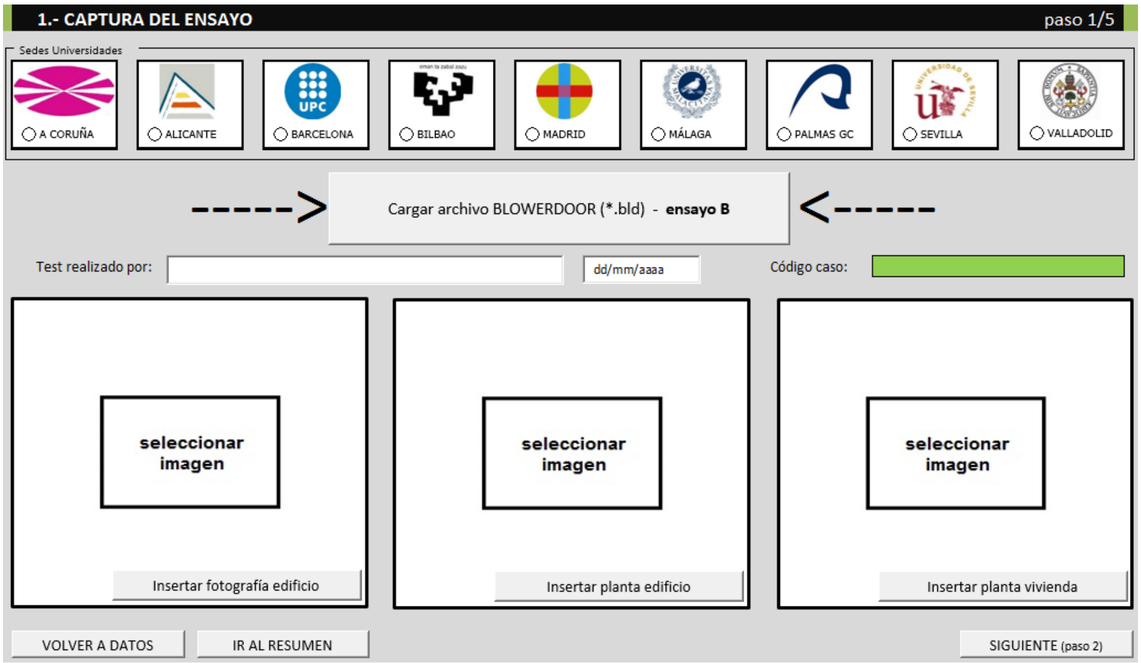
Figure 24. *infilAPP. Information required for the test: data to be introduced at TECTITE*



3.2.1.3 *Dwelling characteristics*

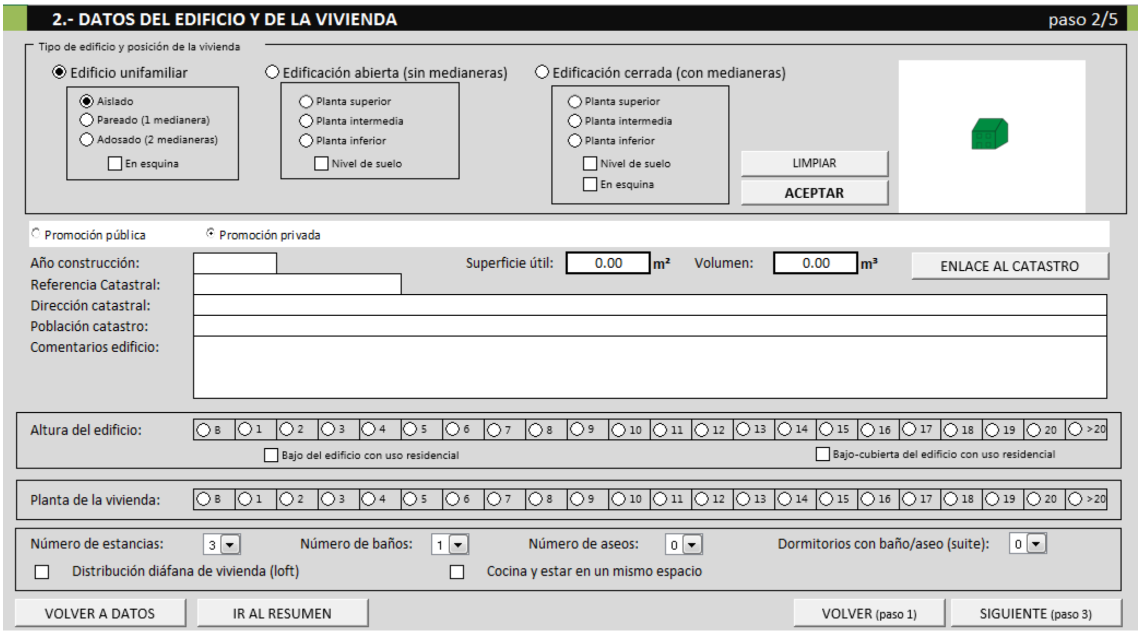
A wide characterisation of different parameters, more than 140, were stored on an external database, whose data entrance was managed by the tool. On a first tab, three images were required to identify each case visually: the exterior of the building, the floor plan of the building and the floor plan of the dwelling or a representative IR thermal image (**Figure** *25*). Pictures of each room, windows, conditioning systems, special features and cracks or other pathologies detected were saved.

Figure 25. *infilAPP. Characterisation of the dwelling: images*



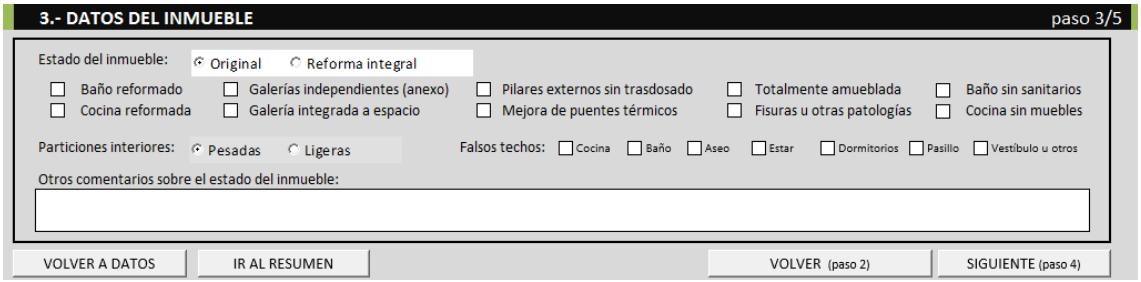
The following tabs referred to the building and dwelling's characteristics. Specifically, the typology, relative position (height, position between other dwellings, on a corner, etc.), and the number of rooms were selected on a first stage (**Figure** *26*). A proper characterisation in this way was found to be key given its impact on the nature of the envelope, and, therefore, airtightness.

Figure 26. *infilAPP. Characterisation of the dwelling: information about the building*



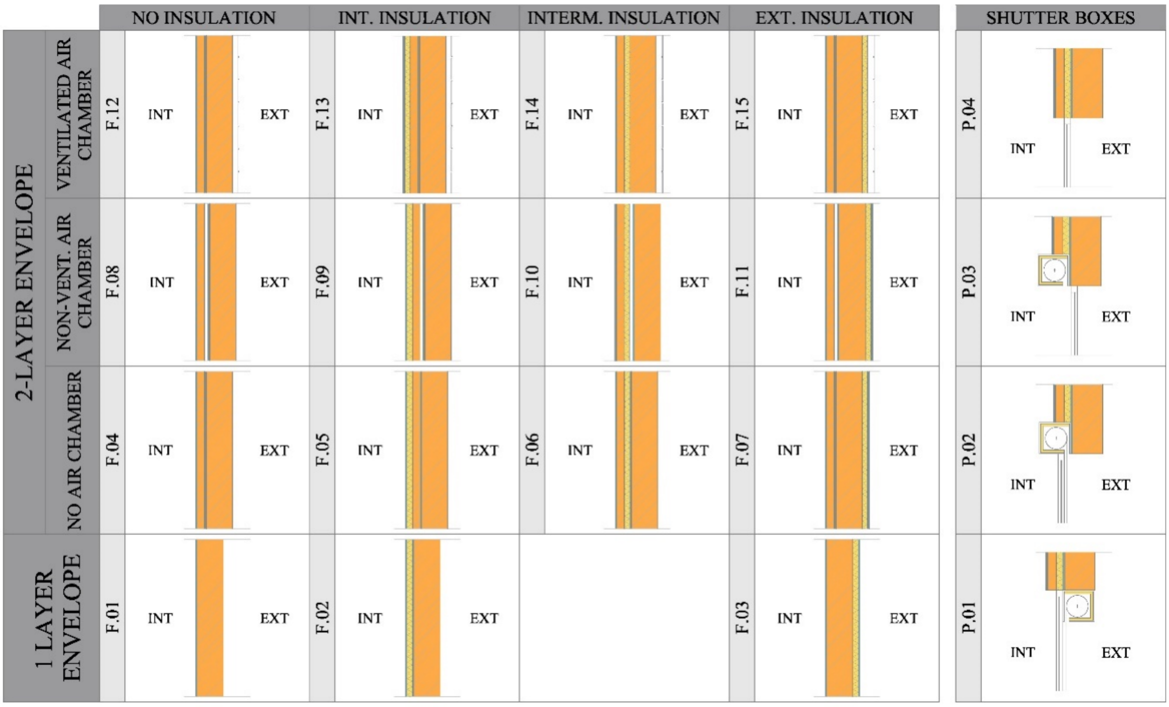
Secondly, the state of the dwelling was assessed in order to identify retrofitting actions, modifications of the envelope or partial variations, construction problems, cracks, thermal bridges, or any other feature that may affect the airtightness of the envelope. At this stage, the presence of false ceilings and types of partitions were also introduced due to their relationship with possible hidden air leakage paths (**Figure** *27*).

Figure 27. *infilAPP. Characterisation of the dwelling: information about the dwelling*



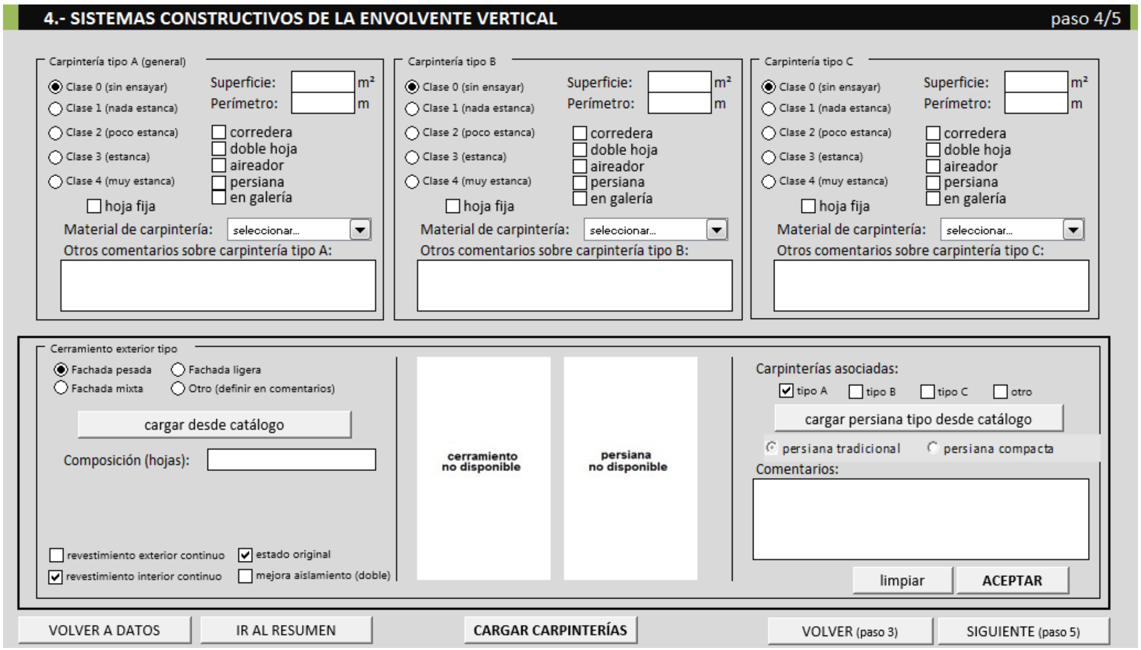
A third tab focused on the vertical envelope characterisation including the opaque construction solution adopted, windows and rolling shutters. A catalogue of pre-set typical construction solutions in Spain was developed (**Figure** *28*), based on (Ministerio de Fomento. Gobierno de España, 2011), paying special attention to singular elements such as rolling shutters. The construction system of the envelope was classified according to its composition: number of massive layers, presence and position of the air chamber and insulation layer. Nevertheless, customised solutions were also possible.

Figure 28. *Classification of building systems of the vertical envelope*



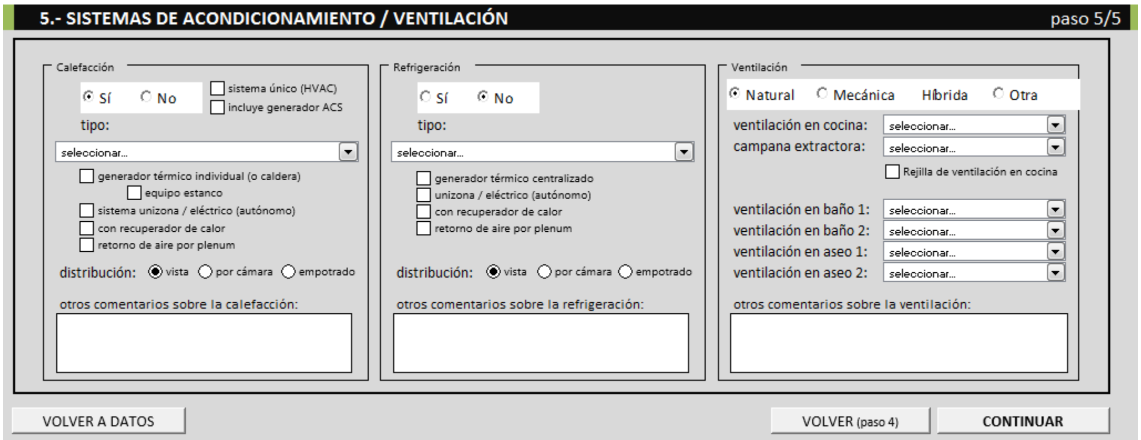
Windows were fully characterised regarding dimensions, permeability class, opening system, material, position, and relevant elements, introducing up to three different types (**Figure** *29*). This detailed information was driven by the great impact of windows on the global airtightness of a dwelling, both due to its internal leakage, but also especially to the presence of rolling shutters and the joints with the opaque part of the envelope.

Figure 29. *infilAPP. Characterisation of the dwelling: building systems of the envelope*



Finally, another tab gathered the characterisation of the ventilation and conditioning systems of the dwelling (**Figure *30***). These systems usually involve the connection of the indoor environment to the outdoor air through inlets, outlets, or ducts, which may feature air leakage paths.

Figure 30. *infilAPP. Characterisation of the dwelling: ventilation and conditioning systems*



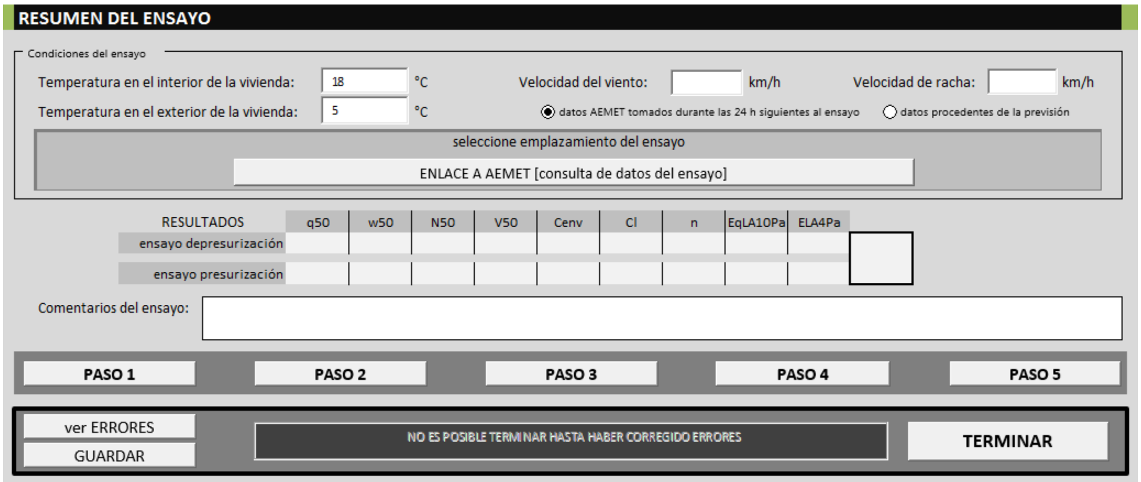
3.2.1.4 Test results

The results obtained from the experimental airtightness test were imported to *infilAPP* automatically, transforming the data of the .bld file. An overview of the test results was shown at the final tab of the tool both for pressurisation and depressurisation (**Figure *31***).

The tool included an error identification applet, checking continuously the concordance of iterative data in order to notify the technician of possible inconsistencies and the most effective way to proceed to their resolution. Once all the information was verified, the test was completed and uploaded to a common shared online repository ready for verification and further acceptance.

The methodology planned a complementary quality management scheme to ensure the accurate fulfilment of the process. This involved the quality control and development of each case. It was considered completed once several files containing the information on each case were generated to be included in de database, as well as the pertinent full report.

Figure 31. *infilAPP. Characterisation of the dwelling: images*

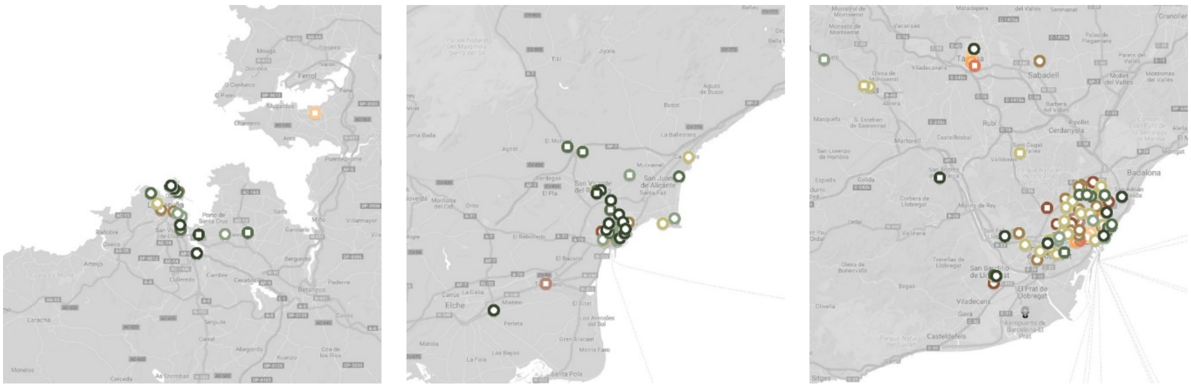


3.3 TESTED DWELLINGS

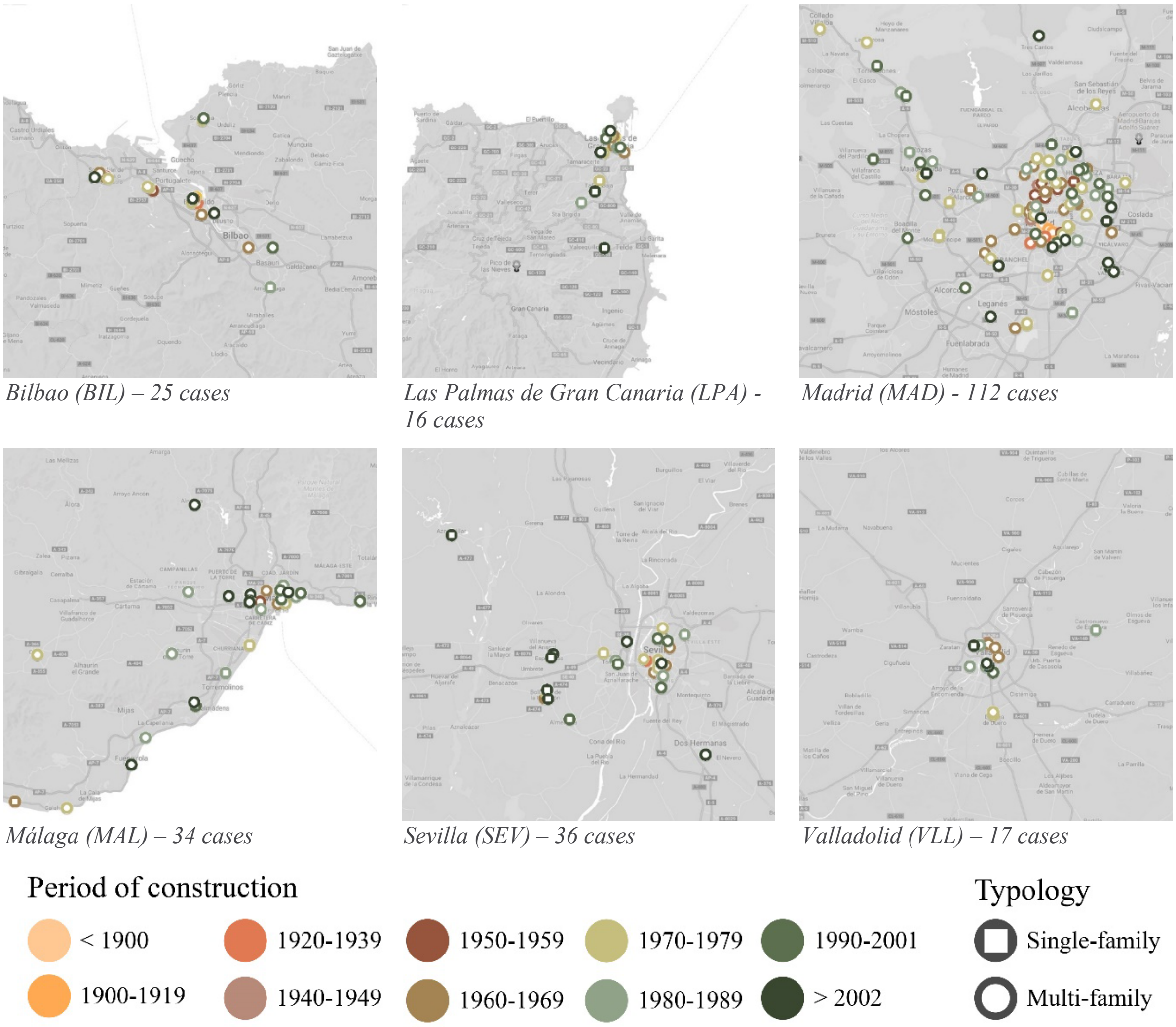
Airtightness tests were conducted in 401 dwellings in Spain whose owners allowed voluntarily the performance of the test. The exclusion of some cases was inevitable due to the difficulties encountered. Some of the planned cases according to the sampling scheme designed were not assessed due to limitations (difficulty to find a dwelling available with specific characteristics, windy conditions during the programmed test period, agenda, and coordination issues, etc.). In order to obtain access to the dwellings required in the sample, campaigns were designed to disseminate and search for volunteers through pamphlets, posters and advertisements on the websites of the participating centres and social networks, and agreements were made with some public administrations.

The final distribution of the dwellings followed strictly the criteria set by the sampling design. The location of the cases tested according to typology and year of construction is shown in **Figure *32***.

Figure 32. *Location of the studied cases*



A Coruña (COR) – 22 cases | *Alicante (ALC) – 49 cases* | *Barcelona (BCN) – 90 cases*

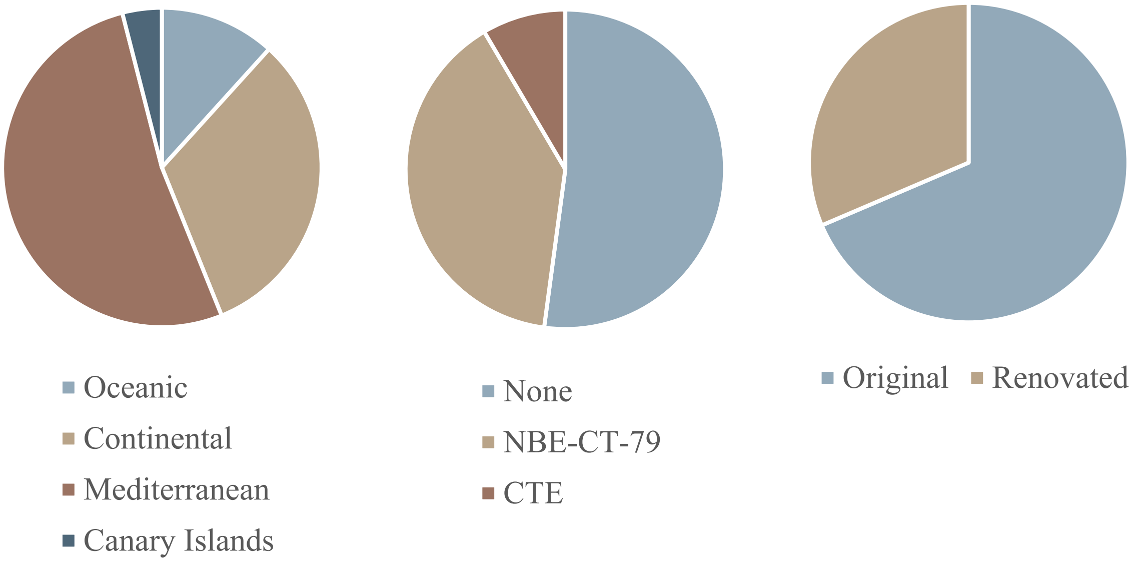


The four climate zones established were characterised according to their representativeness. The Mediterranean climate (209 cases, 52.1%) and Continental zones (129 cases, 32.2%), had a greater number of cases, while in the Oceanic climate zone (47 cases, 11.7%) and the Canary Islands (16 cases, 4%), a lower number of dwellings were analysed as they were less representative (**Figure *33***).

The airtightness tests were performed in dwellings built between 1880 and 2015. The periods of major construction activity in Spain during the decades 1960-1979 (148 cases, 36.9% of the sample), and the period 1980-2006, including the years of the real state bubble, just before its bursting in 2007 (158 cases, 39.4% of the sample) were the most represented ones.

The year of construction was also correlated with Energy Performance Regulations (EPR): 52.1% of the sample was built before NBE-CT-79 was implemented, 39.4% of the cases were built after it came into force and 8.5% after CTE (Figure 33). For sampling purposes, the year of construction was considered either for original dwellings or renovated ones. This fact was taken into account as a characterisation 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%) (**Figure *33***).

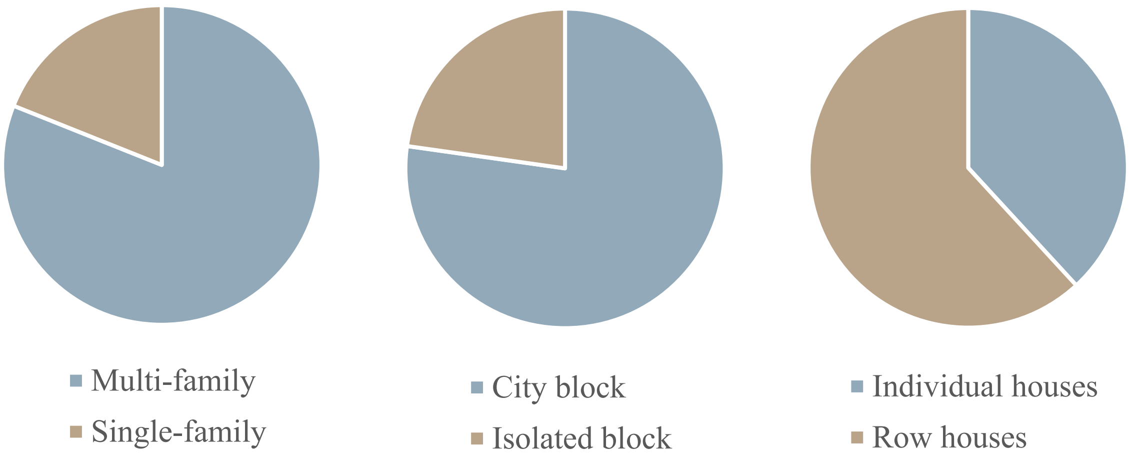
Figure 33. *Distribution of the cases: climate zone, EPR, and state*



Climate zone *EPR* *State*

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. (**Figure 34**). In the cases of apartments, the relative position of the dwelling was assessed: 59.8% of the apartments were located in an intermediate position with conditioned spaces in contact with the horizontal envelope, whereas 18.8% occupied the upper floor and 11.4% the lower floor.

Figure 34. *Distribution of the cases by typology*

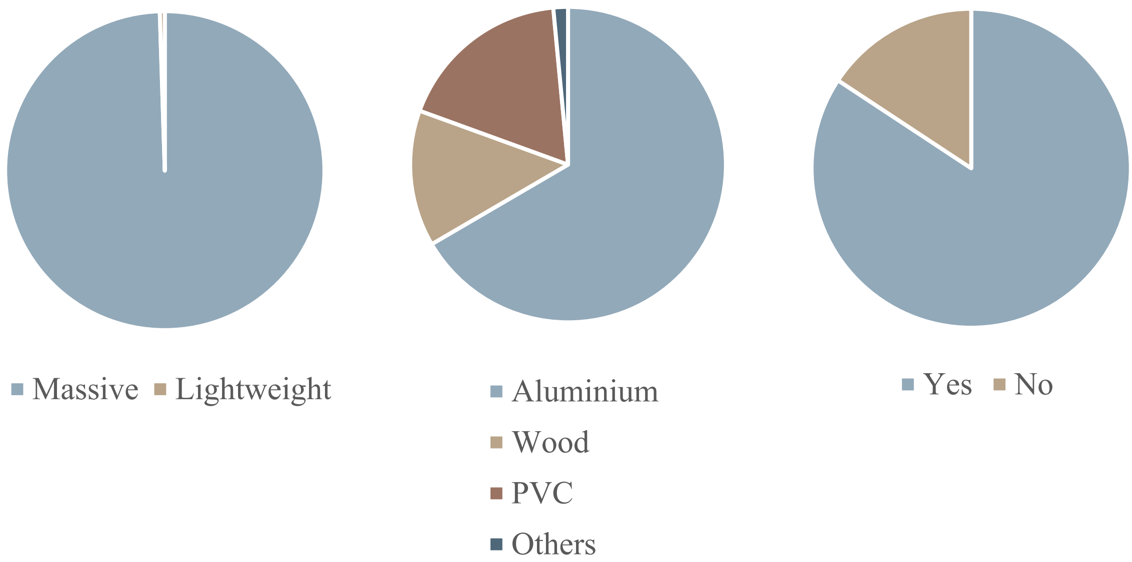


Typology *Multi-family* *Single-family*

Although building characteristics may vary, some common features could define the architectural housing stock in Spain. Massive brick construction system was broadly extended in the country over the past century (99.6% of the sample). Lightweight construction systems are very rarely used in this area (Figure 35). The façade had in around half of the cases (51.6%) an outer coating. The internal layer of the envelope and partition walls were mainly massive as well, although the most recent cases tend to introduce lightweight solutions (7.7% of the sample). It must be noted that there was not often availability concerning construction details or building specifications, so in most of the cases, the construction system had to be deduced visually from the width of the wall and the year of construction.

Regarding windows, which constitute critical points of the envelope, the prevailing material was aluminium (66.5% of the sample). 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 (**Figure *35***).

Figure 35. *Distribution of the cases: construction system, windows, rolling shutters*



Construction system *Multi-family* *Rolling shutters*

Regulations in Spain did not introduce ventilation control in dwellings until 2006 (Ministerio de Vivienda. Gobierno de España, 2006b). This circumstance explains the fact that most of the dwellings tested were ventilated naturally, or just by window airing (99% of the cases). Air renewal is usually provided by opening the outer windows and air infiltration through the building envelope. Kitchens had usually a hood for the exhaust (89.8% of the sample). Figure 36 shows the proportion of the cases, in which the category "Natural" includes also dwellings with no controlled or purpose-provided inlets or exhausts.

Regarding heating and cooling (**Figure 36**), 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.

Figure 36. *Distribution of the cases: ventilation, heating, and refrigeration system*

Ventilation system *Heating system* *Refrigeration system*

3.4 Determination of the air permeability

The airtightness of the cases that encompass this research were measured by means of fan pressurisation tests, also commonly known as blower-door tests or DC Pressurisation tests, whose fundamentals have been detailed in Section "Steady pressurisation method". This method was chosen given its simplicity, the relatively short time that it takes (around 1 hour), the availability of commercial equipment, and because it can be used regardless of the weather conditions (ASHRAE, 2021). The generation of a high-pressure differential is enough to mitigate the wind and temperature action on the envelope, making this method reasonably accurate and reproducible (Sherman & Chan, 2004), although strong winds and large temperature gradients must be avoided in any case (see Section "Measurement uncertainties"). In return, the envelope is subjected to an unreal situation. Pressurisation tests are widely used in other countries to demonstrate compliance with building regulations and on existing airtightness databases (see ***Paper 5***), so results can be easily comparable.

The airtightness tests were performed according to the International Standard UNE-EN 13829 (AENOR, 2002). Further and specific guidelines were gathered in a specific protocol that was developed, whose definition was verified and validated (for more details, see ***Paper 1*** and Annex III: Testing protocol). The protocol specified the correct execution of the experimental procedures and data capture step by step, in such a way that all the cases were analysed systematically and uniformly, and included a checklist of compliance, a troubleshooting section, recommendations, and further guidelines for the test performance:

- Automated tests were performed using the software provided by the blower door manufacturer (TECTITE Express);
- Both pressurisation and depressurisation modes were required to avoid distortions, expressing results as the mean values;
- Pressure stages: 10 data points were taken, with increments of 6 Pa in the range 11-65 Pa, which was considered adequate for the volume and envelope characteristics of the cases under study. Only when the pressure difference of 65 Pa was not achievable in very leaky dwellings or dwellings with particularly large size, lower pressure stages up to the highest pressure difference that could be achievable with the fan were allowed;
- Tests were performed according to Method A (test of the building in use) and Method B (test of the building envelope), considering the different preparations that each method requires. Clarification guidelines for Spanish typical elements (**Table** *7*), always according to UNE-EN 13829 and sealing examples are shown in **Figure** *37*;

- The volume considered for the test performance (V) excluded garages, warehouses, non-conditioned attic spaces, or any other non-conditioned attached structure such as galleries and washing places, typical in Spanish architecture.

Table 7. *Preparation of the building envelope for Methods A and B*

Intentional openings on the envelope	Method A	Method B
Terminal devices of mechanical ventilation or air conditioning systems	◎	◎
Heating systems with indoor air intake	⊗	◎
Natural ventilation with adjustable openings	⊗	◎
Natural ventilation without adjustable openings	○	◎
Exhaust openings	⊗	◎
Enclosed fireplaces	⊗	◎
Open fireplaces	○	◎
Plumbing overflows and drains (without traps)	○	● / ◎
Water taps in plumbing	●	● / ◎
Cupboards and closets doors	⊗	⊗
Exterior windows and doors	⊗	⊗
Interconnecting doors	○	○

○ open position; ⊗ close position; ◎ sealed position; ● filled position

Figure 37. *Examples of the sealing of the openings of the envelope in (a) exhaust openings, (b) terminal devices of mechanical ventilation systems, (c) natural ventilation without adjustable openings for the purposes of Method 2*

(a) (b) (c)

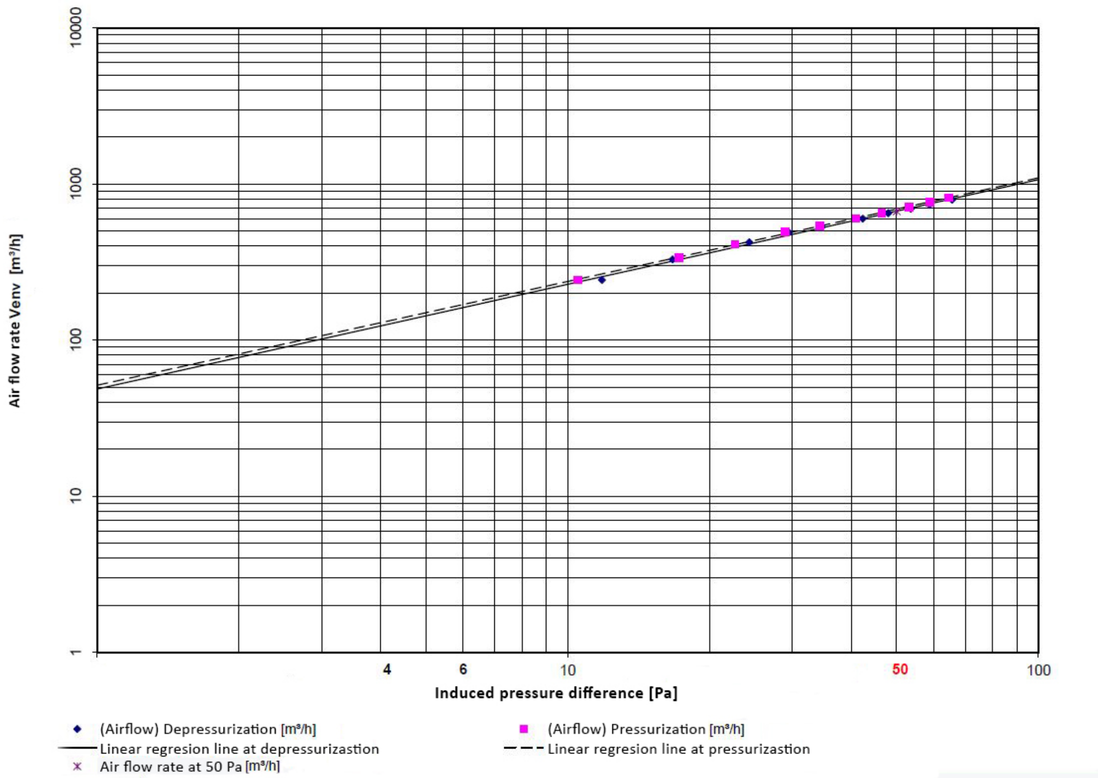
Airflow measurements at the different pressure stages were recorded and a leakage curve (log-log plot) relating the measured airflows through the building envelope at different pressure differences was generated for each case (**Figure 38**). Each leakage curve included both pressurisation and depressurisation measurement sets. An Ordinary Least Square (OLS) regression was used for the calculation of the airflow characteristics (ISO, 2015).

To reduce unwanted uncertainties, the correct calibration of the equipment was ensured to maintain accuracy specifications of 1% of reading, or 0.15 Pa. The overall uncertainty in the parameters obtained with the test using standard equipment was considered to remain below 10% under calm conditions (ISO, 2015). Therefore, test performance was avoided whenever windy conditions were expected.

Results were then normalised by the building envelope area (A_E), and the volume of the premises under study (V), obtaining q_{50} and n_{50} as indicators of the airtightness of the envelope and the air changes per hour at 50 Pa respectively (details on its meaning and calculation can be found in Section “Derived quantities”).

In the case of multi-family dwellings, whole building measurement was discarded given the complexity of the large-scale equipment needed, and the added difficulty when occupants are required to provide access simultaneously. In addition, the obtained information could lack interest if the whole envelope includes lifts and other unconditioned parts of the building. Individual-unit tests were performed, although technical and operational limitations did not allow addressing guarded-zone tests (see Section “Guarded-zone measurements”). Therefore, it was taken into account that dividing walls and horizontal partitions to adjacent spaces were considered as part of the envelope, so leakages connecting different environmental conditions were assessed (Meiss & Feijó-Muñoz, 2015). In any case, the whole envelope airtightness was assessed considering that noise, pollutants, and odours transmission can affect the comfort of the occupants.

Figure 38. *Example of the leakage curve of a pressurisation and depressurisation test of one of the cases studied*



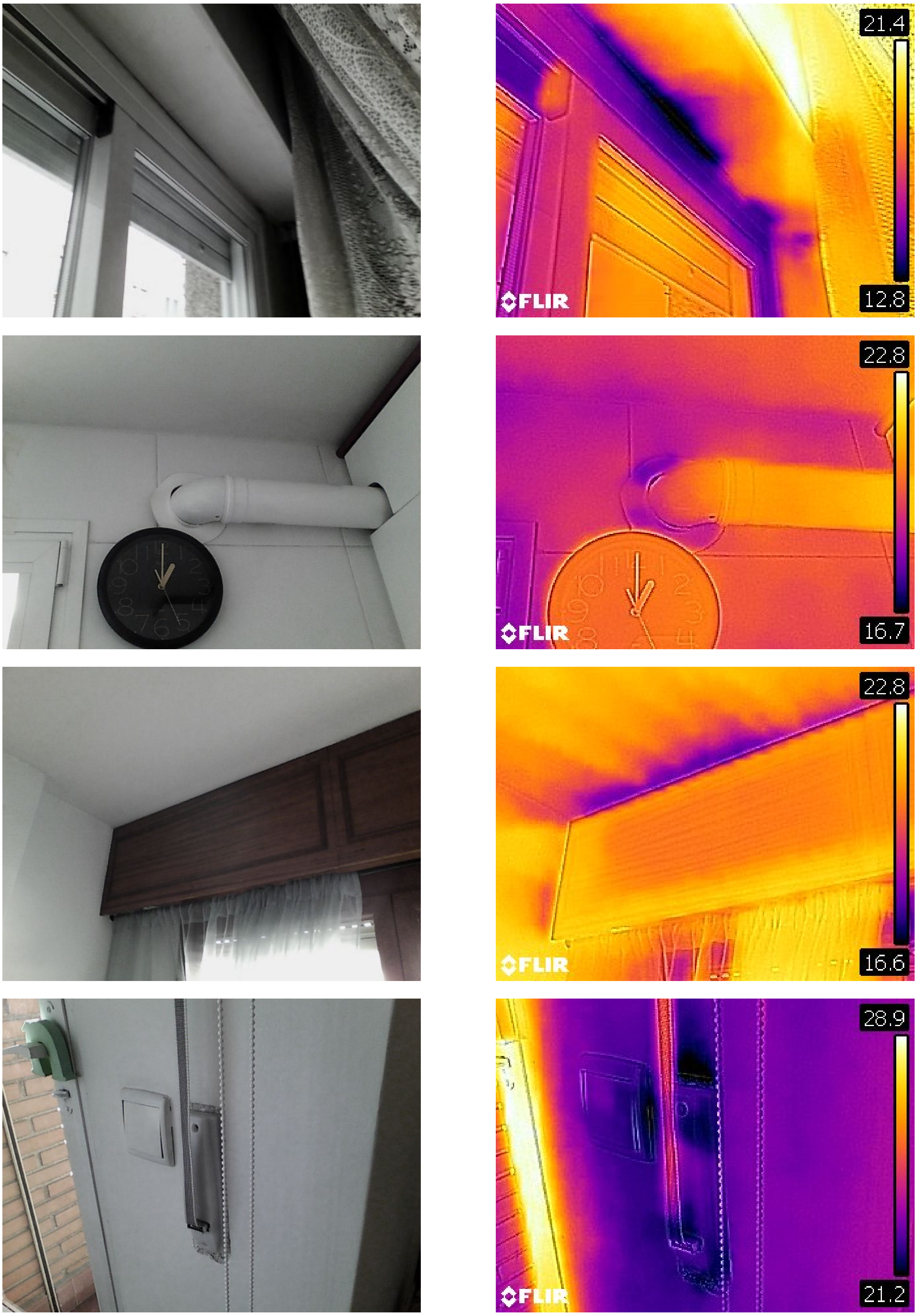
3.5 Leakage location

IR thermal images were taken as a diagnosis tool to qualitatively assess the air leakage paths of the envelope. More details on this detection method were presented in Section “Leakage location”). This non-destructive technique was used as part of the dwellings’ characterisation to visually locate the main leakage paths. The equipment used was a pocket-sized IR thermal camera FLIR C2 with an IR sensor 80 x 60 (4,800 measurement pixels), < 0.10°C thermal sensitivity, object temperature range -10°C to +150°C, and ± 2°C or 2% (whichever is greater), at 25°C nominal. Compactness and easy handling were prioritised.

Leakage paths were identified during the depressurisation stage when the outer air mass was forced by the fan through the leakages of the envelope. Two linked images were simultaneously taken:

one regular photograph, and one image containing the thermal information for better identification of the building element (**Figure *39***).

Figure 39. *Leakage paths detected with IR thermal imaging: (a) window joints, (b) crossing ducts, cables and tubes through the envelope, (c) rolling shutters, (d) strap coilers of rolling shutters, and switches*



One of the limitations of this technique was the need for a temperature gradient between the inner volume and the outer environment to allow thermal observation of the infiltrated air. Therefore, IR leakage detection was fulfilled for tests performed in winter and summer, depending on the climate zone, whereas it could not be possible in some cases where the temperature difference was not enough. Smoke detectors (or simply manual touch) were used in those cases to provide air infiltration paths' information.

3.6 AIR INFILTRATION RATE ESTIMATION

Test results at a reference pressure of 50 Pa were used in order to estimate average annual infiltration rates. As has already been mentioned, this is a complex issue since airtightness tests do not provide information related to the distribution of air leakage paths, and meteorological conditions vary over time. The average annual air change rate of the dwellings under study was estimated applying the infiltration model developed by Sherman (1987) (see Section "Air infiltration rate from airtightness measurements"), which assumes a linear relationship between permeability results at 50 Pa and the average annual air change rate, according to Equation (18) (see ***Paper 3*** and ***Paper 4***). Average meteorological conditions and uniform distribution of leakage paths and constant average leaks over time were presumed.

The model as in Equation (19) was adapted for the characteristics of the cases under study, even though this model was originally developed for single-family houses. However, correction factors for common variations were applied. This simplification may cause error since it is applied to a large number of cases.

The climatic factor C_f was obtained based on the LBL model (Sherman & Modera, 1986), which considers driving forces and their interaction, according to Equation (31).

$$C_f = \frac{1}{s_a}\left(\frac{8\,Pa}{\rho}\right)^{1/2}\left(\frac{50\,Pa}{4\,Pa}\right)^{n} \tag{31}$$

where: C_f is the climatic factor $[-]$; s_a is the typical annual average specific infiltration $[m/s]$; ρ is the density of the air $[kg/m^3]$; n is the airflow exponent $[-]$.

The mean value of the airflow exponent (n) obtained from the dwellings tested on each location was used. The typical annual average specific infiltration s_a was calculated as a function of both wind speed and temperature difference, as well as building-dependent parameters, according to Equation (32).

$$s_a = (f_w^2 \cdot v^2 + f_s^2 \cdot |\Delta T|)^{1/2} \tag{32}$$

where: s_a is the typical annual average specific infiltration $[m/s]$; f_w is the infiltration wind parameter $[-]$; v is the average windspeed $[m/s]$; f_s is the infiltration stack parameter $\left[m/s\,K^{1/2}\right]$; ΔT is the average indoor-outdoor temperature difference (T_{in}-T_{out}) $[K]$.

Reference default values for wind and stack parameters (f_w and f_s) dependent on the leakage distribution and location were used (Sherman & Modera, 1986). All things considered, the climatic factor (C_f) was calculated for the different meteorological conditions of the locations of the cases tested (Instituto para la Diversificación y Ahorro de Energía (IDAE), 2010), as shown in **Table *8***.

Correction factors cf_1, cf_2, and cf_3 were studied as in the model (Sherman, 1987), even though for the estimations made in ***Paper 3*** and ***Paper 4*** their value was simplified to 1. A more accurate approach would correct the leakage infiltration ratio to reduce inaccuracy based on the characteristics of the cases tested. Furthermore, another correction factor could be applied to the cases of the sample considering that most dwellings were located in multi-family buildings, and thus the share of the exterior envelope area should be taken into account. This is suggested as an issue to approach in the future.

Table 8. *Leakage infiltration ratios for each case location*

	ΔT $[K]$	v $[m/s]$	n $[-]$	s_a $[m/s]$	C_f $[-]$	C_{f1} $[-]$	C_{f2} $[-]$	k $[-]$
A Coruña	8.2	3.43	0.62	0.56	21.8	0.7	1.2	18.3
Bilbao	8.3	2.98	0.62	0.52	23.6	0.7	1.2	19.8
Valladolid	10.3	2.31	0.64	0.49	26.4	0.7	1.2	22.2
Madrid	8.0	2.27	0.61	0.45	26.6	0.7	1.2	22.3
Barcelona	6.9	3.42	0.61	0.55	21.9	0.7	1.2	18.4
Alicante	4.7	2.33	0.59	0.40	28.4	0.7	1.2	23.9
Málaga	4.5	3.46	0.60	0.52	22.5	0.7	1.2	18.9
Sevilla	3.8	3.38	0.58	0.50	22.6	0.7	1.2	18.7
Las Palmas	1.9	5.43	0.59	0.73	15.7	0.7	1.2	13.2

Regarding building height, cf_1 adopted the value 0.7 for 3-story buildings, considering that the average height of the dwellings tested for each location was around or just above 3. Coefficient cf_2 corrects the site shielding or environment immediately surrounding the building, which for the dataset tested could be assumed to be around 1.2 given the fact that most of the cases were located in urban areas. Lastly, the values of cf_3 aim at correcting uncertainties derived from the leakage exponent (n). Since for the dataset which is under study this parameter is known, the value of cf_3=1 has been applied, so that it does not alter obtained values. Obtained leakage infiltration ratios (k) are shown in **Table *8***.

Finally, it must be noted that, as stated by Sherman (1987), the model applied could involve large uncertainties, both systematic and random, which are difficult to estimate.

3.7 ENERGY IMPACT ASSESSMENT

The air infiltration that enters a heated building involves energy loss to maintain adequate thermal indoor conditions. The energy load caused by the air infiltration of the cases under study was obtained by means of a simplified model using the classical infiltration calculation according to Equation (33), obtained as a product of the volumetric heat capacity of the air ($c_{p,v}$), the average annual air change rate (ACH), the volume of the dwelling (V), and the temperature difference between the average temperature outside the tested dwellings from specific climate data in the location of the cases, and the comfort indoor temperature through the parameter G_t (see ***Paper 3*** and ***Paper 4***).

$$E_{inf-H/C} = c_{p,v} \cdot ACH \cdot V \cdot G_t \tag{33}$$

where: $E_{inf-H/C}$ is the annual energy loss $[kWh/year]$ due to air infiltration for heating (E_{inf-H}) and cooling (E_{inf-C}); ACH is the average annual air change rate $[h^{-1}]$; V is the internal volume of the deliberately conditioned space of the dwelling $[m^3]$; $c_{p,v}$ is the volumetric heat capacity of the air, which is 0.34 $Wh/(m^3\ K)$; G_t are the annual degree hours $[kKh/year]$, both for heating (G_{t-H}), and for cooling (G_{t-C}).

In this regard, a series of assumptions were made. Comfort indoor temperatures of $21°C$ and $25°C$ for heating and cooling, respectively, were chosen. Those are design operative temperatures based on sedentary metabolic activity of people (1.2 met), clothing (0.5 clo in summer and 1 clo in winter), and the predicted percentage of dissatisfied (PPD index between 10 and 15%), according to Spanish regulations (Ministerio de Industria Energía y Turismo del Gobierno de España, 2013).

Heating degree days (HDD) were obtained from tabulated values (Instituto para la Diversificación y Ahorro de Energía (IDAE), 2010) with a base temperature of $20°C$ for the whole year (Equation (34)).

$$HDD_{20} = \sum_{days} \left(20 - \overline{T_{out-daily}}\right)^{<20} \tag{34}$$

where: HDD_{20} is the Heating Degree Days value [$°C$]; $T_{out-daily}$ is the outdoor air temperature when it is below 20°C [$°C$].

Afterwards, total annual HDD were obtained and transformed to heating degree hours (G_{t-H}) according to Equation (35).

$$G_{t-H} = \frac{24 \cdot HDD_{20}}{1000} \tag{35}$$

where: G_{t-H} is the heating degree hours value for the whole year [$kKh/year$]; HDD_{20} is the Heating Degree Days value [$°C$].

The same rationale was applied for cooling degree days (CDD). However, the application of this method could be considered arguable both due to the associated latent heat component, and because sun gains are essential and not considered.

Furthermore, the relative impact of air infiltration on the heating and cooling demand was approached based on reference values in existing buildings (Instituto para la Diversificación y Ahorro de Energía (IDAE), 2011). This document reports demand reference values for heating and cooling for existing buildings depending on the location and typology.

The demand stated was estimated by means of the official building energy performance simulation tool LIDER-CALENER (Ministerio para la Transición Ecológica y el Reto Demográfico & Ministerio de Transportes Movilidad y Agenda Urbana, 2020) considering typologies and construction systems used during each period according to the distribution of existing buildings in the Spanish residential building stock. The tool LIDER has a dynamic hourly calculation engine of the thermal performance of the building based on ISO 52016-1 (ISO, 2017). A calculation method based on reference heating and cooling demands that depend on coefficients and winter/summer severity according to regulations, which are a function of degree-day and ratio between sun hours and maximum number of sun hours, was used. Degree-days both for winter and summer were calculated using a base temperature of $20°C$, calculated hourly and divided by 24 (Instituto para la Diversificación y Ahorro de Energía (IDAE), 2011).

It is important to note that this estimation is theoretical and real energy loss depends on the particular temperature conditions of the dwellings. This simplified approach encompasses also limitations, and some authors have emphasised that even if it would be well acceptable when calculating the load due to concentrated leakage (through large openings, short paths), it could considerably overestimate the energy impact in the case of diffuse leakage (small cracks, where heat exchange between the infiltrating air and the wall may occur) (Younes et al., 2012).

Furthermore, it is worth mentioning that the non-guarded pressurisation testing method used in apartments did not allow to measure only the permeability of the thermal envelope, and thus, to estimate the air infiltration coming from the outdoor environment in the case of multi-family dwellings. Taking into account that inter-zonal leakages can represent between 2% to more than 60% of the total air leakage (Villi, Peretti, Graci, & De Carli, 2013), the most unfavourable situation was approached, considering that leakages are located on the outer thermal envelope.

Regarding the relative energy impact of air infiltration, the most adverse scenario was also considered in the sense that the total infiltrating airflow was taken into account. This may result in an overestimation of the energy impact since even though tests of the building envelope (Method B) do not consider purpose provided air intakes, infiltrating airflows or any other means of air renewal were not deducted. Results should be understood in this way.

3.8 DATA ANALYSIS

Several common statistical approaches to statistically assess airtightness performance and dwelling characteristics such as ANOVA test of significance, t-test, regression analysis, neural network prediction, or sensitivity analysis have been reviewed in the literature (Bramiana et al., 2016; Prignon & Van Moeseke, 2017; Relander et al., 2012).

The statistical analysis of the Spanish airtightness dataset is gathered in Annex V: Test results and (Poza-Casado et al., 2018). Partial analyses focused on subsets of the sample are shown in ***Paper 2*** (Continental area) and ***Paper 3*** (Mediterranean area). ***Paper 5***, on the other hand, offers a review of the data analyses performed on other airtightness databases and discusses common statistical methods used, highlighting the difficulties regarding data access and harmonisation, which hinders global data analysis and comparison among different datasets.

Only airtightness results obtained for the purposes of Method B according to UNE-EN 13829 (AENOR, 2002) were considered, taking into account the permeability of the building envelope. Normalised parameters q_{50} and n_{50} were selected as indicators, as well as the flow exponent n given its interest regarding the airflow regime. Preliminary partial analyses were performed by climate zone (***Paper 2*** and ***Paper 3***), and also multi-family and single-family dwellings were separately analysed due to their different architectonical configuration concerning external leakages, internal leakages from other apartments and leakages from non-conditioned spaces such as the hallway, elevator or vestibule.

Outliers due to experimental errors were not excluded from the dataset considering the clear guidelines given and quality control during the experimental stage. Outliers were eliminated from the sample only when they caused distortion in the data analysis.

Firstly, the descriptive analysis of the data gathered was addressed. The distribution of the data was studied by evaluating normality, skewness and kurtosis, mean, median, standard deviation, maximum and minimum values (range). The distribution of the airtightness results was analysed by means of Lilliefors corrected Kolmogorov-Smirnov normality test (Field, 2009), and graphically through histograms and Q-Q' plots using the extended statistics tool IBM SPSS Statistics (IBM Corporation, 2015). The null hypothesis of normality h_0 was rejected for given $p - values$ with a significance level applied for the analysis $\alpha = 0.05$ (5%), which indicates the non-normal distribution of the data. Global results were also compared to the ones obtained in other countries (Laverge et al., 2014; Orme et al., 1994)

Analytical statistics were used to assess the influence of different parameters on the airtightness results. Given the non-normal distribution of the sample, non-parametric tests were performed for that purpose. Kruskal-Wallis test was performed in order to statistically verify the independence of the variables with the permeability values obtained (Field, 2009). The test statistic $Chi - square$ value (also known as Kruskal-Wallis H) expresses the differences between the compared groups, and it was used to assess the null hypothesis that the medians are equal across the groups. On the other hand, the significance was studied through the $p - value$ based on the $Chi - square$ approximation. It was considered significant for values < 0.05, that is, with a 5% risk of concluding that a difference exists when there is no actual difference. Graphically, the interdependence of the variables was studied through boxplot sets.

In this sense, the interdependence of airtightness performance and variables related to climate zone, period of construction, regulations in force, typology, relative position within the building, developer, retrofitting state, construction systems (building envelope, insulation layer, air chamber, coating, windows, rolling shutters, partition walls, etc.), ventilation and conditioning system were evaluated.

4 SCIENTIFIC PAPERS THAT SUPPORT THE RESEARCH WORK

The research work that was carried out and led to this Thesis has been published in 5 scientific papers that constitute its core. The papers can be seen together as a whole, and their publication chronogram corresponds to the development of the research.

The combination of the published papers shows the research that aimed at characterising the airtightness of the building envelope in existing dwellings in Spain. To that end, each paper contributes to the development of different aspects that together as a whole achieved this goal. In this sense, a brief overview of each contribution is described, in order to show their relationship and joint relevance.

Paper 1: Methodology for the Study of the Envelope Airtightness of Residential Buildings in Spain: A Case Study

This paper set the basis of the Methods applied for the characterisation of the existing building stock. First, the knowledge gap in Spain was identified, and an overview of the context and the state of the art in Spain was shown.

The Methodology and criteria established to build the Spanish airtightness database of residential buildings were described. It encompassed a sampling method that determined the dwellings that needed to be tested, ensuring their representativeness, heterogeneity, and viability. Furthermore, the testing method by means of fan pressurisation tests was shown. Although tests were performed according to the international standard ISO 9972 (ISO, 2015) or its Spanish version in force at that time (AENOR, 2002), a specific protocol was referenced, including further guidelines. In this paper, the tool *infilAPP*, which was used to gather the characterisation data of each case in a standardised and systematic way, was also presented. This tool was used as a guide for the data introduction for a database creation and management. Organizational issues such as coordination among the participant Universities and teams, test campaigns, training, quality management, and dissemination strategies completed the Methodology designed.

Lastly, the example of a case study, in which the described Methodology was implemented, and the comparison with the results of the database, completed this paper.

Paper 2: Airtightness of residential buildings in the Continental area of Spain

The second paper focused on the cases located in the Continental climate zone of Spain, specifically in Madrid and Valladolid. This partial analysis was carried out given the fact that there are several aspects associated with the region where buildings are located such as differences in construction systems, dwelling design, typical elements, etc. derived from climate characteristics or construction tradition, among others. A wide description of the climate conditions of the node cities was given, as well as the keys to understanding the evolution of the building systems. In this regard, the socioeconomic circumstances of the past century explain somehow the evolution of different regulations and widespread construction characteristics.

The paper explored the dwellings tested in this area, according to the protocols and guidelines established in ***Paper 1***, and validated the Methodology proposed. The sample was described by highlighting its distribution in terms of typology, year of construction, construction system, and ventilation and conditioning systems. The main outcomes revealed the distribution of the airtightness results, whose relationship with some building characteristics (regulations, construction systems, position within the building) was statistically analysed.

Paper 3: Energy impact of the air infiltration in residential buildings in the Mediterranean area of Spain and the Canary Islands

This paper was developed in parallel with ***Paper 2*** and had some common points derived from the fact that both papers were partial analyses of the database in specific climate zones. In this case, the dwellings located in the Mediterranean area of the Peninsula (Barcelona, Alicante, Málaga, and Sevilla) and the Canary Islands (Las Palmas de Gran Canaria) were presented. The general structure reproduces the one presented in ***Paper 2***.

Again, a description of the climate conditions was given together with an overview of the socioeconomic context of the past century. Different building systems were listed divided by periods that correspond to the regulations in force. A special mention was dedicated to ventilation and conditioning systems and special typical features in this area given its repercussion on airtightness.

The Methods made reference to the protocol established in ***Paper 1***, describing also the sample and its distribution according to building characteristics. In addition, ***Paper 3*** introduces the energy impact assessment, estimating the energy loss from the airtightness results. Therefore, the airtightness results, their distribution, and the analysis of their relationship with some building characteristics were complemented with the energy impact estimation both for the hot and the cold seasons.

Following the logic and the common thread of the papers' progress, a specific paper focusing on the Oceanic climate zone of the country would be expected. However, some drawbacks did not allow to fulfil the sample determined for this area, and, thus, the data is incomplete. A paper based on this approach is expected to be published in the near future to complete and complement this line.

Paper 4: Airtightness and energy impact of air infiltration in residential buildings in Spain

In a logical workflow of the research, ***Paper 4*** presented an analysis of the whole database regarding airtightness and the energy impact caused by air infiltration through the building envelope. It entirely focused on the global airtightness results and the energy assessment by detailing the relative impact on the heating and cooling demand in all the cities in which the dwellings were tested. Airtightness results were compared to the limits established in the regulations of other countries.

Paper 5: Residential buildings airtightness frameworks: A review on the main databases and setups in Europe and North America

The last paper that constitutes this Thesis, ***Paper 5***, presented a different approach. It is a review paper on the main airtightness databases in Europe and North America that focused on building regulations, datasets, operativity and testing protocols found in different countries. The urge for this work arose naturally after the experience of the first approach to a national airtightness database in Spain. It was a result of the collaboration between researchers of Universidade do Porto and Universidad de Valladolid who had been carrying out research in this field. The previous experience, the similar context in both countries, and the imminent change on the Spanish national regulations that introduced whole building airtightness limitations for the first time awoke the interest for this new perspective.

Airtightness databases have proved to be of great interest for different purposes (gathering information for modelling, to assess the factors that have a major impact on airtightness, visualise time trends, evaluate the progress of the building stock in meeting energy performance objectives, or compare the building performance with other countries, among others). ***Paper 2*** and ***Paper 3*** were referred in this regard to underline the importance of databases to evaluate building design, construction practices and quality. In this sense, ***Paper 5*** was seen as an opportunity to set a theoretical framework that could be used by national administrations to set a common database for one country or even internationally.

This review described the normative framework on requirements and recommendations found in different countries, followed by the description and comparison of the most relevant airtightness databases found. Their structure and measurement data acquisition protocols were detailed. In addition, different characterisation and data gathered were assessed from the studied databases, and the main analysis outcomes related to the importance of influencing factors on airtightness was analysed.

Among the airtightness regulations and databases reviewed, the Spanish case was analysed regarding regulations and the database structure and management, including the characterisation and testing protocols described in ***Paper 1***. Therefore, ***Paper 5*** could be seen not only as an evaluation tool that was used to identify the weaknesses and strengths of the previous experience, whose main outcomes were described in Papers 1-4 but also as a wide range of opportunities for the future.

Overall, a great connection with the common ground could be confirmed from the global study of the 5 contributions. The papers are closely related to each other, including constant references to the previous work developed. The different aspects of the research were published with a natural flow as the different stages of the research were being fulfilled, and their combination resulted in this Thesis as the joint of the whole efforts.

4.1 METHODOLOGY FOR THE STUDY OF THE ENVELOPE AIRTIGHTNESS OF RESIDENTIAL BUILDINGS IN SPAIN: A CASE STUDY

Feijó-Muñoz, J., Poza-Casado, I., González-Lezcano, R. A., Pardal, C., Echarri, V., Assiego De Larriva, R., Fernández-Agüera, J., Dios-Viéitez, M. J., Del Campo-Díaz, V. J., Montesdeoca Calderín, M., Padilla-Marcos, M. Á., Meiss, A.

4.1.1 Abstract

Air leakage and its impact on the energy performance of dwellings has been broadly studied in countries with cold climates in Europe, US, and Canada. However, there is a lack of knowledge in this field in Mediterranean countries. Current Spanish building regulations establish ventilation rates based on ideal airtight envelopes, causing problems of over-ventilation and substantial energy losses. The aim of this paper is to develop a methodology that allows the characterization of the envelope of the housing stock in Spain in order to adjust ventilation rates taking into consideration air leakage. A methodology that is easily applicable to other countries that consider studying the airtightness of the envelope and its energetic behaviour improvement is proposed. A statistical sampling method has been established to determine the dwellings to be tested, considering relevant variables concerning airtightness: climate zone, year of construction, and typology. The air leakage rate is determined using a standardized building pressurization technique according to European Standard EN 13829. A representative case study has been presented as an example of the implementation of the designed methodology and results are compared to preliminary values obtained from the database

Keywords: infiltrations; airtightness of the envelope; blower door test; residential buildings

4.1.2 Reference

Feijó-Muñoz, J., Poza-Casado, I., González-Lezcano, R. A., Pardal, C., Echarri, V., Assiego De Larriva, R., … Meiss, A. (2018). Methodology for the Study of the Envelope Airtightness of Residential Buildings in Spain: A Case Study. Energies, 11(4), 704. https://doi.org/10.3390/en11040704

4.1.3 Contribution of the doctoral candidate

Design of the sampling method, collaboration in the development of the protocol and the performance of the case study test, as well as the writing of the manuscript.

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Methodology for the Study of the Envelope Airtightness of Residential Buildings in Spain: A Case Study

Feijó-Muñoz Jesús [1], Poza-Casado Irene [1,*], González-Lezcano Roberto Alonso [2], Pardal Cristina [3], Echarri Víctor [4], Assiego de Larriva Rafael [5], Fernández-Agüera Jesica [6], Dios-Viéitez María Jesús [7], del Campo-Díaz Víctor José [8], Montesdeoca Calderín Manuel [9], Padilla-Marcos Miguel Ángel [1] and Meiss Alberto [1]

1. RG Architecture & Energy, Universidad de Valladolid; Valladolid 47014, Spain; feijo@arq.uva.es (F.-M.J.); miguelangel.padilla@uva.es (P.-M.M.A.); meiss@arq.uva.es (M.A.)
2. Department of Architecture and Design, Universidad CEU San Pablo; Boadilla del Monte, Madrid 28668, Spain; rgonzalezcano@ceu.es
3. Department of Architectural Technology, Universidad Politécnica de Cataluña; Barcelona 08028, Spain; cristina.pardal@upc.edu
4. Architectural Constructions Department, Universidad de Alicante; San Vicente del Raspeig, Alicante 03690, Spain; victor.echarri@ua.es
5. Art and Architecture Department, Universidad de Málaga; Málaga 29071, Spain; rassiegodl@uma.es
6. Instituto de Ciencias de la Construcción Eduardo Torroja, Consejo Superior de Investigaciones Científicas; Madrid 28033, Spain; jfernandezaguera@us.es
7. Architectural Constructions Department, Universidade da Coruña; A Coruña 15008, Spain; mjdios@udc.es
8. Department of Thermal Engines and Machines, Universidad del País Vasco, UPV/EHU; Bilbao 48013, Spain; victor.delcampo@ehu.es
9. Architectural Constructions Department, Universidad de Las Palmas de Gran Canaria; Las Palmas de Gran Canaria 35017, Spain; manuel.montesdeoca@ulpgc.es

* Correspondence: irene.poza@uva.es; Tel.: +34-983-423-462

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Abstract: Air leakage and its impact on the energy performance of dwellings has been broadly studied in countries with cold climates in Europe, US, and Canada. However, there is a lack of knowledge in this field in Mediterranean countries. Current Spanish building regulations establish ventilation rates based on ideal airtight envelopes, causing problems of over-ventilation and substantial energy losses. The aim of this paper is to develop a methodology that allows the characterization of the envelope of the housing stock in Spain in order to adjust ventilation rates taking into consideration air leakage. A methodology that is easily applicable to other countries that consider studying the airtightness of the envelope and its energetic behaviour improvement is proposed. A statistical sampling method has been established to determine the dwellings to be tested, considering relevant variables concerning airtightness: climate zone, year of construction, and typology. The air leakage rate is determined using a standardized building pressurization technique according to European Standard EN 13829. A representative case study has been presented as an example of the implementation of the designed methodology and results are compared to preliminary values obtained from the database.

Keywords: infiltrations; airtightness of the envelope; blower door test; residential buildings

1. Introduction

In recent years, the interest in air infiltrations has significantly grown. The uncontrolled intake access through the envelope of buildings generates a series of problems that affect its occupants [1]:

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higher energy consumption, lack of thermal comfort, entry of pollutants and odours, noise, inadequate functioning of ventilation systems, less protection against fire, etc.

There are numerous studies that have been carried out in Northern Europe, USA, and Canada for decades [2]. However, in Mediterranean countries there is still a lack of knowledge in this area [3]. Some field studies have been carried out to characterize the behaviour of the envelope of residential buildings concerning infiltration (Table 1):

Table 1. Examples of studies of airtightness characterization carried out in Mediterranean countries.

Country	Ref.	Year	Sample Size	Year of Construction	Typologies [1]	Testing Method [2]	Leakage Detection [3]
Italy	[4]	2012	20	1810–2010	M/S	BD	T/A/PT
Italy	[5]	2013	5	1970's	M	BD/S	A
Greece	[6]	2007	20	unspecified	S	BD/TG	-
Portugal	[3]	2017	4	unspecified	M/S	BD	-
Portugal	[7]	2015	49	1972–1974	M	BD/TG	-
Croatia	[8]	2014	58	different periods	M/S	BD	-
Turkey	[9]	1990	52	1980's	M	BD/TG	-
Spain	[10]	2013	>120	unspecified	M	BD	T
Spain	[11]	2014	13	1973–2012	M	BD	T
Spain	[12]	2015	6	1960–1976	M	BD	T/SD
Spain	[13]	2012	45	2003–2011	M	BD	T/SD

[1] Multi-family dwellings: M/Single-family houses: S; [2] Pressurization method: BD/Tracer gas decay method: TG/Software simulation: S; [3] Thermography: T/Anemometer: A/Pitot tube: PT/Smoke detector: SD.

In the south of Italy, an experimental study [4] was carried out in 20 residential buildings of different periods (1810–2010), climatic zones, and typologies (cottages, terraced houses, apartments, and large buildings). The study focused on the impact of infiltrations on energy consumption and thermal comfort, analysing the influence of several parameters: net floor area, envelope area, internal volume, typology, type of window frames, and year of construction.

Another study in Italy [5] analysed the airtightness of a three-story building of the 1970s recently renovated with six apartments to know the influence of air leakage on energy losses and indoor air quality. Repeated tests sealing different elements revealed the influence of each component on the total infiltration rate.

Sfakianaki et al. [6] conducted a study in 20 single-family homes in the Attica area, Greece. Both the tracer gas decay and pressurization methods were used. In this way, the cases were classified into three categories according to EN ISO 13,790 [14] and the influence of different parameters on the global infiltration rate was statistically evaluated.

In Coimbra, Portugal [3], four retrofitted and original buildings of the historic centre were studied. Three of them were multi-family buildings and one was a detached house. The objective was to know the air change rate (ACH) of the chosen sample and to establish the minimum ACH to maintain good indoor air quality and acceptable thermal behaviour. Another more extensive testing campaign in Portugal [7] analysed 49 apartments in two social housing neighbourhoods in order to know the relationship between the behaviour of the users of the dwellings and their airtightness and ventilation. One of the neighbourhoods had recently been rehabilitated. Tests were also carried out in an apartment to find out the individual impact of different elements on the airtightness of the whole envelope (window frame, self-regulated air inlets, mechanical extraction in kitchens, fixed air inlets in the laundry, and mechanical fan in the bathroom).

A study in Osijek, Croatia, [8] obtained a database with airtightness test results in 58 residential units. The sample was considered representative in terms of year of construction after finding a relationship between the elements of the sample and the statistical data of residential buildings in Croatia. The purpose was to establish a method for predicting the airtightness of the envelope applying neural networks, which has been subsequently validated [15,16].

In Turkey [9], another study was carried out after the detection of problems in dwellings such as inadequate air conditioning and ventilation or condensation. Airtightness tests were conducted in 52 newly built unoccupied homes to analyse the behaviour of the envelope and to proceed with a possible revision of the regulations.

In the case of Spain, only partial studies have been carried out so far to characterize the airtightness of the envelope of the housing stock. None of them has covered the entire geography of the country. The study with the largest number of tests fulfilled was conducted in recently built dwellings in northern Spain [10] to determine the level of infiltration in residential buildings and to establish the determining factors. Also, in northern and central Spain, Meiss and Feijó-Muñoz [11] developed a procedure to evaluate the excess energy consumption caused by air infiltration, analysing 13 homes in residential buildings. The lack of airtightness in Spain was estimated to represent between 10.5% and 25.4% of the energy demand in winter in buildings built under current regulations [17].

Several social housing units in Madrid and Seville were analysed to determine the degree of airtightness and indoor air quality [12]. The sample was chosen paying attention to the representativeness of the architectural and construction typologies used in the period 1940–1980 and presented different degrees of retrofitting of the envelope. The airtightness of the envelope in residential buildings at the beginning of the 21st century in the south of Spain has also been characterized [13]. The selection of cases to be analysed in each building was made with a stratified probabilistic design.

The objective of this work is to establish a rigorous and simple methodology in order to carry out a characterization of the envelope of residential buildings in Spain in terms of airtightness, through coordinated testing campaigns. A broad database of 411 cases that collects characterization information and results is being created. In a later phase, the analysis of the data under a unified procedure and criteria will be guaranteed. In this sense, it will be possible to know the impact that different factors have on airtightness, as well as the infiltration rates corresponding to the most widespread constructive solutions in Spain.

This methodology has been conceived in such a way that it is easily applicable to other countries that intend to evaluate the energy impact of air leakage of existing buildings.

Regulations in Spain

The European Directive on the energy performance of buildings [18] is committed to the generalization of nearly-zero energy buildings (nZEB) by 2020. In response to it, many countries have been incorporating limitations in their regulations regarding the airtightness of the envelope [19] since the beginning of the 2000s.

However, in Mediterranean countries with a temperate climate, where ventilation has traditionally been done in a natural and manually controlled way, infiltrations have been part of the air supply and have compensated the lack of regulation of specific controlled ventilation systems [13].

In Spain, after the oil energy crisis in the 70s, the building regulations NBE-CT-79 [20], relating to thermal conditions of buildings, tended to increase thermal insulation, achieving an improvement in the energy performance of buildings. NBE-CT-79 also affected indoor air quality as a consequence of the lack of ventilation. To give an answer to this problem, in 2006 regulations of the Technical Building Code (CTE) DB HS3 [21] were approved. This document implemented specific ventilation requirements and proceedings to ensure adequate indoor air quality, establishing minimum ventilation flows.

The current version of the CTE [21], in spite of not contemplating a minimum requirement of global airtightness of the envelope, gives the option to consider the equivalent infiltration area as part of the ventilation opening area. In this way, using technical specifications tables or minimum values of airtightness established for each type of window (Table 2) it is possible to adjust the required flow rates. However, the obtaining of a precise value for the entire enclosure considering not only the airtightness of its elements separately, but also the encounters of each solution, would be necessary. In any case, the lack of knowledge of airtightness values results in the oversizing of the ventilation systems.

Table 2. DB HE1: Limitation of the energy demand [22]: maximum air permeability values of the windows of the thermal envelope by winter climate zone [1].

Parameter	Zone α	Zone A	Zone B	Zone C	Zone D	Zone E
Window air permeability [2] ($m^3/h{\cdot}m^2$)	≤50 [3]	≤50	≤50	≤27	≤27	≤27

[1] Zones A, B, C, D and E refer to Continental Spain. Zone α refers to Canary Islands. [2] Airtightness measured with 100 Pa overpressure. [3] The values correspond to the window classification established in the EN 12207 [23]: class 1 (≤50 $m^3/h{\cdot}m^2$) and class 2 (≤27 $m^3/h{\cdot}m^2$).

2. Methodology

2.1. Sampling

Given the impossibility of testing and characterizing each home in the Spanish residential stock, sampling has been used, selecting a set of elements (sample), from which to extrapolate the results and establish statements. In this sense, the maximum representativeness of the sample has been ensured in order to characterize the existing housing stock in Spanish geography in the most reliable way.

In the theoretical framework, the best way to estimate a relevant statistical distribution would be to analyse cases in a random sample of buildings in Spain that would ensure the representativeness of the sample [24]. However, taking into account the objectives and characteristics of the present study, a more realistic and efficient approach has been considered, proposing a non-probabilistic quota sampling scheme. The sample reproduces the population on a smaller scale, ensuring the heterogeneity and proportionality of the selected cases. The problem of this methodology lies mainly in the possibility of bias in the sample when the cases are selected in a very specific environment. The appropriate measures to avoid it have been taken. It is also necessary to indicate that sampling errors cannot be estimated because the probability of each case being selected is unknown [25].

2.1.1. Parameters

The Spanish residential stock has been stratified into subgroups (strata) according to a series of control variables. In order to define relevant control variables, a review of previous studies that have established predictive airtightness models in residential buildings [26] has been used. It is deduced that one of the variables with greater relevance is the year of construction [27–30]. Also, characteristics of the building such as typology [31], type of construction [30], type of window/glazing [15] and window frame [6,32], foundation [28], construction system [33], materials [15,24,32,34], floor area [28], total height [28], number of storeys [33], ventilation system [35,36], type of insulation [30] and sealing devices [34], and management type [31] should be considered. In addition, the execution also seems to be a relevant factor in the airtightness of the envelope [36,37]. Several authors have also considered that the climatic zone is a variable to consider [28,38].

There are many factors that have an impact on airtightness. However, in order to be considered as control variables for sampling, its distribution must be known. Finally, the year of construction, typology, and climatic zone have been taken as control variables for the sampling, given their relevance. The impact on the infiltration rate generated by the other parameters will be evaluated afterwards, during the data analysis phase.

The year of construction is relevant for several aspects. First, materials and joints deteriorate over time [39]. A 10–15% increase in the infiltration rate has been estimated every 10 years [40,41]. Second, construction systems are evolving and improving, although in countries with temperate climates where there are no regulations that limit the infiltration rate, the most recent buildings are not necessarily the most airtight [2]. Third, the year of construction is linked to the regulations in force at each moment, which establishes the requirements and conditions of the construction systems. A total of 10 groups have been determined by periods, based on statistical sources [42].

Regarding the typology, a distinction has been made between single-family and multi-family dwellings, which represent more than 70% of the residential stock in Spain [40].

The climatic zone also has a significant impact on airtightness. Buildings located in cold climates tend to be more airtight than others located in temperate climates [41]. Climatic zones do not only affect weather conditions, but they can also establish differences in regulatory requirements or different construction systems [28]. A simplification of the climatic zones in Spain has been made, obtaining a total of four zones: Continental, Oceanic, Mediterranean, and Canary Islands (Figure 1).

The number of cases belonging to each stratum has been made proportionally, according to the statistical distribution of the housing stock in Spain [42]. This way, a stratified representation of the population is obtained.

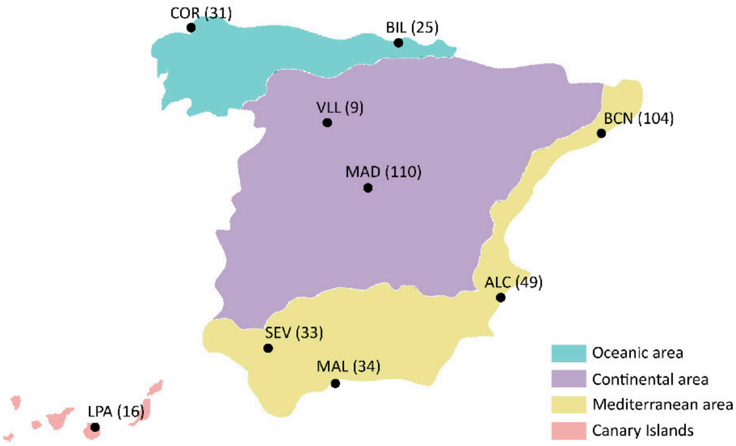


Figure 1. Considered climate zones in Spain, location of the participant Universities, and size of the sample of each of them.

2.1.2. Size and Distribution of the Sample

Once the control variables were defined, the number of cases to be analysed and the stratification of the population is carried out. The size of the sample depends on three variables: the level of confidence, the variance, and the margin of error that is considered acceptable [43]. Statistically, the Spanish residential stock is considered an infinite population. This means that the size of the sample will be determined by the following Equation (1):

$$n_0 = \frac{Z^2 \sigma^2}{e^2} \quad (1)$$

where:

n_0: sample size (number of dwellings to be studied)
Z: critical value, depending on the confidence level
σ: population standard deviation (unknown value in Spain)
e: margin of error

The value of Z is given by the Gaussian distribution, depending on the level of confidence accepted. The most frequent values are Z = 1.645, Z = 1.96 and Z = 2.575, for confidence levels of 90%, 95% and 99% respectively.

The value of the variance in terms of the airtightness of the envelope in Spain is an unknown value, since there is still no representative data in this regard. Values obtained in a study carried out in Italy were taken as reference, by proximity, constructive, and climatic analogy [44]. The study carried out analysed 20 cases of several typologies and year of construction, resulting from the air change rates values at 50 Pa (n_{50}) a variance of 17.584.

Taking into account that a higher level of confidence or a minor admissible error significantly increases the sample size and that the number of cases to be analysed is conditioned by the purpose of the study, the availability of resources, and the time limitation, a confidence level of 95% and an error of ±0.4 have been considered acceptable, resulting in a sample size of 423 cases. This figure has finally been reduced to 411 due to numerical rounding in the stratification process. The distribution of the samples and their location are detailed in Table 3 and in Figure 1.

Table 3. Distribution of the sample.

		Climate Zone								
		Oceanic		Continental		Mediterranean				Canary Islands
Period	Typology [1]	COR	BIL	VLL	MAD	BCN	ALC	MAL	SEV	LPA
<1900	S	1	-	-	-	1	1	-	-	-
	M	-	1	-	2	3	-	-	-	-
1900–1920	S	1	-	-	-	1	-	-	-	-
	M	-	1	-	2	3	-	-	-	-
1921–1940	S	1	-	-	-	1	-	-	-	-
	M	-	1	-	3	4	-	-	-	-
1941–1950	S	1	-	-	-	1	1	-	1	-
	M	-	1	-	3	3	1	-	1	-
1951–1960	S	1	-	-	1	1	1	1	1	-
	M	1	3	-	8	7	1	1	1	1
1961–1970	S	1	-	-	1	2	1	1	2	1
	M	3	7	2	19	19	5	3	4	2
1971–1980	S	1	-	-	3	3	2	2	2	1
	M	5	5	2	23	22	8	6	5	2
1981–1990	S	1	-	-	3	3	3	2	2	1
	M	2	1	1	9	6	5	5	2	2
1991–2001	S	1	-	1	4	3	2	2	3	1
	M	3	2	1	13	10	3	4	3	2
2002–2011	S	2	-	1	3	2	3	1	3	1
	M	6	3	1	13	9	12	6	3	2
	TOTAL	31	25	9	110	104	49	34	33	16

[1] S are single-family houses and M multi-family or apartment buildings.

2.2. *Tests Assessment*

2.2.1. Testing Method

The evaluation of the leakages is carried out in accordance with EN 13829 standard [45], used for the determination of air permeability of buildings by the fan pressurization method, commonly known as Blower door test (Figure 2).

There are other measurement techniques such as the tracer gas method, which is more accurate but requires well-trained experts and also higher costs [3]. The blower door test has been considered the most appropriate technique because it is simpler and comparatively inexpensive. The generation of a high-pressure differential (50 Pa) is sufficient to mitigate the wind and temperature action on the envelope. In this sense, it is reasonably accurate and reproducible [2]. In return, the envelope is subjected to an unreal situation, because the average pressure differential under normal environmental circumstances is around 1–4 Pa.

Measurement sets are made both for pressurization and depressurization, in the internal volume of the deliberately conditioned space of the house. In the case of apartment buildings, in which part of the envelope is in contact with other conditioned or unconditioned spaces different from the outdoor space, the air permeability of each dwelling is measured individually. Dividing walls and horizontal partitions to adjacent spaces are considered to be part of the envelope. It must be taken into account, though, that there are air inlets with different environmental conditions [11]. Thus, envelope areas from different conditions are measured in a differentiated way. Technical and operational limitations do not allow addressing more accurate approaches like the pressure equalization method [46].

Figure 2. Blower door system.

Through an automated test using the software provided by the blower door manufacturer (TECTITE Express), a total of 10 data points were measured, with increments of 6 Pa in the range 11–65 Pa.

The infiltration curve is calculated according to the power law equation (Equation (2)), based on the fundamental mechanics airflow, to establish the relationship between the fan flow (q_{env}) and the building pressure difference (Δp):

$$V_{env} = C_{env}(\Delta p^n) \quad (2)$$

where:

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

The pressure exponent n provides an indication of the flow regime. It has the limiting values of 0.5 and 1 [2]. On the one hand, when n is closer to 0.5, the flow regime is turbulent and leakage paths are expected to be large, short leaks. On the other hand, when the exponent is closer to 1, the flow is laminar and long-path leaks are expected. Typical flow exponent values range between 0.6 and 0.7 [47].

Two procedures are carried out by Methods A (testing of a building in use) and B (testing of the building envelope), as described in standard EN 13829 [45], taking into account the different preparations of the building that each method requires (Table 4).

Table 4. Preparation of the building envelope for Methods A and B.

Openings on the Envelope	Method A	Method B
Terminal devices of mechanical ventilation or air conditioning systems	◎	◎
Terminal devices of mechanical ventilation or air conditioning systems	◎	◎
Heating systems with indoor air intake	⊗	◎
Natural ventilation with adjustable openings	⊗	◎
Natural ventilation without adjustable openings	○	◎
Exhaust openings	⊗	◎
Enclosed fireplaces	⊗	◎
Open fireplaces	○	◎
Plumbing overflows and drains (without traps)	○	●/◎
Water traps in plumbing	●	●/◎
Cupboards and closets doors	⊗	⊗
Exterior windows and doors	⊗	⊗
Interconnecting doors	○	○

○ open position; ⊗ close position; ◎ sealed position; ●filled position.

The parameters obtained from the power law, defined in the EN 13829 standard [45] that allow the comparison of results in different buildings (Table 5) are listed below:

Table 5. Parameters obtained from the power law.

	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	$m^3/h{\cdot}m^2$

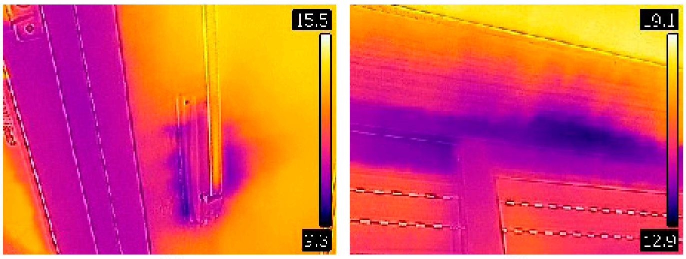
V (m^3): internal volume. Volume of air inside the measured building, calculated by multiplying the net floor area by the ceiling height. The volume of the furniture is not subtracted. A_E (m^2): envelope area. Total area of walls, floors, and ceilings bordering the internal volume subject to the test.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

Additionally, two parameters are considered:

- EqLA (10 Pa): equivalent leakage area—National Research Council (NRC) of Canada Model (cm^2). It is defined as the area of a sharp-edged orifice that would leak the same amount of air as the building does at a pressure of 10 Pa [48].
- ELA (4 Pa): effective leakage area—Lawrence Berkeley Laboratories Model (LBNL) (cm^2). It is defined as the area of a special nozzle-shaped hole that would leak the same amount of air as the building does at a pressure of 4 Pa.

During the depressurization stage, leakage points were identified by thermography (Figure 3). However, due to the climatological conditions of the areas where the tests were carried out, a large thermal gradient to allow thermographic observation was not always expected. In these cases, thermography will be replaced by the use of smoke generators.

For the assessment of the tests, a common protocol based on the standard [45] has been developed, which specifies the correct execution of the experimental procedures and data capture, in such a way that all the cases are analysed in a systematic and uniform way.



(a) (b)

Figure 3. Usual leakage paths detected with thermography. (**a**) Leakage path at the strap coilers of rolling shutters; (**b**) Leakage path at window joints.

2.2.2. Software Development for Data Gathering

A specific tool has been developed to store all the data from each case, "infil-APP" (Figures 4–7). A wide characterization of different parameters, up to a total of more than 140, are stored in a tabulated way, detailed in Table 6. The application has been conceived to allow a simple, fast, and intuitive operation. Its structure is in accordance to the testing process, so that technicians only need to follow the steps. The information needed in order to perform the test is gathered in advance, so that the minimum time is spent on site.

The first stage is completed before the test performance and comprises data of the technicians and the owner, responsible university, location, and year of construction of the dwelling (Figure 4). A code is automatically generated for each case, which allows personal data protection and the identification of each case. Dimensions are also gathered at this stage whenever graphical documentation of the dwelling is available. Otherwise, simple floor plans are sketched on site in order to obtain the required information. Dimensions such as floor area (A_F), volume (V), envelope area (A_E), or shape factor (Sf) are automatically calculated from partial dimensions. In order to guarantee suitable meteorological conditions limited by EN 13829 standard [45], weather forecast at the expected date, and time of the test is also introduced. If the wind speed exceeds 6 m/s, "infil-APP" does not allow one to continue to further steps and the test needs to be postponed.

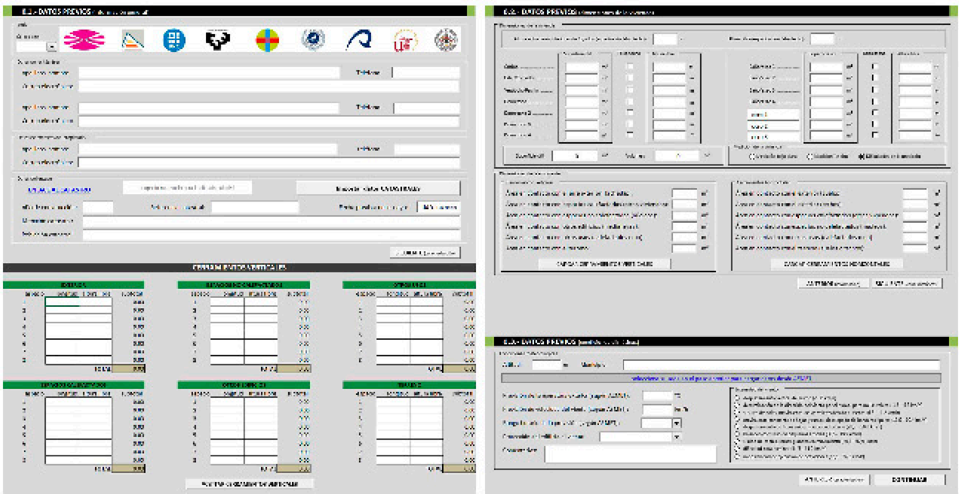


Figure 4. Screenshots of "infil-APP". Previous Data.

The second stage is the characterization of the case (Figure 5). It is done during the visit to the dwelling. Pictures of the exterior, each room, windows, systems, special features, and cracks or other pathologies detected are taken. General information about the dwelling, construction systems, and conditioning and ventilation systems are saved in "infil-APP".

A catalogue of preset typical construction solutions in Spain has been developed (Figure 6), paying attention to singular elements such as shutters. Nevertheless, customized solutions are also possible to introduce. The retrofitting state of each case has been considered in detail due to its decisive relevance.

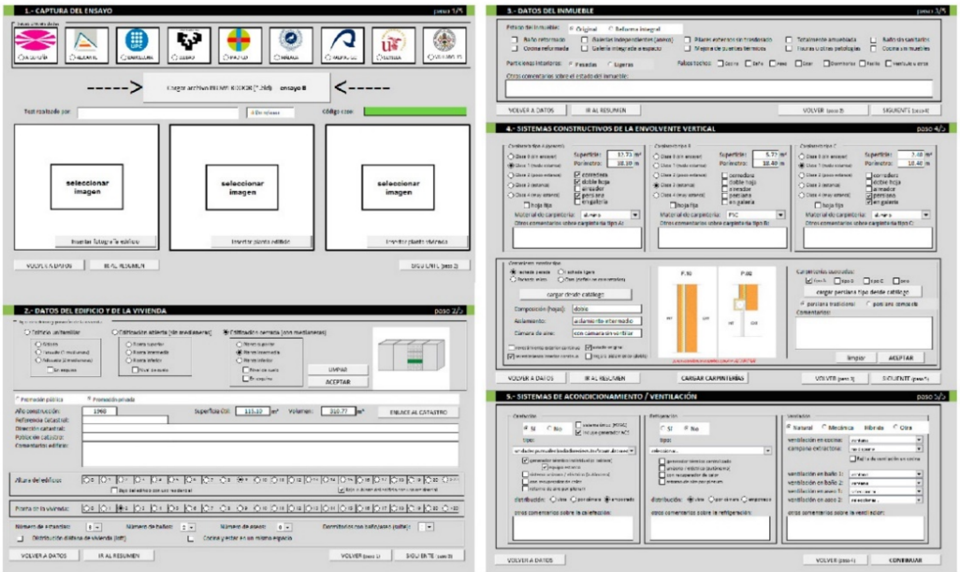


Figure 5. Screenshots of "infil-APP". Characterization of the case.

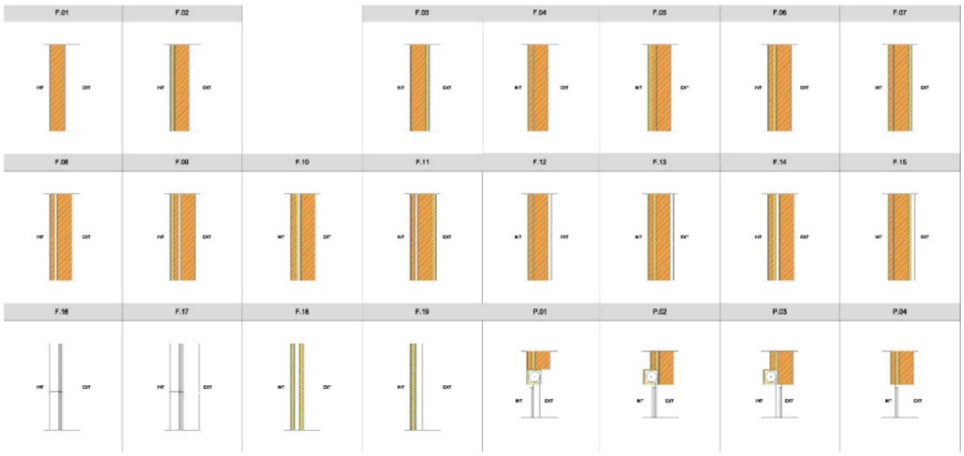


Figure 6. Catalog of preset typical façade and rolling shutters in Spain.

Once the pressurization test is performed, tests results are imported into "infil-APP", together with environmental conditions details during the test (Figure 7). As soon as the case is completed, it is automatically uploaded to the cloud server, ready to be reviewed by the coordinating university (VLL) and geolocated in an interactive map. A full report and a test certificate are automatically obtained.

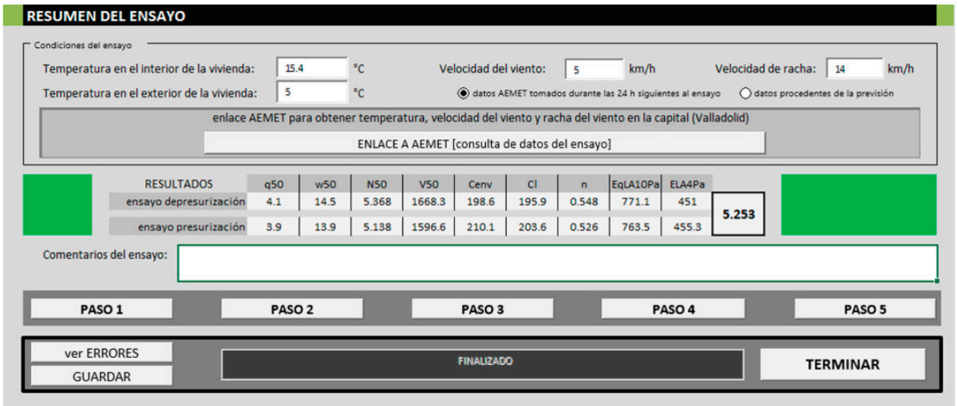


Figure 7. Screenshots of "infil-APP". Results and environmental conditions.

Table 6. Parameters that the tool "infil-APP" retains.

1. PREVIOUS DATA		
General information		
Participating University	Name, phone and email address of technician 1	Name, phone and email address of technician 2
Name, phone and email address of the owner	Year of construction	Cadastral reference
Bar code	Full address of the case	Planned test date
Dimensions of the dwelling		
Global ceiling height	Floor area and ceiling height of each room	Presence of false ceilings
A_F (m^2), automatically calculated	V (m^3), automatically calculated	Vertical A_E by adjacent space (exterior, heated space, unheated space, other building, other use, ground)
Horizontal A_E by adjacent space (exterior, heated space, unheated space, other use, ground)	A_E (m^2), automatically calculated	Sf (h^{-1}), automatically calculated
Expected weather conditions during the test		
Altitude	Temperature	Wind speed
Wind speed according to Beaufort scale	Wind exposure	Time
2. CHARACTERIZATION DATA		
Graphic information		
Floor plan	Exterior image of the building	Thermographic image

Table 6. *Cont.*

General information about the dwelling		
Typology and its position with respect to adjacent houses or apartments	Property developer	Height of the building
Use of the basement	Use under the roof	Height of the dwelling
Number of rooms	Number of bathrooms	Layout of the floor plan
Dwelling state		
Retrofitting state	Refurbishment of the kitchen	Refurbishment of bathrooms
Presence of closed balconies	Extension of the heated volume	Furbishing
Detected cracks or other pathologies	Detected thermal bridges	Improvement of thermal bridges
Construction systems		
Class of the windows	Area of the windows	Windows joint length
Windows opening system	Presence of double window	Windows material
Presence of shutters	Type of shutters	Position of the shutter
Type of façade	Presence of outer cladding	State of the façade
Conditioning and ventilation systems		
Type of heating system	Individual/whole building heat generation	Heating system distribution
Type of refrigerating system	Individual/whole building refrigeration	Refrigerating system distribution
Type of ventilation	Ventilation of the kitchen	Kitchen hood extraction
Presence of ventilation grids	Ventilation in bathrooms	Others
Environmental conditions during the test		
Indoor temperature	Outdoor temperature	Mean and Gust wind speed
3. BLOWER DOOR TEST RESULTS		

The development of the protocol and the software described allow the performance of standardized tests and data systematization that enables results interpretation. Its extended use would allow the construction of a single national database developed by multiple agents. Besides, its basis is replicable in other scenarios, such as other areas with a lack of knowledge on this field, or countries that do not count on a standardized database.

2.2.3. Test Campaigns

A total of nine universities (Figure 1) participated in the characterization and testing of the required cases. To this end, testing campaigns have been organized throughout 2016 and 2017, taking into account the number of cases assigned to each site and paying special attention to the expected climatic conditions, given that the EN 13829 standard [45] determines limitations with respect to the wind during the test. Each site consisted of a coordinator and one or two teams of technicians, with a total of 11 teams to cover the field work. These teams were trained before the campaigns to ensure proper compliance with the developed protocol. A common cloud server was created to allow constant data transfer and supervision from the coordinating University (VLL).

In order to obtain access to the dwellings required in the sampling, dissemination campaigns and search for volunteers through leaflets, posters and advertisements on the websites of participating universities and social networks were designed. Agreements with public administrations were established, which allowed access to a number of cases for the study.

3. Case Study

A case study is presented in order to show the implementation of the designed methodology. An apartment located in the city centre of Valladolid (Figure 8) has been chosen due to its representativeness of the residential building stock in Spain (case 09683460651630036). The climate of Valladolid belongs to the "Continental" area of the country and it is classified by CTE as D2 area.

Figure 8. Exterior image of the case study 09683460651630036.

The building was constructed in 1968, before regulations in Spain considering energy losses were implemented. The building consists of 9 floors and an attic. The apartment is on the ninth floor and has a south orientation in its main façade to Padilla Street and a secondary façade to a wide internal courtyard with east orientation (Figure 9). All the specifics are detailed in Table 7.

Table 7. Case study 09683460651630036 characteristics.

	Case study's code	09683460651630036	
Building information	**Location**	Valladolid	
	Climatic zone	Continental (D2)	
	Year of construction	1968	
	Typology of the building	Closed block, multi-family housing	
	Height	9th floor	
Construction system	**Refurbishment state**	Original. Minor refurbishment in kitchen and bathroom.	
	Type of construction	On site	
	Structure	Reinforced concrete	
	Envelope material	Exposed brick/hollow brick and mortar	
	Partition walls	Hollow brick	
	Type of windows	Wooden casement window	
	Type of shutters	Built-in rolling shutters	
Systems	**Heating system**	Central heating radiators	
	Refrigeration system	None	
	Ventilation	natural	
Dimensions	**Floor area (A_F)**	58.81 m^2	
	Volume (V)	152.4 m^3	
	Surface area (A_E)	231.89 m^2	61% heated spaces 16% exterior 13.75% non-heated spaces 9.25% other buildings
	Sf	1.52 m^{-1}	
	Glazing area/A_E	4.2%	

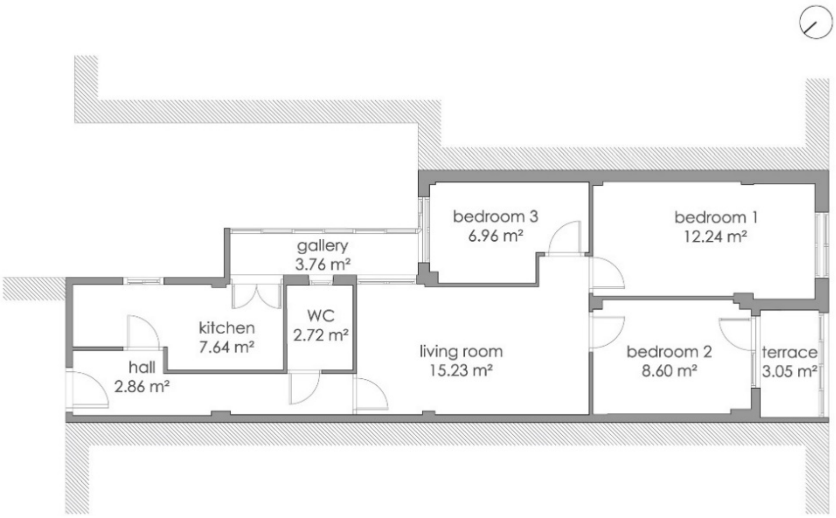
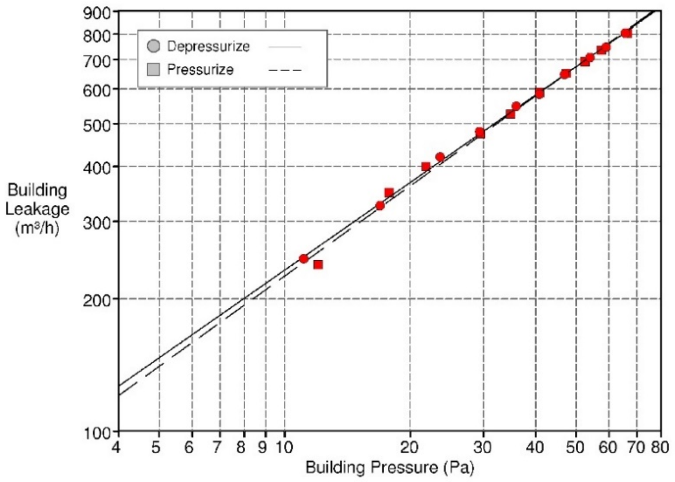


Figure 9. Floor plan of the dwelling.

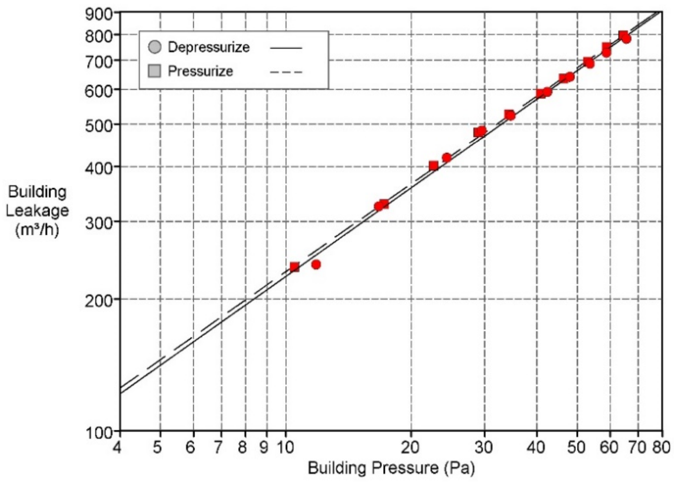
3.1. Results and Discussion

In order to measure the airtightness of the dwelling, blower door tests are carried out with an automated performance testing system and following the project protocols (Figure 10). Tests were carried out in February 2017 with the environmental conditions described in Table 8. Test results are detailed in Table 9.



(a)

Figure 10. *Cont.*



(**b**)

Figure 10. Automated test graph. (**a**) graph for Method A; (**b**) graph for Method B.

Table 8. Meteorological conditions during the test.

Test Method	T_i (°C)	T_o (°C)	ΔT (°C)	W_a (m/s)	W_g (m/s)	W_{max} (m/s)
A	20.1	7	14.1	0.55	2.5	3
B	20	11.2	8.8	0.55	2.5	3

T_i (°C): indoor air temperature. T_o (°C): outdoor air temperature. ΔT (°C): indoor/outdoor air temperature difference. W_a (m/s): average wind speed. W_g (m/s): gust wind speed. W_{max} (m/s): maximum wind speed allowed.

The overall uncertainty in the parameters obtained with the test using standard equipment remains below 15% in most cases [4,35,45] under calm conditions.

The mean air change rate of the dwelling for Method B at 50 Pa (n_{50}) is 4.38 h^{-1} and the mean air permeability rate at 50 Pa (q_{50}) is 2.9 $m^3/m^2 \cdot h$.

The exponent n has a typical value close to 0.67. Consequently, the flow is neither fully turbulent nor dominated by laminar characteristics and the shape of leakage paths cannot be clearly defined.

Table 9. Test results for Methods A and B.

Test Method	Test Mode	n_{50} (h^{-1})	V_{50} (m^3/h)	q_{50} ($m^3/m^2 \cdot h$)	W_{50} ($m^3/m^2 \cdot h$)	n	EqLA (10 Pa) (cm^2)	ELA (4 Pa) (cm^2)
A	depressurization	4.422	674	2.9	11.5	0.661	259.5	136.8
	pressurization	4.428	674.8	2.9	11.5	0.681	251.2	130
B	depressurization	4.345	662.1	2.9	11.3	0.67	251.1	131.2
	pressurization	4.41	672	2.9	11.4	0.664	257.5	135.3

There is barely any difference between the results obtained for Methods A (test of the building in use) and B (test of the building envelope). This can be explained because there are no mechanical supply or exhaust systems nor adjustable openings. There is only one natural ventilation grid in the kitchen, which was left open for the purposes of Method A and sealed for Method B.

3.2. Comparison of the Results

The case study results are compared to preliminary results of 343 buildings tested in the database (Table 10). Building airtightness is expressed by either the air change rate (n_{50}) or the air permeability rate (q_{50}).

As a preliminary analysis of the results, the control variables used to design the sample were studied: climate zone, year of construction, and typology. Figure 11 represents graphically the comparison between the case study results and the database results for Method B concerning dwellings from the same climate zone (Continental), built within the same period (1960–1979) and dwellings with the same typology (multi-family housing).

Although there is a wide spread of the values obtained from the database, the mean values according to the chosen parameters do not differ in a meaningful way. It seems clear the fact that significantly better results have been obtained for the case study dwelling than the general trend of the database.

According to ISO 13790 [14] the case-study dwelling has a "medium airtightness level", having a value within the range of 2–5 h^{-1}. However, the mean n_{50} value for multifamily dwellings of the database is 7.26 h^{-1}, which, according to ISO 13790 [14], corresponds to a "low airtightness level".

Table 10. Comparison of results of the case study and the database.

Chosen Cases	Database Cases					Case Study	
	n	Mean n_{50} (h^{-1})	St. dev.	Mean q_{50} ($m^3/m^2{\cdot}h$)	St. dev.	n_{50} (h^{-1})	q_{50} ($m^3/m^2{\cdot}h$)
Complete database	334	7.12	3.29	5.63	2.72	4.38	2.9
Dwellings in the Continental area	127	6.77	3.18	5.50	2.76		
Dwellings built 1960–1979	121	7.18	3.23	5.54	2.63		
Multi-family dwellings	267	7.26	3.28	5.44	2.42		

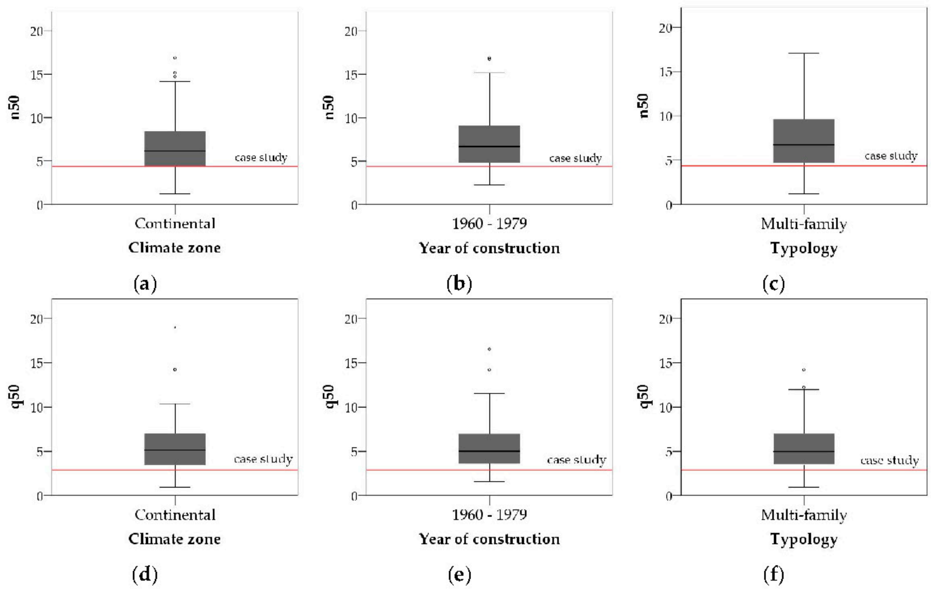
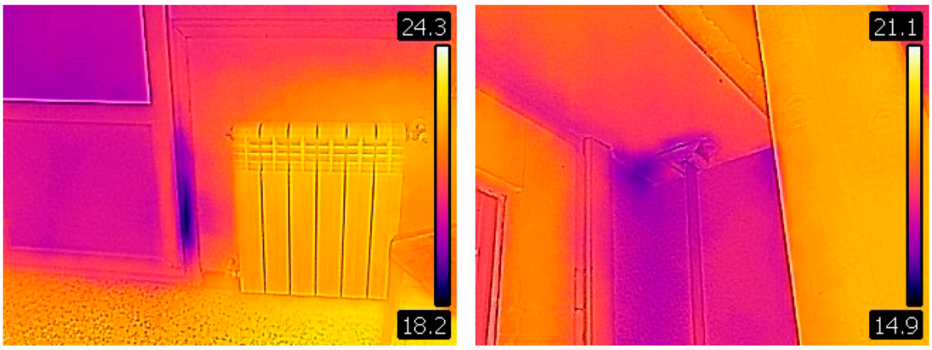


Figure 11. Boxplot of database results compared to the case study results, indicated by the red line. (**a**) n_{50} for Continental climate zone; (**b**) n_{50} for dwellings built within the period 1960–1979; (**c**) n_{50} for multi-family dwellings; (**d**) q_{50} for Continental climate zone; (**e**) q_{50} for dwellings built within the period 1960–1979; (**f**) q_{50} for multi-family dwellings.

When compared to regulations in other European countries, the case study dwelling would comply with UK ($q_{50} < 10\ m^3/m^2{\cdot}h$) and Ireland ($q_{50} < 7\ m^3/m^2{\cdot}h$) or Czech Republic ($n_{50} < 4.5\ h^{-1}$) regulations but not with German regulations nor Polish recommendations ($n_{50} < 3\ h^{-1}$) for new buildings [49]. The comparison with French regulations has not been made since its indicator is measured at 4 Pa and a direct translation of the results would not be accurate.

3.3. Leakages Location

To determine infiltration locations and distribution, thermal imaging was undertaken during the depressurization stage. Since there was a great temperature difference between the inside and the outside of the dwelling leakage points were easily visualized. Most leakages were located in window frames and shutter boxes (Figure 12).



(**a**) (**b**)

Figure 12. Leakage paths detected with thermography. (**a**) Leakage path located in a door frame; (**b**) Leakage path located in the tape guide of the rolling shutter.

4. Conclusions

A methodology has been developed to investigate the airtightness of the architectural envelope of the existing residential stock in Spain through an experimental study carried out throughout the Spanish geography. Considering a proportional quota sampling scheme, a representative number of 411 cases has been selected. In this way it is possible to extrapolate the results to other Spanish residential buildings. The sample includes different typologies, construction years, and climatic zones. The study will allow the creation of an extensive database and the identification of the factors that have a greater impact on airtightness and the infiltration rates of typical constructive solutions. The methodology has been conceived in such a way that it can be applied to other countries where there is no data regarding the airtightness of the envelope in residential buildings.

A case study in Valladolid has been presented in order to show an example of the implementation of the methodology. Airtightness results are compared to mean values obtained from the database, considering the control variables used to design the sample: climate zone, year of construction, and typology. Results obtained indicate that the dwelling has a medium airtightness level, significantly higher than the mean values obtained from the database. Leakages at the case study were located mainly around window joints and frames and shutter boxes.

Further work will include a deep analysis of the complete dataset obtained during the test campaigns in order to establish infiltration rates for typical Spanish constructive solutions, the impact of different parameters on the envelope permeability, and the impact of infiltrations on the ventilation and energy performance of dwellings.

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Author Contributions: Feijó-Muñoz Jesús directed the study; Padilla-Marcos Miguel Ángel and Meiss Alberto conceived and designed the experiments; Poza-Casado Irene designed the sampling method; González-Lezcano Roberto Alonso, Pardal Cristina, Echarri Víctor, Assiego de Larriva Rafael, Fernández-Agüera Jesica, Dios-Viéitez María Jesús, del Campo-Díaz Víctor José and Montesdeoca Calderín Manuel coordinated the field test campaigns from each university; Padilla-Marcos Miguel Ángel developed the tool "infil-APP".

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4.2 AIRTIGHTNESS OF RESIDENTIAL BUILDINGS IN THE CONTINENTAL AREA OF SPAIN

Feijó-Muñoz, J., González-Lezcano, R. A., Poza-Casado, I., Padilla-Marcos, M. Á., & Meiss, A.

4.2.1 Abstract

Infiltration plays a relevant role regarding the energy performance of buildings. Many European countries have already established standards which aim to limit the energy waste through the envelope following the European Energy Performance of Buildings Directive guidelines. However, in Mediterranean countries there is still a lack of knowledge in this field. An extensive study has been carried out in order to characterize the air leakage through the envelope of the existing housing stock in the Continental climate area of Spain. Results of 129 dwellings tested, including different typologies and periods of construction, are shown. Blower door tests were performed, and thermal imaging was used to locate leakage paths. Single-family dwellings were found to be more airtight than apartments, given that the mean air permeability rate at 50 Pa (q_{50}) was 5.4 $m^3/(h\, m^2)$ and 6.8 $m^3/(h\, m^2)$ respectively. The mean air change rate at 50 Pa (n_{50}) was 6.1 h^{-1} for single-family dwellings and 7.1 h^{-1} for multi-family housing. Nevertheless, great dispersion of results and extreme values were found. In addition, the influence of several construction characteristics on permeability results was assessed.

Keywords: infiltrations; airtightness; blower door test; residential buildings; database

4.2.2 Reference

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4.2.3 Contribution of the doctoral candidate

Design of the sampling and collaboration in the development of the protocol, supervision of the tests of the presented cases, analysis of the results, as well as the writing of the manuscript.

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Airtightness of residential buildings in the Continental area of Spain

Jesús Feijó-Muñoz[a], Roberto Alonso González-Lezcano[b], Irene Poza-Casado[a,*], Miguel Ángel Padilla-Marcos[a], Alberto Meiss[a]

[a] RG Architecture & Energy, Universidad de Valladolid, Ventilation Laboratory, Avda/ Salamanca, 18, 47014, Valladolid, Spain
[b] Department of Architecture and Design, Universidad CEU San Pablo, Escuela Politécnica Superior, Universidad CEU San Pablo, Urb. Montepríncipe, Ctra. de Boadilla del Monte Km 5.300, 28925, Alcorcón, Madrid, Spain

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ABSTRACT

Infiltration plays a relevant role regarding the energy performance of buildings. Many European countries have already established standards which aim to limit the energy waste through the envelope following the European Energy Performance of Buildings Directive guidelines. However, in Mediterranean countries there is still a lack of knowledge in this field. An extensive study has been carried out in order to characterize the air leakage through the envelope of the existing housing stock in the Continental climate area of Spain. Results of 129 dwellings tested, including different typologies and periods of construction, are shown. Blower door tests were performed, and thermal imaging was used to locate leakage paths. Single-family dwellings were found to be more airtight than apartments, given that the mean air permeability rate at 50 Pa (q_{50}) was 5.4 $m^3/h{\cdot}m^2$ and 6.8 $m^3/h{\cdot}m^2$ respectively. The mean air change rate at 50 Pa (n_{50}) was 6.1 h^{-1} for single-family dwellings and 7.1 h^{-1} for multi-family housing. Nevertheless, great dispersion of results and extreme values were found. In addition, the influence of several construction characteristics on permeability results was assessed.

1. Introduction

Building energy demand has become one of the most important concerns in the construction sector. The European Energy Performance of Buildings Directive (EPBD) is committed to achieve a highly efficient and decarbonised building stock, considering that almost 50% of the final energy consumption is used for heating and cooling, of which 80% is used in buildings [1].

Since infiltrations play an important role regarding the energy consumption of dwellings, many European countries have already established standards which aim to limit the energy consumption through the envelope. In Europe, minimum requirements on airtightness have been imposed in Czech Republic, Estonia, France, Germany, Ireland and UK, either in the context of the energy performance regulations or specific programmes. Systematic justification is only required in France, Ireland and UK [2].

However, in Mediterranean countries with mild climates and the tradition of natural ventilation by opening windows, air infiltration has complemented the natural air supply. Regulations still do not consider limitations regarding the airtightness of the envelope. In Spain specifically, since 2006 the Spanish Building Code (CTE) [3] stablishes the implementation of controlled ventilation systems in new and refurbished buildings to ensure adequate indoor quality. Equivalent leakage area can be considered as part of the effective area of the ventilation openings, but airtightness testing is very rarely performed to justify this considered area. Therefore, these ventilation systems are generally oversized since the envelope is presumed to be airtight.

Several studies regarding this matter have been carried out so far in dwellings across Europe, but they tend to focus on a particular aspect and therefore the data collected belong to a specific sample and are not representative of the current building stock [4]. Air leakage measurements are commonly performed in order to evaluate building design and construction practices. Countries like UK, Germany, Belgium, Czech Republic, Estonia and France have created a database [2] in order to have a record of the evaluated cases. Required reporting of the data must be enforced to support data analysis [4]. Average leakage rates (n_{50}) in Europe have been found to be around 7.5 [5]. As for other previous studies carried out in other Mediterranean countries [6,7], results have shown values around 7.0.

An experimental study carried out in Spain has been addressed [8]. This way, a national air leakage database which can set the basis to establish a series of real data and parameters for energy and ventilation

* Corresponding author.
E-mail addresses: feijo@arq.uva.es (J. Feijó-Muñoz), rgonzalezcano@ceu.es (R.A. González-Lezcano), irene.poza@uva.es (I. Poza-Casado), miguelangel.padilla@uva.es (M.Á. Padilla-Marcos), meiss@arq.uva.es (A. Meiss).

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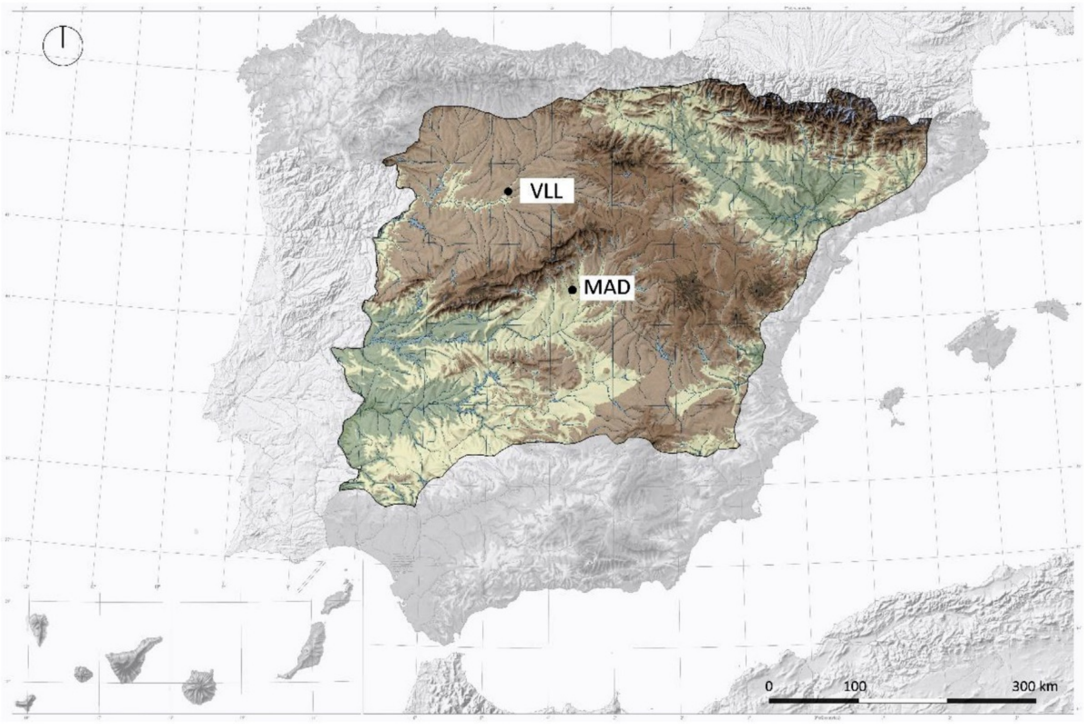

Fig. 1. Location of the tested dwellings in the Continental climate area of Spain [11].

calculations can be originated. A common protocol has been developed with the aim of performing the tests following the same guidelines and gathering a complete set of characterization data [9].

This paper focuses on the characterization of the residential building stock in the Continental area. Despite the fact that no evidence was found to justify that climate is a significant variable in terms of airtightness [10], it seems clear that there are different aspects associated to the region where the building is located such as differences in construction quality, dwelling design or materials, or due to differences in building size or age (status).

1.1. Climate conditions

There is a wide variety of climates in Spain. The country was divided into four main different climate areas: Continental, Oceanic, Mediterranean and Canary Islands. For the purposes of this paper, the study focused on the Continental region. The dwellings tested were located in two different cities in the hinterland of the country: Madrid (MAD) and Valladolid (VLL), that lie on the southern and north plateaus respectively (Fig. 1). Both cities were selected in order to provide representative examples of the Continental climate zone building stock.

In order to identify the climate of the areas analysed, the Köppen Climate Classification system was applied [12]. Both cities are classified as temperate climates-Type C, with a continental influenced climate. Madrid has a *Csa* climate (temperate with dry or hot summer), which covers most of the Iberian Peninsula and the Balearics, occupying approximately 40% of its surface. On the other hand, Valladolid has a *Csb* climate (temperate with dry or temperate summer), which covers the majority of the northeast of the Peninsula. In both cities rainfall is scarce during the summer. In terms of temperatures, perhaps the most important fact is the significant daily thermal oscillation, since thermal differences between day and night often exceed 20 °C.

1.2. The constitution of the building envelope

The housing stock in the Continental area of Spain is dominated by dwellings built over the past century, whose construction followed a common trend throughout the country conditioned by socioeconomic circumstances during this period. A progressive generalization of formal and constructive solutions, which were repeated frequently, can be found, both in Madrid, Valladolid, as well as in other cities of the continental climate area.

The prominence of the exposed brick in the architecture of the 20th century in this area can be highlighted [13]. Only after the 60's hollow brick is employed when exterior mortar plaster is applied.

Broadly speaking, façade systems evolved with the industrialization of metal structures and, above all, with the massive introduction of reinforced concrete in construction from the 40's [14]. The wall as a bearing system was abandoned giving way to the use of grid structures. This allowed the façade to have only function as enclosure and thus it could be thinner and lighter [13].

However, this evolution was gradual and, during the first years of the 20th century, the use of mixed solutions with internal framework and massive load-bearing walls [15] with one layer up to two feet thick was still common. The first examples of cavity walls in Madrid were originated as a result of the desire to hide the line of pillars on the façade. Thus, very wide air chambers were generated, conditioned by the section of the pillars. The use of this resource was a contradiction, since the enclosure, which did not have a structural function any more, gained in thickness [15].

Openings were commonly wooden swing windows with monolithic glass. When the metalwork window appeared, they came to be used in the main façade, placing the wooden windows in the courtyards facades [16].

After the Spanish Civil War (1933–1936), numerous cities received a growing migratory flow from the countryside [17]. There was an important demand for housing that private developers could not cope with, largely due to the period of autarchy that the country was going through and the important restrictions on steel, cement and the transport of materials to construction sites [18]. The State became the main housing developer [17], which favoured traditional constructive techniques. Quick, simple and repetitive solutions were employed [15]. The most widespread façade solution during the 40's was exposed brick of different thickness ranging from a foot and a half to half a foot [18]. In most cases the façade worked as load bearing wall with an internal reinforced concrete structure.

The regulations applied to public housing construction had a decisive influence. From 1940 onwards, the hygrothermal behaviour of the enclosure was contemplated, establishing minimum quality requirements [15].

In large cities like Madrid, the construction of low-cost housing in satellite neighbourhoods was frequently carried out with load-bearing walls perpendicular to the façade. On the other hand, high-class housing recovered the technical development started in the 30's with reticulated reinforced concrete structures, making use of insulating materials of cork on several occasions. Nevertheless, thick wall cavities for regularization of the wall and concealment of pillars were still employed [15].

In Valladolid, the State intervention in the field of housing was very early and ambitious. There were some municipal public housing construction interventions in the 40s, although the state did not act until a decade later when its first project was approved in 1951 [17].

During the period 1956–1961 the largest number of public housing was built in Spain (Fig. 2). These complexes prevailed in this first stage [17]. These were unitary operations with similar typological and constructive characteristics throughout Spain with slight adaptations to different climates [20], although there innumerable deficiencies affecting most of the public constructions can be found [21].

The construction of these neighbourhoods was based on solutions of maximum simplicity, although attention was payed to health standards and environmental comfort issues [15]. A new Standard in 1954 forced the use of the cavity walls, regulating the double layer system with national scope [15]. From this moment, it can be said that the façade abandoned its structural function, reducing its thickness [18]. The single foot brick wall was used especially as an outer layer, cladded with a simple hollow layer and, sometimes, insulating material in the cavity between them [14]. The appearance of new insulating materials offered by the industry (foams and glass fibres, wood sawdust, cellular glass …) allowed the cavity wall system to be economically competitive. Aluminium sliding windows with monolithic glass were also introduced [16].

In Madrid, however, the resistant role of the enclosure prevailed, with a single thick massive wall of a foot in the construction of low-rise social housing. In taller buildings, two layers with cavity were combined [15].

Around 1955 and 1960 a singular type of façade became very popular, fitting the enclosure between the slabs and beams of the main structure, reducing its thickness to the maximum. They assumed the function of pure enclosure of the exterior walls, with insulating material in most cases [15]. This solution was extended in Spain until the 80's [13,14]. In Valladolid, this system was usually employed with a single layer and it was not until the 60's that the cavity walls were introduced.

In the following decades there was a gradual entry of private development and the State initiative ended up assuming a mere subsidiary function from 1963 [17].

In the 70's, electromechanical conditioning systems were generalized. Façades were definitively lightened, already mostly cavity walls, executing the external layer with half a foot in an almost exclusive way [14], even replacing the perforated brick with the cheapest alternative: a half foot hollow brick wall covered and painted [16].

With the entry into force of the Standard NBE-CT-79 [22], thermal insulating were placed into the air chambers, already in a generalized way [16]. The enclosure was finally continuous, setting back the line of pillars towards the interior.

From 2006, new dwellings have to comply with CTE Regulations [23], paying special attention to its performance concerning energy saving and protection against noise. Although construction techniques have evolved, it can be said that conventional solutions still prevail: massive brick construction with air chamber and intermediate insulation is still a widespread solution in this area. A catalogue of constructive elements [24] collects information on the characteristics and benefits of generic constructive solutions related to the basic requirements of the CTE.

In general, the main hygrothermal problem of the most used façade solutions in the Continental climate area of Spain throughout the century is the interruption of the external layer of the massive wall and the insulating material in the joint with the horizontal structure or the pillars. There were no movement joints between structural components and facades, which caused numerous cracks and fissures in the brick walls [16]. Thermal bridges and problems of interstitial condensation and water leaks appeared in the joints between brick and mortar and cracks [14].

Another problematic point of the façade solutions is rolling shutters. Traditionally, the protection and solar control function had been solved with rope or booklet blinds [25]. It is from the decade of the 50's when the use of the rolling shutters in the inner sheet of the enclosure, without insulation in most cases, was generalized. Only in the last decades has this solution been improved with integrated shutters in windows with insulation.

2. Methods

2.1. Fundamentals

Airtightness is usually expressed by means of a power law (Equation (1)) that measures the flow through the building envelope as a function of the pressure gradient across the building envelope:

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

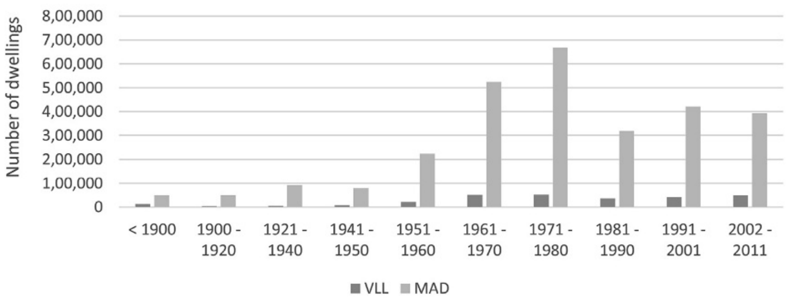

Fig. 2. Number of dwellings built in Madrid and Valladolid for decades [19].

Table 1
Parameters obtained from the power law.

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_F	$m^3/h{\cdot}m^2$
q_{50}	air permeability rate at 50 Pa	V_{50}/A_E	$m^3/h{\cdot}m^2$

where:

V_{env}: air flow rate through the envelope of the dwelling (m^3/h)
C_{env}: air flow coefficient, which is related to the size of the opening ($m^3/(h{\cdot}Pa^n)$)
Δp: induced pressure gradient (Pa)
n: pressure exponent

The parameters obtained from the power law, defined in the EN 13829 standard [26] that allow the comparison of results in different buildings are listed below (Table 1):

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.

Additionally, two parameters can be considered:

- EqLA (10 Pa): equivalent leakage area (cm^2)—National Research Council (NRC) of Canada Model. It is defined as the area of a sharp-edged orifice that would leak the same amount of air as the building does at a pressure of 10 Pa.
- ELA (4 Pa): effective leakage area (cm^2)—Lawrence Berkeley Laboratories Model (LBNL). It is defined as the area of a special nozzle-shaped hole that would leak the same amount of air as the building does at a pressure of 4 Pa.

2.2. Studied dwellings

A total of 129 dwellings located in Madrid and Valladolid (Fig. 3) were analysed in the Continental area of Spain. The cases were chosen according to a stratified sampling scheme [9] with the purpose of gathering a representative sample of the existing residential stock in this climatic area.

The sample reflects the fact that the stock is considerably larger in Madrid. Thus, a total of 112 dwellings (86.8% of the sample) were tested in Madrid and 17 (13.2%) in Valladolid. The sampling method took also into account the prevalence of multi-family housing. 111 cases (86%) were dwellings within blocks of apartments whereas only 18 (14%) were single-family houses. The relative position within the building was also considered for apartments: 15 cases (13.5%) were located in the lower floor, 74 cases (66.7%) had an intermediate position and 22 (19.8) were in the upper floor.

The sample chosen is also representative in terms of the age of the dwellings. Airtightness tests were conducted in dwellings built between 1880 and 2011. The periods of a major construction activity in the Continental climatic area during the decades 1960–1979 (48 cases, 37.2% of the sample) and the period 1980–2006 including the years of the real state bubble, just before its bursting in 2007 (59 cases, 45.7% of the sample), are represented in the sample with a prevalence of cases belonging to these periods.

All the dwellings had a massive construction system, prevailing brick as the main material used to build the opaque area of the envelope. Lightweight construction systems are very rarely used in this area. The construction system of the façade was classified according to its composition: number of massive layers, presence and position of the air chamber and insulation layer. It must be noted that there was not often availability concerning construction details or building specifications, so in most of the cases the construction system had to be deduced visually from the width of the wall and the year of construction. Table 2 shows the types of envelope found in this area and the number of cases associated to each one. Double massive wall prevails, with no insulation nor air chamber (F.03), with air chamber but no insulation (F.06) and with intermediate insulation and air chamber (F.08).

As for ventilation characteristics, the vast majority of the tested cases (98.4%) was ventilated in a natural way, by manually opening the windows, meaning that infiltration is the only constant source of air intake. Most kitchens are supplied with a hood (90.7% of the sample).

Given the extreme winter temperatures in the Continental area of Spain, all the tested dwellings were provided with some sort of heating system. Most of them were based on radiators or individual units (118 cases, 91.5% of the sample), although radiant panel systems (5 cases, 3.9%) or duct systems (6 cases, 4.7%) could also be found. The situation is different concerning cooling systems. Only 73 cases (56.6%) were refrigerated, 74% of them by individual units (ductless split air conditioners) and 26% by a central duct-based system.

2.3. Measurement methods

The prime building factor in determining infiltration and air leakage is airtightness [27], which was determined by the fan-pressurization method, according to EN 13829:2000 standard [26]. For single-family houses the test was performed within the deliberately conditioned space, excluding garages, warehouses, non-conditioned attic spaces or attached structures. The permeability of apartments in blocks was measured individually, considering that the measured air leakage can include possible flows through leaks to adjacent apartments or non-conditioned spaces. Equal pressures were not induced in adjacent zones. In any case, leakages must be considered not only from an energetic point of view but also considering that noise, pollutants and odours transmission can affect the comfort of the occupants and the lack of airtightness can compromise the fire safety of the dwelling.

Recent studies performed with and without guard-zone pressure have shown that inter-zone leakage can represent around 27% of the total leakage [28].

The dwellings were tested following two methods with different preparation of the building described in EN 13829:2000 standard [26]. Method A was performed to measure the air permeability of the building in use in its condition during the season in which heating or cooling systems are used, while Method B was performed to measure the permeability of the building envelope. All the intentional exterior openings were closed, the terminal devices of mechanical ventilation or air conditioning systems were sealed and the interconnecting doors in the part of the building to be tested were opened for the purposes of both tests. In addition, intentional openings were sealed for Method B.

An automated test was performed taking measurements of the air flow rate over a range of applied pressure differences of 11–65 Pa in increments of 6 Pa. Two sets of measurements for pressurization and depressurization tests were undertaken (Fig. 4). According to EN 13829:2000 standard [26] the overall uncertainty is highly dependent upon the environment during the test, being lower than 10% in most cases in calm conditions. Therefore, tests were avoided if the presence of wind was expected during the test in order to minimise uncertainty.

It is essential to know the main sources of infiltration to be able to propose effective constructive solutions to improve the airtightness of existing buildings. During the depressurization stage the main air leakage paths were identified using thermal imaging when there was sufficient temperature difference between the internal volume and the outside environment (Fig. 5). Tests were carried out mostly during the winter season (period November 2016 to March 2017 in Madrid and January to April 2016 in Valladolid). This way a large temperature

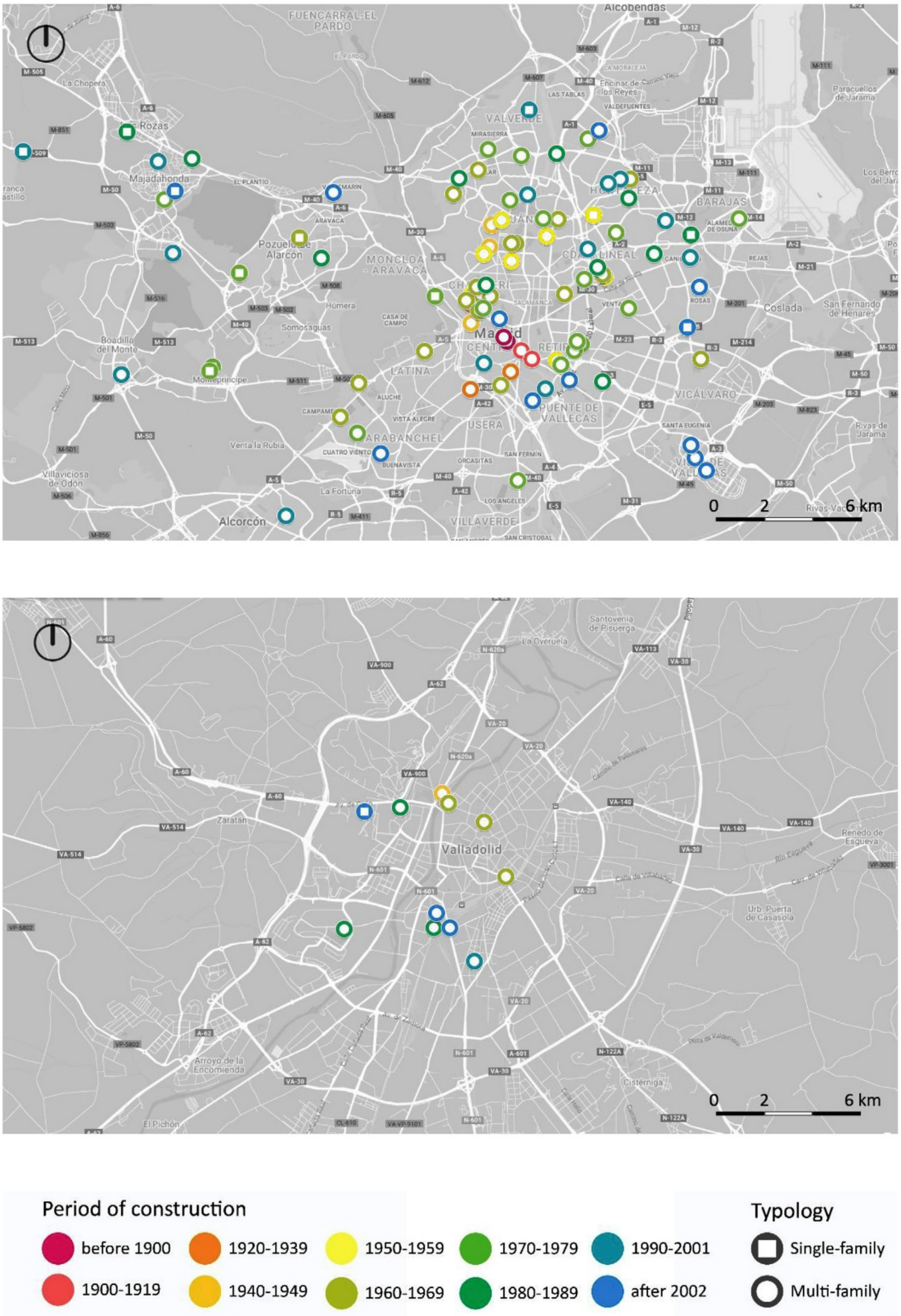

Fig. 3. Location of the tested dwellings in Madrid and Valladolid.

Table 2
Types of envelope of the tested cases.

Code	F.01	F.02	F.03	F.04	F.05	F.06	F.07	F.08	F.09	F.10
										
Layers (in-out)	IP-ML-(EC)	IP-IL-ML-(EC)	IP-ML-ML-(EC)	IP-IL-ML-ML-(EC)	IP-ML-IL-ML-(EC)	IP-ML-AC-ML-(EC)	IP-ML-IL-AC-ML-(EC)	IP- IL-ML- AC-ML-(EC)	IP- ML- AC-ML-IL- EC	IP- ML- ML- IL-VAC-EC
n	9	1	17	1	2	60	6	28	2	3
%	7	0.8	13.2	0.8	1.6	46.5	4.7	21.7	1.6	2.4

Where IP: interior plaster; ML: massive layer; EC: exterior cladding; IL: insulation layer; AC: air chamber; VAC: ventilated air chamber.

gradient was guaranteed, with a mean value of 19.9 °C for the indoor air temperature and 12.9 °C for the outdoor air.

The performed pressurization method does not allow to quantify specifically the contribution of each leakage point to the global air flow rate. Nevertheless, the exponent of the air flow n is a non-dimensional parameter that provides information relative to the resistance to the passage of air of the leakage paths. The theoretical limit of the n value is within the range 0.5–1 [29]. When the envelope is leaky n tends to approach 0.5 (fully turbulent flow), while in very airtight dwellings, the resistance offered by the facade is high and n approaches 1 (fully laminar flow). Normally, the air flow adopts a turbulent character in a variable intensity, taking an intermediate n value.

Apart from blower door test results, characterization information of each case was gathered by means of a specific tool developed for the purposes of the study: "infil-APP". Different parameters including basic information, dimensions, environmental conditions during the test, type of building, conservation state, construction technology or systems were stored in a tabulated way to facilitate a subsequent analysis of the data. Further details concerning the methodology followed can be found in Ref. [9].

3. Results

The results obtained for the 129 cases analysed are shown. Only data from the tests carried out following protocols for Method B are analysed, given that this method measures the permeability of the building envelope, discarding ventilation openings.

Firstly, the distribution of the dataset obtained for air permeability rate results (q_{50}) of the 129 cases studied was analysed by means of Lilliefors corrected Kolmogorov-Smirnov test [30] and graphically by means of a histogram and a Q-Q' plot (Fig. 6) using the extended statistics tool IBM SPSS Statistics [31]. The null hypothesis of normality H_0 was rejected, given the obtained *p-value* = 0.00 with a significance level applied for the analysis α = 0.05 (5%), which indicates non-normal distribution of the data. The obtained values for skewness and kurtosis were 1.7 and 4.8 respectively. Outliers were not excluded from the dataset, given that they were not considered as experimental errors, but as very leaky dwellings.

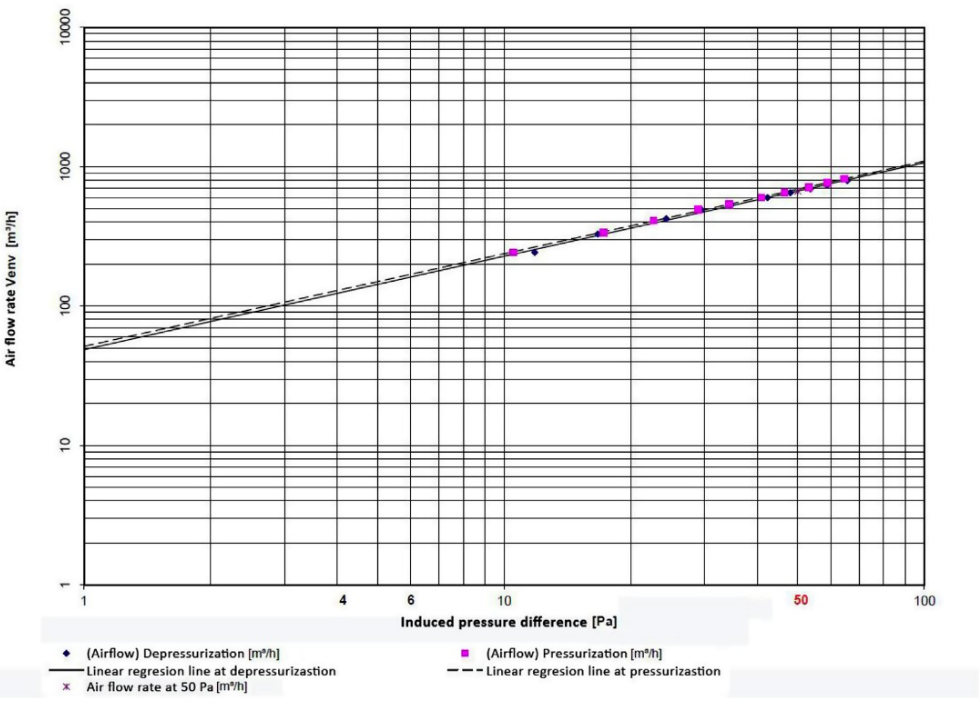

Fig. 4. Example of an automated test graphic.

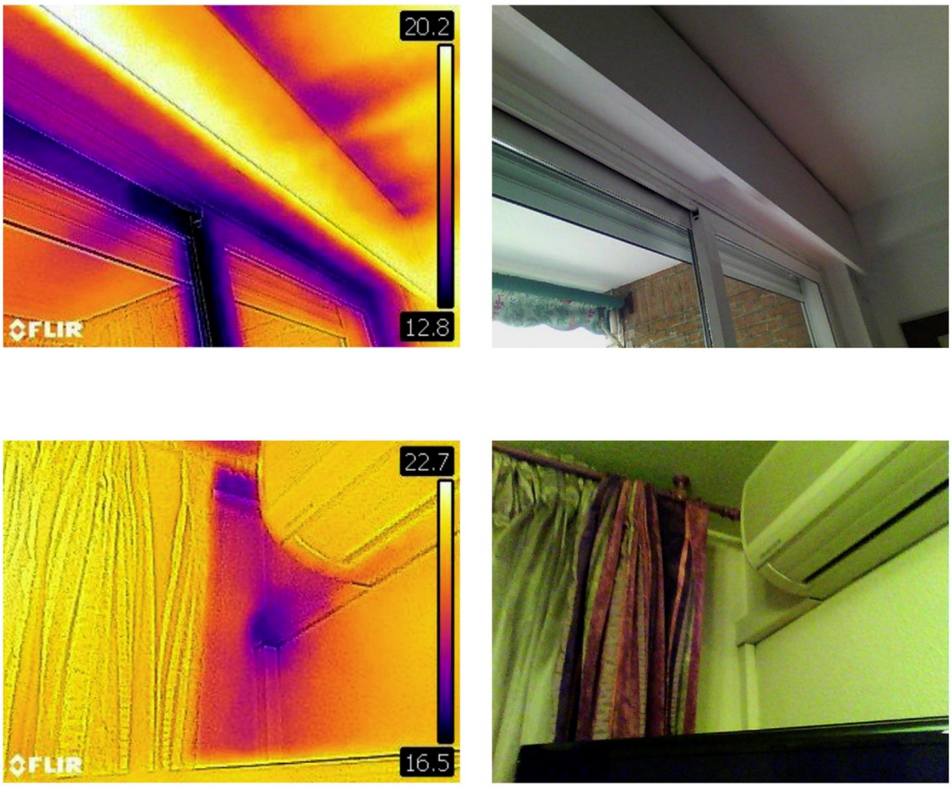

Fig. 5. Thermal images of typical air leakage paths in window, rolling shutter box and duct.

Detailed results of the most significant parameters obtained from the power law are shown in Table 3. Results have been considered separately for multi-family and single-family dwellings given that results obtained for dwellings placed within blocks of apartments include external leakages, internal leakages from other apartments and leakages from non-conditioned spaces such as the hallway, elevator or vestibule. The envelope of the apartments measured delimited 23.7% with the outdoors, 57.5% with other apartments, 12.2% with non-conditioned spaces, 4.9% with other buildings, 1.5% with other spaces and 0.2% with the ground.

The range of the permeability measurements (q_{50}) was large, ranging from 1 to 18.6 $m^3/h{\cdot}m^2$ for multi-family dwellings and from 1.6 to 19.0 $m^3/h{\cdot}m^2$ for single-family dwellings. Single-family dwellings were found to be more airtight than apartments, given that the mean air permeability rate at 50 Pa is 5.4 $m^3/h{\cdot}m^2$ and 6.8 $m^3/h{\cdot}m^2$ respectively.

Accordingly, the air change rate (n_{50}) was also lower for single-family houses (6.1 h^{-1}). The mean air change rate obtained for multi-family dwellings ($n_{50} = 7.1$ h^{-1}) was closer to the average leakage rates at 7.5 h^{-1} found in other case studies on dwellings in different European countries [5].

Leakage paths were identified by means of a thermographic camera. Typical leakage places were located mostly in window frames, rolling shutters, pipe and duct paths and construction joints. It is shown in many cases that the quality of carpentry is scarce and, above all, that the execution of construction joints has been careless.

The flow exponent *n* is related to the size of the opening. It can be

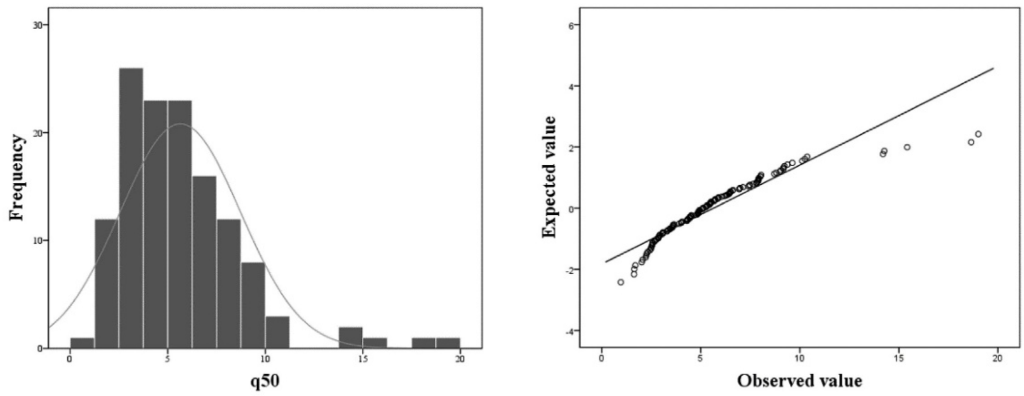

Fig. 6. Distribution of the dataset and Q-Q′ plot of the observed and expected values for air permeability results.

Table 3
Results obtained for the 129 cases analysed expressed by typology.

Parameter	mean		median		sd		minimum		maximum	
Cases	M	S	M	S	M	S	M	S	M	S
V_{50} (m^3/h)	1436.9	2966.0	1212.9	2458.6	891.0	2045.6	226.9	662.0	484.7	9099.3
n_{50} (h^{-1})	7.1	6.1	6.7	5.4	3.7	2.9	1.2	1.4	21.8	12.4
q_{50} ($m^3/h{\cdot}m^2$)	5.4	6.8	4.9	6.1	2.8	4.3	1.0	1.6	18.6	19.0
w_{50} ($m^3/h{\cdot}m^2$)	18.0	15.3	16.3	13.6	9.3	7.6	3.2	3.1	54.5	32.5
n	0.62	0.62	0.61	0.63	0.04	0.03	0.54	0.55	0.72	0.66
ELA 4 Pa (cm^2)	599.3	1239.3	510.4	1022.9	372.5	891.7	87.0	267.7	2117.2	4068.6
$EqLA$ 10 Pa (cm^2)	331.4	675.8	281.0	568.4	206.9	512.8	45.8	145.3	1195.9	2337.3

Where, M: multi-family housing (111 cases).
S: single-family housing (18 cases).
sd: standard deviation.

Table 4
Test results according to different parameters and Kruskal-Wallis test values.

Variable	Category	n	n_{50}	q_{50}	w_{50}	n	Chi-square	Sig.
Regulations	None	65	7.0	5.5	17.9	0.62	3.17	0.20
	NBE-CT-79	59	6.8	5.7	16.9	0.62		
	CTE	5	8.9	6.8	22.2	0.61		
Façace type	F.01	9	5.7	4.2	15.1	0.61	12.63	0.18
	F.02	1	3.2	2.5	8.4	0.66		
	F.03	17	7.77	6.0	19.9	0.62		
	F.04	1	5.3	4.1	13.4	0.63		
	F.05	2	10.5	8.0	25.4	0.60		
	F.06	60	6.9	5.6	17.3	0.62		
	F.07	6	7.4	6.5	18.7	0.62		
	F.08	28	6.9	5.8	17.1	0.62		
	F.09	2	4.3	3.3	11.0	0.66		
	F10	3	9.7	6.5	24.0	0.61		
Insulation layer	None	86	6.9	5.6	17.6	0.62	2.35	0.50
	Interior	8	6.6	5.7	16.7	0.63		
	Intermediate	31	7.2	5.9	17.8	0.61		
	Outer	4	7.2	5.0	17.7	0.63		
Air chamber	None	30	7.1	5.4	18.2	0.62	3.49	0.17
	Non-ventilated	91	6.8	5.6	17.0	0.62		
	Ventilated	8	8.6	6.55	21.6	0.59		
Outer coating	No	96	7.2	5.8	18.1	0.62	0.59	0.44
	Yes	33	6.4	5.1	16.2	0.61		
Window material	Steel	1	11.1	6.6	26.9	0.59	6.77	0.08
	Aluminium	86	7.4	6.0	18.5	0.6		
	Wood	7	7.7	6.4	20.4	0.63		
	PVC	35	5.8	4.6	14.5	0.62		
Rolling shutters	With	122	6.9	5.6	17.4	0.62	0.76	0.38
	Without	7	8.3	6.3	20.9	0.62		
Position within the building	Lower floor	15	8.0	6.3	20.5	0.61	2.48	0.29
	Intermediate position	74	6.7	5.1	16.8	0.62		
	Upper floor	22	8.0	6.2	20.1	0.62		

seen in Table 4 that the mean flow exponent found was 0.62 for both typologies. This value is slightly lower than the one commonly accepted as a reference value (n = 0.65) when the flow exponent is unknown, taken from a study with measurements from Canada, Netherlands, New Zealand, UK and USA [32]. This difference can be explained due to the different building systems employed in Mediterranean areas, where massive construction prevails, and handwork plays an important role. Flow exponent *n* tends to be higher in leakage openings with larger flow resistance than those found in the Mediterranean area [7]. Values around 0.6 are associated with leakage through the interfaces between openings and their opaque surrounds [33].

Furthermore, the influence of different parameters on the airtightness results was analysed (Table 4 and Fig. 7). Given the non-normal distribution of the sample, non-parametric tests were performed for that purpose. Kruskal-Wallis test [30] was performed in order to statistically verify the independence of the variables with the permeability values obtained (q_{50}). The test statistic *Chi-square* value (also known as *Kruskal-Wallis H*) expresses the differences between the compared groups and it is used to assess the null hypothesis that the medians are equal across the groups. On the other hand, the significance (Sig.) is the *p-value* based on the chi-square approximation. It is considered significant for values below 0.05, that is, with a 5% risk of concluding that a difference exists when there is no actual difference. However, the test did not allow to verify a statistically significant relationship between permeability results and any of the parameters assessed (*p-value* > 0.05).

The influence of constructions systems on airtightness was statistically addressed. Since there is a dependency relationship between the construction system and regulations applied, results were analysed according to three periods: 1800–1979 (no regulations regarding the energy performance of buildings were in force), 1980–2006 (after the entry into force of NBE-CT-79), after 2007 (with the obligatory compliance of CTE). It is remarkable that mean airtightness values do not improve with the entry into force of more recent regulations. The fact that none of them considers airtightness nor establish any limitation could explain that building systems and construction is done careless regarding this aspect.

Results for the different types of façade described in section 3.2 are also shown in Table 4. There is a wide spread of the results and differences between the categories, but it must be noticed that the sample size for some categories is scarce so as to draw further conclusions.

Permeability results regarding the insulation layer follow no clear trend. Dwellings without any insulation layer do not have necessarily a worse performance, whereas its position does not seem relevant given that the sample size is not representative for some categories.

The impact of the air chamber was also analysed. Cases with a ventilated chamber (only 8 samples) obtained the worse results. On the other hand, dwellings with a non-ventilated air chamber were found to be the most airtight.

Another relevant factor regarding the permeability of the envelope is the presence of an outer coating, usually mortar. As explained on section 3.2, there is a prominence of the exposed brick in the architecture of this area. However, dwellings with an outer coating performed better in terms of airtightness. It seems logical that a continuous coating can substantially reduce the presence of leakage paths.

Regarding windows, the impact of different materials was assessed. It must be taken into account, that the most representative material was considered when more than one type of window was found. Aluminium and PVC windows prevail in the sample, with better results obtained for PVC windows.

Rolling shutters play an important role on airtightness. However, results do not indicate that these elements constitute important leakage paths. This fact can be explained given that most of the dwellings without rolling shutters were the oldest ones and often in an original state. In Spain, it is a common practice that owners incorporate shutters when dwellings are retrofitted.

Finally, the position of the apartment for multi-family housing has

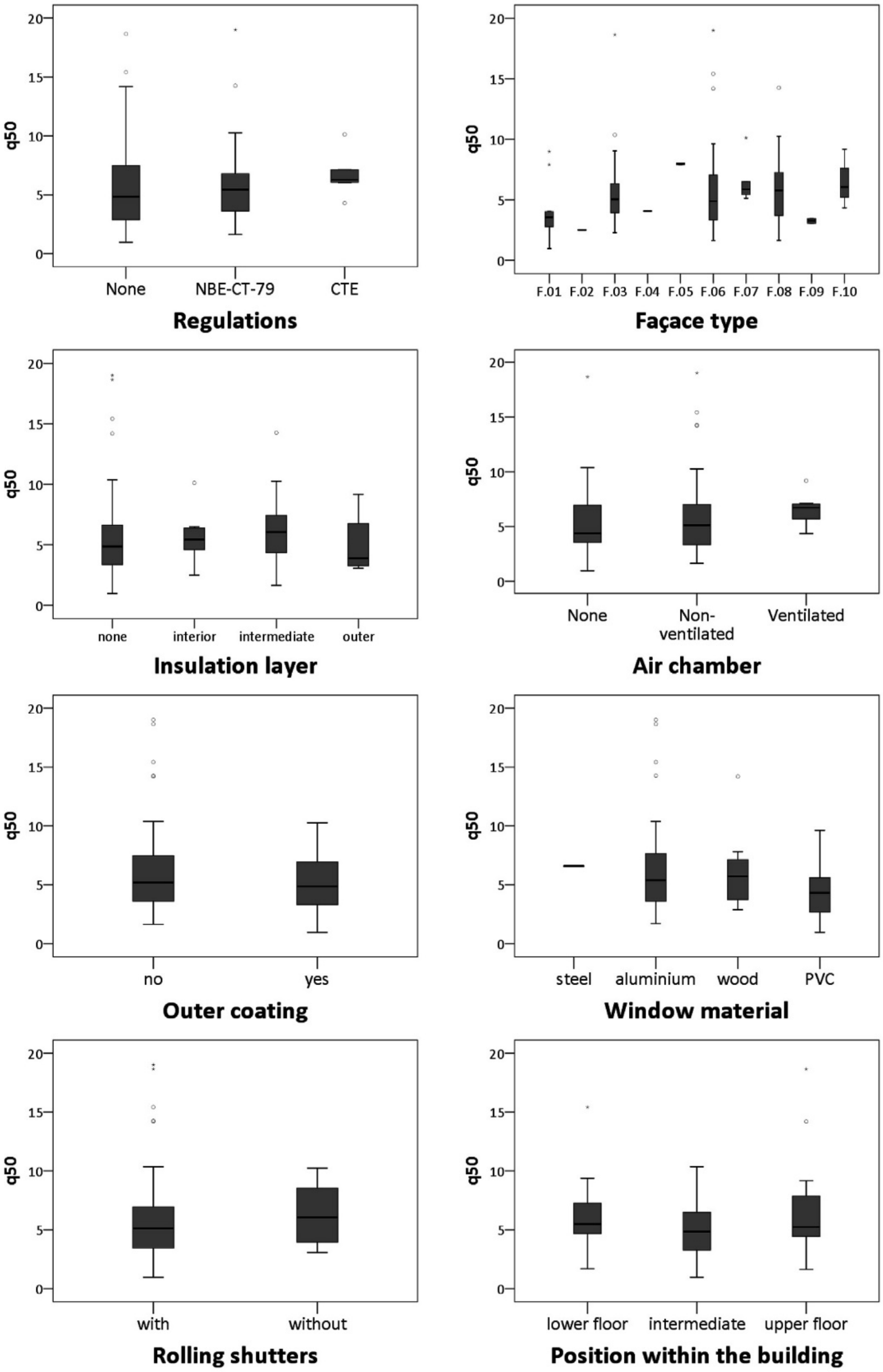

Fig. 7. Boxplots of permeability results of the tested dwellings.

been addressed. Although most of the dwellings where placed in an intermediate position, it seems clear that those are more airtight than the ones placed in an extreme position.

4. Conclusions

Airtightness tests on 129 dwellings in the Continental climate area of Spain were performed. The sample was chosen according to a stratified sampling scheme, which aimed to be representative of the existing residential building stock. Each case was tested by means of an automated blower door test and fully characterized for its inclusion in a new national airtightness database.

Leakage paths were identified with thermal imaging and were found mostly around windows, pipe and duct paths and construction joints. Rolling shutters, a widespread element in this area, constitute a discontinuity of the envelope and thus an especially relevant leakage path. A mean value of 0.62 was obtained for the flow exponent n, associated with leakage through the interfaces between openings and their opaque surrounds. These values are consistent with the ones found in precedent studies in other Mediterranean countries.

Permeability results show a wide spread of values, ranging from 1.0 to 18.6 $m^3/h{\cdot}m^2$ for multi-family-dwellings and from 1.6 to 19.0 $m^3/h{\cdot}m^2$ for single-family buildings. Results were considered differently for both typologies in order to differentiate the type of air infiltration source.

In addition, the influence of several construction characteristics on permeability results was assessed. General trends have been identified. Nevertheless, no statistically significant results could be obtained, in part due to the reduced sample size for some categories and also because of the difficulty of isolating the variables.

Further research includes a deeper analysis of the results regarding the parameters that have a major impact on the global result and its impact on ventilation and the energy performance of the dwelling.

Declarations of interest

None.

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4.3 ENERGY IMPACT OF THE AIR INFILTRATION IN RESIDENTIAL BUILDINGS IN THE MEDITERRANEAN AREA OF SPAIN AND THE CANARY ISLANDS

Feijó-Muñoz, J., Pardal, C., Echarri, V., Fernández-Agüera, J., Assiego de Larriva, R., Montesdeoca Calderín, M., Poza-Casado, I., Padilla-Marcos, M. Á., Meiss, A.

4.3.1 Abstract

Air infiltration through the building envelope has already been proven to have a significant energy impact in dwellings. Different studies have been carried out in Europe, but there is still a lack of knowledge in this field regarding mild climates. An experimental field study has been carried out in the Mediterranean climate area of Spain and the Canary Islands in order to assess the air permeability of the building envelope and its energy impact. A wide characterization and Blower Door tests have been performed in 225 cases in Alicante, Barcelona, Málaga, Sevilla and Las Palmas de Gran Canaria for this purpose. The obtained mean air permeability rate for the 225 studied cases was 6.56 $m^3/(h\,m^2)$. The influence of several variables on airtightness was statistically analysed, although only location, climate zone and window material were found to be significant. Air infiltration has an energy impact between 2.43 and 16.44 $kWh/(m^2\,y)$ on the heating demand and between 0.54 and 3.06 $kWh/(m^2\,y)$ on the cooling demand.

Keywords: air infiltration; airtightness; blower door test; residential buildings; database

4.3.2 Reference

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4.3.3 Contribution of the doctoral candidate

Design of the sampling and collaboration in the development of the protocol, supervision of the tests of the presented cases, analysis of the results, as well as the writing of the manuscript.

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Energy impact of the air infiltration in residential buildings in the Mediterranean area of Spain and the Canary islands

Jesús Feijó-Muñoz [a], Cristina Pardal [b], Víctor Echarri [c], Jesica Fernández-Agüera [d], Rafael Assiego de Larriva [e], Manuel Montesdeoca Calderín [f], Irene Poza-Casado [a,*], Miguel Ángel Padilla-Marcos [a], Alberto Meiss [a]

[a] RG Architecture & Energy, Universidad de Valladolid, Avda/ Salamanca, 18, Valladolid 47014, Spain
[b] Universidad Politécnica de Cataluña, Avda. Diagonal, 649, Barcelona 08028, Spain
[c] Department of Building Construction, Universidad de Alicante, Carretera de San Vicente s/n, San Vicente del Raspeig, Alicante 03690, Spain
[d] Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Avda. Reina Mercedes, 2, Sevilla 41012, Spain
[e] Art and Architecture Department, Universidad de Málaga, Plaza del Ejido s/n, Málaga 29071, Spain
[f] Department of Architectural Constructions, Universidad de Las Palmas de Gran Canaria, Campus Universitario de Tafira s/n, Las Palmas de Gran Canaria 35017, Spain

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A B S T R A C T

Air infiltration through the building envelope has already been proven to have a significant energy impact in dwellings. Different studies have been carried out in Europe, but there is still a lack of knowledge in this field regarding mild climates. An experimental field study has been carried out in the Mediterranean climate area of Spain and the Canary Islands in order to assess the air permeability of the building envelope and its energy impact. A wide characterization and Blower Door tests have been performed in 225 cases in Alicante, Barcelona, Málaga, Sevilla and Las Palmas de Gran Canaria for this purpose. The obtained mean air permeability rate for the 225 studied cases was 6.56 $m^3/(h{\cdot}m^2)$. The influence of several variables on airtightness was statistically analysed, although only location, climate zone and window material were found to be significant. Air infiltration has an energy impact between 2.43 and 16.44 $kWh/m^2{\cdot}$year on the heating demand and between 0.54 and 3.06 $kWh/m^2{\cdot}$year on the cooling demand.

1. Introduction

Residential buildings are responsible for one of the highest levels of energy consumption. It is the most common building use in the world with approximately 2 billion dwellings and around 214 million in the European Union alone. In Spain there are about 26 million homes, being 66.1% of them apartments in multi-family buildings [1].

The European Strategy for Sustainable Development, as well as the Paris Agreement reached after the United Nations Climate Change Conference [2] in 2015 (XXI UNFCCC) have promoted political awareness and established contemporary criteria of energy saving and efficiency and the reduction of emissions, especially from buildings. This has led to the need to define joint strategies aimed at achieving solutions to the high energy consumption related to building development.

However, the low replacement rate of existing and outdated dwellings by new ones under the new energy standards requires action with applicable models on existing buildings. These strategies are oriented towards the achievement of a low-energy housing stock or near Zero Energy Buildings (*nZEB*). These strategies seek to reduce energy losses through the envelope by improving heat transmission by conduction, which has been extensively solved through the use of more and better thermal insulation. In this sense, energy loss due to infiltration becomes a relevant issue to the overall energy impact of the building.

Previous studies have assessed the energy loss through ventilation processes, which is greater than 30% of the final energy used in dwellings [3]. The nZEB strategies consider the heat recovery from the extraction air, improving this way the energy efficiency. However, heat recovery is only possible in controlled ventilation

* Corresponding author at: Ventilation Laboratory, Avda/ Salamanca, 18, Valladolid 47014, Spain.
E-mail addresses: feijo@arq.uva.es (J. Feijó-Muñoz), cristina.pardal@upc.edu (C. Pardal), victor.echarri@ua.es (V. Echarri), jfernandezaguera@us.es (J. Fernández-Agüera), rassiego@uma.es (R. Assiego de Larriva), manuel.montesdeoca@ulpgc.es (M. Montesdeoca Calderín), irene.poza@uva.es (I. Poza-Casado), miguelangel.padilla@uva.es (M.Á. Padilla-Marcos), meiss@arq.uva.es (A. Meiss).

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processes. Thus, in order to achieve nZEB, it is important to limit infiltration to tolerable limits. The uncontrolled ventilation through leakage paths due to a deficient design and construction entails a challenge.

Air infiltrations through the building envelope produce a phenomenon of air mass exchange between the inside and the outside of the conditioned space, causing energy transfer with different hygrothermal conditions of the air. This transfer means not only the reduction of the conditions of comfort of the occupants but also extra energy consumption. Therefore, airtight envelopes must be designed in order to reduce the uncontrolled consumption of hygrothermal energy caused by infiltrations but also, they must be combined with efficient HVAC systems to provide a sufficient clean air flow in the optimum hygrothermal comfort conditions.

Numerous studies have been carried out so far in northern Europe, which estimate an energy impact of air infiltration on heating demand of around 10 kWh/m^2·year in regions with a moderately cold climate (2500 degree days) [4]. Other studies indicate that the lack of airtightness of the building envelope can increase the heating demand from 5 to 20 kWh/m^2·year in countries with temperate climates [5]. However, in Spain knowledge regarding this issue is still scarce. Some studies have been carried out in the south of the country [6,7] and in the Continental climate area of the country [8]. From the energy point of view, a study carried out by Meiss and Feijó [9] in 13 dwellings in the north of Spain obtained the first results to this respect. It was estimated an energy impact of infiltration between 10.5 and 27.4% of the energy demand in buildings built under the Technical Building Code (CTE) [10], between 21.9 and 27% in buildings regulated by the standard NBE CT-79 [11] and between 11.3 and 13% in buildings of previous construction but retrofitted by their occupants.

The vast existing housing stock in the eastern and southern coast of Spain has required the detailed evaluation of the energy impact of the air infiltration. In these regions, it is typical the absence of thermal insulation of the envelope, as well as constructions defects due to an accelerated urban expansion in recent decades.

The objective of this study is to collect and classify relevant information regarding the energy impact of air leakage through the thermal envelope of residential buildings located in the Mediterranean climate area of Spain in order to reduce its energy impact. The coastal regions around the Mediterranean Sea and the archipelago formed by the Canary Islands are evaluated. This study seeks not only to characterize the current housing stock, but also to establish construction systems that have an impact on air infiltration.

1.1. Climate classification

Permeability tests were performed in 5 locations in Mediterranean climate areas of Spain and the Canary Islands: Alicante (ALC), Barcelona (BCN), Málaga (MAL), Sevilla (SEV) and Las Palmas de Gran Canaria (LPA) (Fig. 1). In order to define the specific climatic conditions of each location, Köppen Climate Classification [12,13] was applied. This system defines distinct types of climate using average monthly values for precipitation and air temperature.

Type *B* climates are characterized for being dry climates, which Köppen distinguished between sub-type *BS* (steppe), and the subtype *BW* (desert), in relation to the annual rainfall. These areas are also classified as hot climates (h), or cold climates (k) depending on whether the average annual temperature is below or above 18 °C. Climate type *BSh* can be found in Alicante and *BWh* climate in Las Palmas de Gran Canaria. On the other hand, climates type C are classified as temperate climates, where the average temperature in the coldest months is between 0 and 18 °C. Sub-type *Csa* climate refers to dry and hot summers (average temperature in the hottest month above 22 °C) whereas in *Csb* climates summers are temperate. Climate type *Csa* can be found in Sevilla, Málaga and Barcelona, covering most of the Iberian Peninsula and the Balearic archipelago, occupying approximately 40% of its surface.

1.2. The building envelope in the Mediterranean area of Spain and the Canary islands

These areas are characterized by a low construction quality of the residential buildings. This is due to a large degree to the rapid building expansion suffered in the 70 s and 80 s derived from the great growth of tourism, which required a large number of dwellings in a short period of time. This fact resulted in deficit buildings that entail an important energetic impact.

Traditional building systems, usually before the 50 s, are based on load-bearing walls of a single layer of variable thickness (always greater or equal to one foot), of ceramic bricks of different qualities coated with lime mortar to the exterior. With the generalization of concrete in the 60 s, the facades have no longer a structural function and, therefore, they are lightened. Also remarkable is a significant proportion of self-built single-family housing.

In general terms, the construction systems during the 20th century in the Mediterranean area of Spain and the Canary Islands can be classified in three periods divided by the introduction of regulations regarding the energy performance of the buildings, namely, the NBE CT-79 [11] in 1979 and the Spanish Technical Building Code (CTE) [10] in 2006:

- Dwellings before 1979:
  - Façade: usually built with two layers of hollow brick, a small air chamber between them, and a finishing layer with cement mortar and painting. No thermal insulation is used. The interior finish is normally made of continuous plaster. In the specific case of the Canary Islands, the façade is made with a single layer of concrete hollow block with, without thermal insulation.
  - Roof: conventional trafficable flat roof, with terrazzo or ceramic tiles or gravel finish.
  - Windows: made of lacquered wood, aluminium or steel without thermal bridge break. In kitchens and bathrooms, it is common to place windows with orientable glass slats. Simple glass of 4 mm.
  - Shading: shutters, folding blinds, traditional exterior wooden rolling shutters or rolling shutters integrated into the enclosure.
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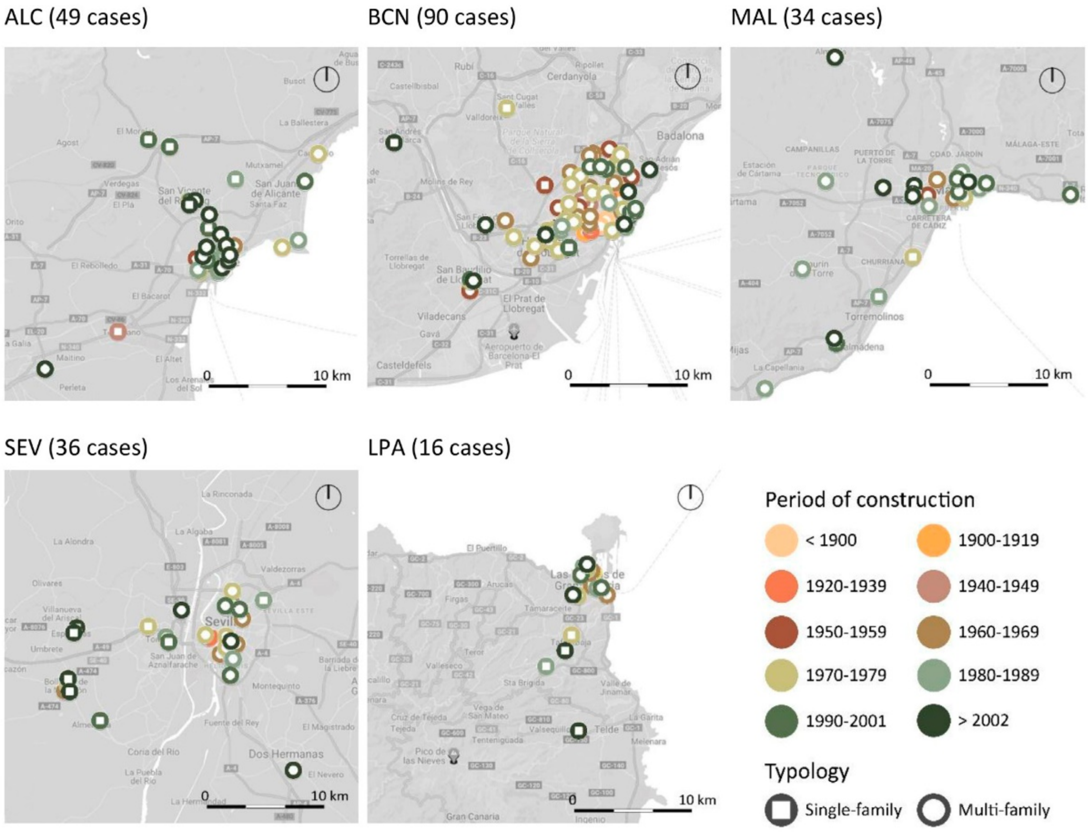

Fig. 2. Location of the studied cases.

lesser extent, installations of hot water radiators with gas heater and boiler have been carried out in single-family homes, combined with a multi-split system for summer.

2. Methodology

2.1. Sample

The study has focused on the building typologies of the area of interest, ensuring the representativeness of the sample. A non-probabilistic quota sampling scheme has been considered in order to ensure the heterogeneity and proportionality of the selected cases. This method reproduces the population on a smaller scale on the basis of a considered sample size [14]. The residential stock in the Mediterranean area of Spain including the Canary Islands has been proportionally stratified into subgroups (strata) according to a series of control variables, namely, the period of construction, typology (single-family or multi-family housing) and the climate zone. The control variables have been chosen due to its impact on airtightness according to previous studies, being its distribution known [14].

A total of 225 cases built between 1890 and 2015 have been studied. The location of the cases according to typology and year of construction is shown in Fig. 2. The distribution of the cases according to its main characteristics was assessed in order to verify the representativeness of the sample tested.

The year of construction has proven to be a significant factor regarding airtightness because it is related to regulations, deterioration of materials and joints [15] and development of construction systems. Regarding regulations (aforementioned in Section 1.2) 53% of the sample was built before NBE CT-79 was implemented, 37% of the cases were built after it came into force and 10% after CTE. However, it was also taken into account if dwellings were in an original state (71%) or, by contrast, it had been retrofitted (29%).

Typology has also been considered, clearly reflecting the fact that multi-family housing prevails in this area. 76% of the cases were apartments within buildings and only 24% of the sample were single-family houses (isolated or detached). In the cases of apartments, the relative position of the dwelling was assessed: 72% of the apartments were located in an intermediate position with conditioned spaces in contact with the horizontal envelope, whereas 19% occupied the upper floor and only 9% the lower floor.

Construction systems were analysed from different points of view. Massive construction tradition can be proved in the sample with 99% of the cases. The envelope is usually built with a double massive layer (80% of the sample), intermediate insulation material (54%) or no insulation (44% of the cases) and air chamber (56%) or none (44% of the sample). The façade has in most of the cases (64%) an outer coating. The internal massive layer of the envelope and partition walls are mainly massive as well, although the most recent cases tend to introduce lightweight solutions (8% of the sample). Regarding windows, which constitute critical points of the envelope, the prevailing material is aluminium (71% of the sample) and most of the cases had rolling shutters (76%).

Finally, ventilation and conditioning systems have been assessed. Most of the housing stock in this area (90%) has natural ventilation by manually open the windows, given that regulations did not implemented controlled ventilation systems until the entry

Table 1
Preparation of the building envelope for Methods A and B.

	Method A	Method B
Mechanical ventilation openings (air shafts, exhaust hood, etc.)	Closed and switched off	Sealed and switched off
HVAC ducts	Closed and switched off	Closed and switched off
Atmospheric open heaters	Closed and switched off	Sealed and switched off
Natural ventilation openings (adjustable)	Closed	Sealed
Natural ventilation openings (always open)	Opened	Sealed
Closing shaft chimney ducts	Closed	Sealed
Opened shaft chimney ducts	Opened	Sealed
Overflow sinks and sinks without hydraulic seal	Opened	Fulfilled/sealed
Hydraulic seal	Fulfilled	Fulfilled/sealed
Cupboards and closets	Closed	Closed
Outer doors and windows	Closed	Closed
Inner doors	Opened	Opened

into force of CTE. Most of the cases had some sort of heating system (75%, 58% with water or electric radiators), whereas 45% had a refrigeration system, mostly based on individual units. The distribution of the cases according to its main characteristics is detailed in Annex I.

2.2. Testing method

The evaluation of the airtightness of the envelope has been carried out by means of the procedure described by the European Standard EN 13,829 [16] which is a modified version of the International Standard ISO 9972:2006. The procedure, commonly called Blower Door Test, causes a stationary pressure differential inside the area to be tested with respect to the atmospheric conditions of the exterior. This standardized procedure establishes two possible evaluation methods:

- Method A is a test of the building in use. It evaluates the condition of the building envelope in its condition during the season in which the heating or cooling systems are used.
- Method B tests the building envelope. For that purpose, any intentional opening in the building envelope shall be closed or sealed (Table 1).

For the objectives proposed for this study, the analysis of Method B is considered more adequate, although tests are carried out by both methods in order to consolidate the results and perform possible complementary studies. A protocol was designed to ensure that the preparation of each dwelling was consistent for all the cases.

In addition, each case is tested under pressurization and depressurization conditions, minimizing the influence of wind and temperature action on the envelope. The final results of the infiltration and exfiltration flows are averaged to obtain a global value.

The correct calibration of the equipment was ensured to maintain accuracy specifications of 1% of reading, or 0.15 Pa.

2.3. Fundamentals

The infiltration curve is calculated according to the power law equation, based on the fundamental mechanics airflow [16] (Eqs. (1)–(3)).

$$n = \frac{\sum_r \left(Ln(|\bar{p}_r - \Delta p|) - \frac{\sum_r Ln(|\bar{p}_r - \Delta p|)}{r} \right)^2}{\sum_r Ln(|\bar{p}_r - \Delta p|) - \frac{\sum_r Ln(|\bar{p}_r - \Delta p|)}{r} \cdot Ln\left(c_d \cdot P_r^{n_d} \cdot \frac{\rho_o}{\rho_i} \cdot \sqrt{\frac{\rho_{20^\circ C}}{\rho_o}} \right) - \frac{\sum_r Ln\left(c_d \cdot P_r^{n_d} \cdot \frac{\rho_o}{\rho_i} \cdot \sqrt{\frac{\rho_{20^\circ C}}{\rho_o}} \right)}{r}} \quad (1)$$

$$Cenv = e^{\left(\frac{\sum_r Ln\left(c_d \cdot P_r^{n_d} \cdot \frac{\rho_o}{\rho_i} \cdot \sqrt{\frac{\rho_{20^\circ C}}{\rho_o}} \right)}{r} - \frac{n \cdot \sum_r Ln(|\bar{p}_r - \Delta p|)}{r} \right)} \quad (2)$$

$$Cl = Cenv \cdot \left(\frac{\rho_o}{\rho_k} \right)^{1-n} \quad (3)$$

where:

r is the number of samples taken in each case at different pressures [-].
$\bar{p}_r$ is the average pressure in each test sample [Pa].
Δp is the pressure differential in the test [Pa].
c_d is the reference flow rate for each diaphragm of the Blower-Door [m^3/h].
P_r is the ventilation pressure in each sample [Pa].
n_d is the reference exponent for each diaphragm [-].
n is the air flow exponent [-].
ρ_o is the air density outside the building [kg/m^3].
ρ_i is the air density inside the tested dwelling [kg/m^3].
$\rho_{20^\circ C}$ is the reference air density at 20 °C [kg/m^3].
ρ_k is the calculation density for the interior temperature [kg/m^3].
$Cenv$ is the air Flow coefficient [m^3/(h·Pa^n)].
Cl is the air leakage coefficient [m^3/(h·Pa^n)].

The following parameters related to the infiltration phenomenon, which allow the comparison of results in different buildings, are evaluated (equations 4 – 7):

$$V_{50} = Cl \cdot 50^n \quad (4)$$

$$q_{50} = \frac{V50}{Ae} \quad (5)$$

$$w_{50} = \frac{V50}{Af} \quad (6)$$

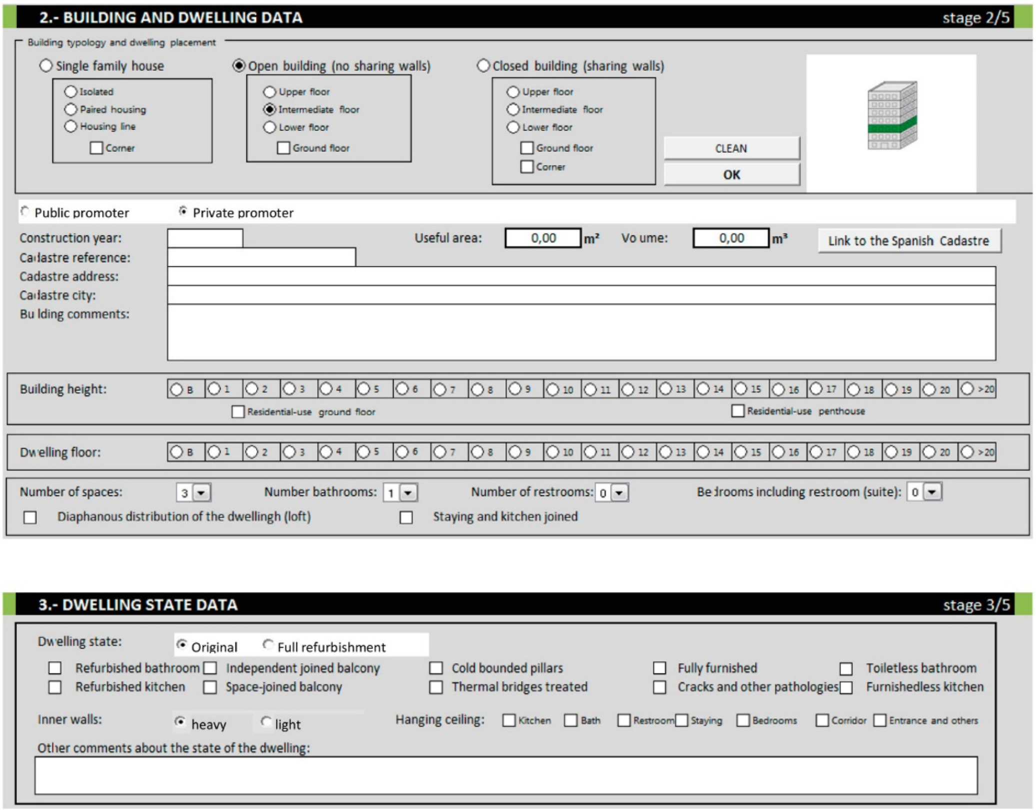

Fig. 3. Screenshot of "infil-APP". Characterization of the dwelling.

$$n_{50} = \frac{V50}{Vol} \tag{7}$$

where:

- V_{50} is the air leakage rate at 50 Pa [m^3/h].
- q_{50} is the air permeability at 50 Pa [m^3/(h·m^2)].
- w_{50} is the specific leakage rate at 50 Pa [m^3/(h·m^2)].
- n_{50} is the air change rate at 50 Pa [h^{-1}].
- Ae is the envelope area [m^2].
- Af is the floor area [m^2].
- Vol is the internal air volume [m^3].

It is important to note that in multi-family dwellings the non-guarded pressurization test does not allow to distinguish between the infiltration that occurs through the façade and the one produced in walls in contact with conditioned spaces (other dwellings) or unconditioned zones (common areas of the building). Inter-zonal leakages have been previously assessed by several studies with different methods in buildings with varying characteristics. It has been estimated that inter-zonal leakages can account for 2 to more than 60% of the total air leakage [17]. Therefore, the proportion of leakage between internal units in multi-family buildings can be within a wide range depending on building characteristics. In any case, the total infiltration rate was taken, which for energy impact purposes is the most unfavourable situation.

2.4. Energy impact assessment

The estimation of the energy impact of infiltration is a complex issue, given that it depends not only on the airtightness of the building envelope, but also on meteorological conditions that are sometimes difficult to predict. There is no common criterion about the appropriate model to evaluate the energy impact of infiltrations. Different calculation models have been developed so far with varying degrees of complexity and reliability. The more simplified models assume a uniform distribution of leakage paths and constant average leaks over time.

The energy impact of infiltrations has been assessed by means of a simplified model (Eq. (8)), applying the concept of degree-day, which relates the average temperature outside the tested dwelling and the comfort indoor temperature (21 °C for heating and 25 °C for cooling). It is important to note that this estimation is theoretical and real energy consumption depends on the particular temperature conditions of the dwellings. This calculation procedure allows to evaluate the energy impact considering specific climate data of the locations where the tests have been performed, as a product of the air infiltration flow, the specific air capacity and the temperature difference between the inside and the outside of the dwelling [18].

$$Q_{inf} = C_p \cdot G_t \cdot V_{inf} \tag{8}$$

where:

- Q_{inf} is the annual energy loss [kWh/y] due to air infiltration for heating $Q_{\inf-H}$ and cooling $Q_{\inf-C}$. Annual energy losses are expressed per unit area.
- C_p is the specific heat capacity of the air, which is 0.34 Wh/m^3·K.
- G_t are the annual degree days [kKh/year], both for heating (G_{t-C}) with a base comfort temperature of 21 °C, and for cooling G_{t-R} with a base comfort temperature of 25 °C.

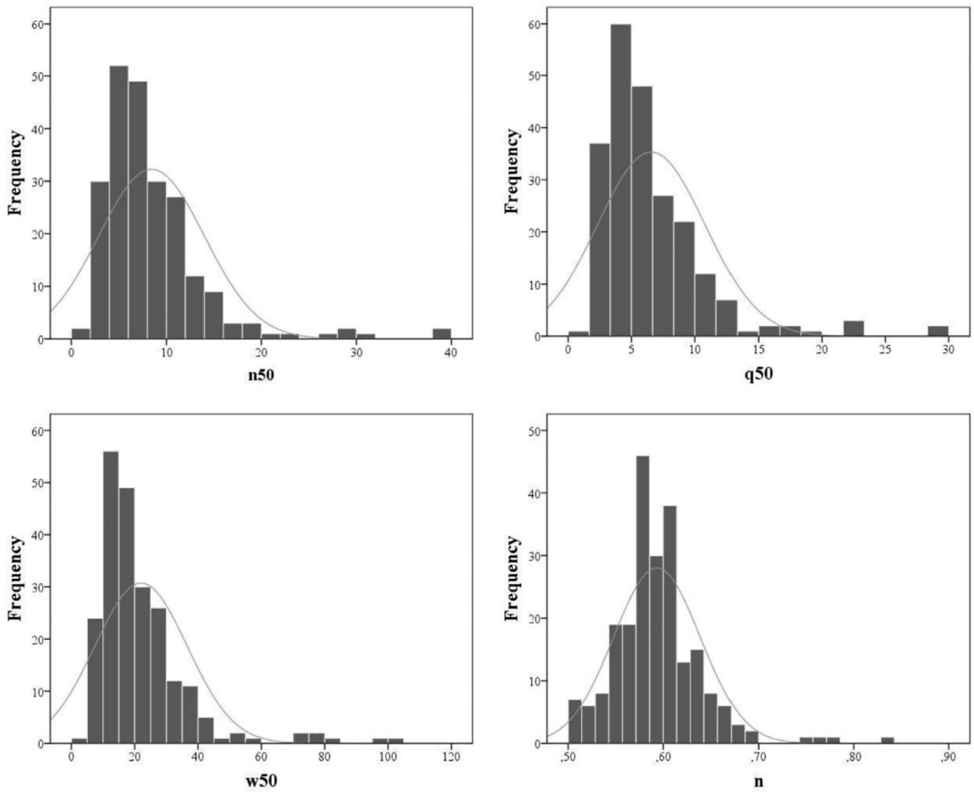

Fig. 4. Distribution of test results for the whole sample.

V_{inf} is the air leakage rate [m^3/h].

V_{inf} needs to be obtained from the values obtained from the test, which are expressed at a pressure difference of 50 Pa and do not reflect the actual filtration process to which the dwelling is subjected. Therefore, the results must be transformed into real filtration equivalent flows. The estimation of the actual filtration is complex, given that the wind and temperature conditions throughout the year are difficult to foresee and the test does not give precise information related to the distribution of infiltration leakages.

The Persily-Kronvall estimate [19], is a simple and widespread model in the scientific community. Its origin is uncertain, and it assumes a linear relationship between permeability at 50 Pa and the average annual infiltration (Eq. (9)).

$$q_{inf} = \frac{q_{50}}{20} \quad (9)$$

where:

q_{inf} is the air permeability [$m^3/(h \cdot m^2)$].

Subsequently, this linear relationship between airtightness and infiltration evolved [19] incorporating coefficients according to the characteristics of the location Eqs. (10) and ((11)).

$$q_{inf} = \frac{q_{50}}{N} \quad (10)$$

$$N = C \cdot cf_1 \cdot cf_2 \cdot cf_3 \quad (11)$$

where:

N is a constant.

C it is the climatic factor, calculated in the model from hourly climate data for more than 200 points in the US and Canada. Its value is in the range 15 - 30.

cf_1 is the height correction factor of the building, applicable to buildings in which the tested spaces are in 1 floor ($cf_1 = 1$) up to 3 floors ($cf_1 = 0.7$).

cf_2 is the site shielding correction factor, for well shielded cases ($cf_2 = 1.2$), ($cf_2 = 1$) or exposed dwellings ($cf_2 = 0.9$).

cf_3 is the leakiness correction factor, dependent on the value of the leakage exponent n. Buildings with small cracks, a typical situation of typical tighter buildings are given a correction factor $cf_3 = 1.4$, whereas leakier buildings with large holes have a correction factor $cf_3 = 0.7$.

This extended simplified model has been adopted for the calculation of the average infiltration flow in the Mediterranean area of Spain and the Canary Islands, obtaining the value of the climatic factor C by assimilation to the US climates, comparatively according to the average temperature and wind speed. For the coefficients cf_1, cf_2 and cf_3 a value equal to 1 has been adopted in the three cases. The type of infiltration opening was obtained from the mean value of the flow exponent $n = 0.59$.

The air leakage rate V_{inf} needed for the calculation of the energy impact is calculated from the air permeability rate and the envelope area (Eq. (12)):

$$V_{inf} = q_{inf} \cdot A_E \quad (12)$$

2.5. Airtightness database

The performance of the tests in each case was carried out by trained technicians, who have a tool (*infil-APP* [14]) to capture

Table 2
Mean values obtained depending on different variables and Kruskal-Wallis test results.

Variable	Category	cases	n_{50} [h^{-1}]	q_{50} [$m^3/(h{\cdot}m^2)$]	w_{50} [$m^3/(h{\cdot}m^2)$]	n [-]	Chi-square (q_{50})	Sig. (q_{50})
Total	–	225	8.43	6.56	21.97	0.59	–	–
Location	ALC	49	7.78	6.26	19.99	0.61	13.89	0.008*
	BCN	90	9.78	7.53	25.79	0.58		
	MAL	34	5.81	5.16	17.23	0.60		
	LPA	16	5.43	4.60	14.78	0.59		
	SEV	36	8.88	6.81	23.16	0.58		
Climate zone	BSh	49	7.78	6.26	19.99	0.61	7.83	0.020*
	BWh	16	5.43	4.60	14.78	0.59		
	Csa	160	8.93	6.84	23.30	0.59		
Regulations	None	118	8.99	6.96	23.83	0.59	2.17	0.338
	CT-79	84	8.11	6.35	20.64	0.60		
	CTE	23	6.78	5.25	17.27	0.60		
Typology	Multi-family	172	8.80	6.51	22.62	0.59	0.88	0.348
	Single-family	53	7.25	6.73	19.85	0.59		
Relative position	Lower	16	8.15	6.04	20.96	0.59	0.20	0.905
	Intermediate	123	9.14	6.75	23.62	0.59		
	Upper	33	7.84	5.82	19.72	0.59		
Developer	Private	188	8.56	6.77	22.42	0.59	0.93	0.335
	Public	37	7.76	5.49	19.70	0.60		
Retrofitting state	Original	159	8.51	6.52	22.09	0.59		
	Retrofitted	66	8.24	6.64	21.69	0.60		
Window material	Steel	4	8.85	6.75	22.92	0.59	18.03	0.000*
	Aluminium	158	7.67	5.90	19.64	0.60		
	Wood	46	11.19	8.87	30.49	0.58		
	PVC	16	7.53	6.18	19.24	0.59		
Rolling shutters	None	54	7.48	5.70	20.43	0.60	3.13	0.209
	Added	16	8.07	5.87	20.22	0.58		
	Integrated	155	8.80	6.93	22.69	0.59		
Massive layers	Single	46	7.46	5.98	20.93	0.59	0.85	0.357
	Double	179	8.68	6.71	20.93	0.59		
Insulation layer	None	120	8.97	6.84	23.79	0.59	1.12	0.249
	Interior	6	5.09	4.79	12.56	0.61		
	Intermediate	97	7.95	6.27	20.24	0.60		
	Exterior	2	9.74	8.84	24.76	0.55		
Air chamber	None	99	7.96	6.21	21.42	0.59	3.37	0.186
	Regular	118	8.81	6.77	22.39	0.59		
	Ventilated	8	8.81	7.62	22.71	0.58		
Partition walls	Lightweight	18	10.31	7.87	26.37	0.60	2.42	0.120
	Massive	207	8.27	6.44	21.59	.059		
Outer coating	No	81	8.45	6.65	21.98	0.59	0.00	0.961
	Yes	144	8.42	6.51	21.97	0.59		
Ventilation system	Natural	202	8.62	6.71	22.51	0.59	1.71	0.191
	Mechanical	23	6.78	5.25	17.27	0.60		
Heating system	No	56	9.18	6.68	24.19	0.58	0.25	0.616
	Yes	169	8.19	5.52	21.24	0.60		
Refrigerating system	No	121	8.50	6.76	22.63	0.59	1.02	0.312
	Yes	104	8.36	6.33	21.20	0.60		

characterization information (Fig. 3) and to import test data from the software provided by *Minneapolis Blower Door Model 3* (TECTITE 5.0).

This tool was specifically developed for the characterization of 140 parameters that can intervene in the phenomenon of filtration. These parameters are collected in a database that is used for the global evaluation of the results.

3. Results

3.1. Airtightness results

The distribution of the values obtained for the air change rate (n_{50}), the air permeability (q_{50}), the specific leakage rate (w_{50}) at 50 Pa and the air flow exponent (n) for the whole sample are shown in Fig. 4.

Mean values obtained for the assessed sample are shown in Table 2. The results obtained for q_{50} ranged from 1.90 to 39.42 $m^3/(h{\cdot}m^2)$ with a mean value of 6.56 $m^3/(h{\cdot}m^2)$, median 5.48 $m^3/(h{\cdot}m^2)$ with a standard deviation of 4.24.

The flow exponent (n value) gives information regarding the resistance to the passage of air of the leakage paths, being close to 1 for laminar flows (airtight dwellings) and close to 0.5 for turbulent flows (leaky dwellings) [20]. The mean flow exponent n for the whole sample was 0.59.

The influence of different parameters on the air permeability rate at 50 Pa (q_{50}) has been assessed by means of Kruskal-Wallis test [21] in order to statistically verify the independence of the variables. Table 2 shows the values obtained for the test statistic *Chi-square* and the significance (*Sig.*), which can be considered significant for values below 0.05 (indicated by a *). Thus, a statistically significant relationship was found between the air permeability rate and the location of the dwellings, climate zone and window material (*Sig.* < 0.05).

Maximum q_{50} values were found in Barcelona and Sevilla (q_{50} = 7.53 and 6.81 $m^3/(h{\cdot}m^2)$ respectively) and minimum values in Las Palmas de Gran Canaria (q_{50}= 4.60 $m^3/(h{\cdot}m^2)$). Dwellings located in temperate climates with dry and hot summers (*Csa*) performed worse in terms of airtightness (q_{50} = 6.84 $m^3/(h{\cdot}m^2)$) than those in dry hot desert climates (*BWh*), with q_{50} = 4.60 $m^3/(h{\cdot}m^2)$. Although the sample size was irregular for different window

Table 3
Energy impact of infiltration results.

	Ud.	ALC	BCN	MAL	SEV	LPA
N	–	22	22	23	20	19
q_{inf}	$m^3/(h{\cdot}m^2)$	0.28	0.34	0.22	0.34	0.24
Q_{inf-H}	$kWh/m^2{\cdot}year$	10.02	16.44	8.61	14.21	2.43
Q_{inf-C}	$kWh/m^2{\cdot}year$	1.60	0.73	0.78	3.06	0.54
Q_{inf-H} **(no regulations)**	$kWh/m^2{\cdot}year$	10.42	16.43	10.55	14.63	3.55
Q_{inf-C} **(no regulations)**	$kWh/m^2{\cdot}year$	1.66	0.73	0.96	3.16	0.75
Q_{inf-H} **(CT-79)**	$kWh/m^2{\cdot}year$	10.08	16.90	8.03	15.92	1.89
Q_{inf-C} **(CT-79)**	$kWh/m^2{\cdot}year$	1.61	0.75	0.73	3.43	0.42
Q_{inf-H} **(CTE)**	$kWh/m^2{\cdot}year$	8.42	14.14	6.36	9.92	1.39
Q_{inf-C} **(CTE)**	$kWh/m^2{\cdot}year$	1.34	0.63	0.58	2.14	0.31

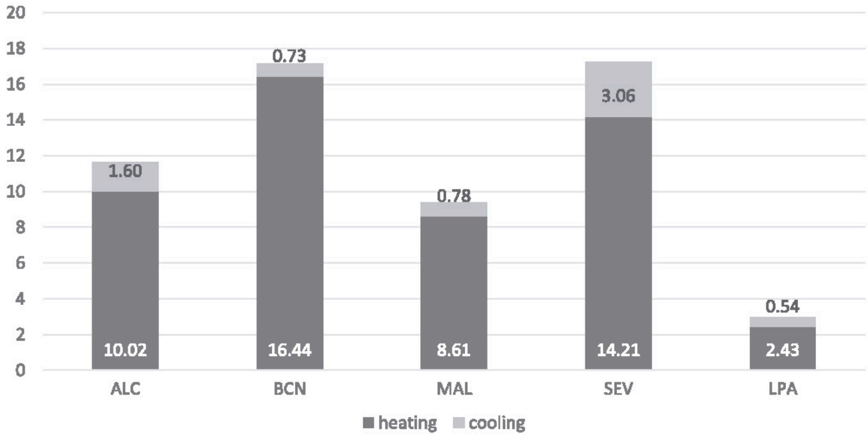

Fig. 5. Annual energy losses (kWh/m²·a) for heating and cooling due to infiltration.

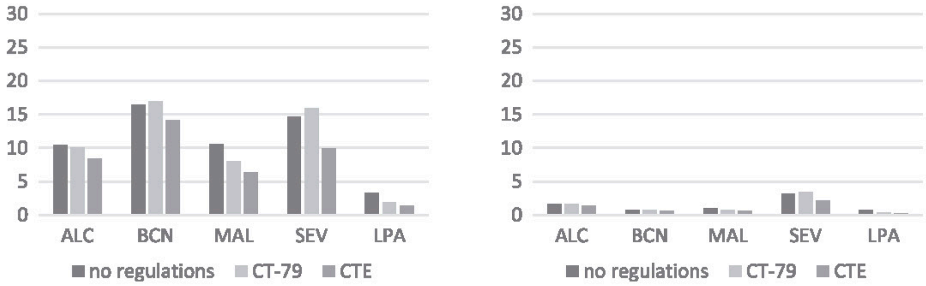

Fig. 6. Annual energy losses (kWh/m²·a) for heating (left) and cooling (right) due to infiltration, classified per regulations.

materials, dwellings with aluminium windows ($q_{50} = 5.90$ $m^3/(h{\cdot}m^2)$) performed better than those made of wood ($q_{50} = 8.87$ $m^3/(h{\cdot}m^2)$).

3.2. Energy impact

The energy impact estimation of the air infiltration obtained, both for the heating and cooling demand, is shown in Table 3 and Fig. 5 for each of the locations studied. Furthermore, results are also expressed according to the period of construction, corresponding to implemented regulations. Fig. 6 shows the tendency for each city where the study has been carried out.

The energy impact has a greater impact on the heating demand, especially in Barcelona and Sevilla (Table 3). Values up to 16.44 $kWh/m^2{\cdot}y$ have been obtained for the energy impact corresponding to the heating demand in the case of Barcelona, while in Las Palmas de Gran Canaria with hot climate, the value is reduced to 2.43 $kWh/m^2{\cdot}year$. In the case of cooling demand, the energy impact of air infiltration is lower, with maximum values of 3.06 $kWh/m^2{\cdot}y$ in the case of Sevilla, whereas in Las Palmas de Gran Canaria this value is reduced to 0.54 $kWh/m^2{\cdot}year$.

Regarding regulations, there is a general progressive improvement trend in all locations. It can be pointed out, though, that in Barcelona and Sevilla the oldest dwellings built during the first period performed better than the ones built after the entry into force of NBE CT-79.

4. Conclusion

The airtightness and the impact of the air infiltration through the building envelope in dwellings in Spanish cities with a Mediterranean climate and the Canary Islands has been assessed.

The mean air permeability rate at 50 Pa for the 225 studied cases was found to be 6.56 $m^3/(h{\cdot}m^2)$, whereas for the air change rate at 50 Pa the mean obtained value was 8.43 h^{-1}. These results are significantly higher than the average air change rate of

7.5 h^{-1} obtained for other case studies in different European countries [22] and the average air change rate 6.99 h^{-1} obtained in a previous study in the Continental area of Spain [8].

As for the flow exponent n, the obtained mean value was 0.59, associated to air loose construction solutions related to massive systems found in this area. Values close to 0.6 have been associated with leakage around the openings of the envelope [7].

Location, climate zone and window material were found to be statistically significant parameters that have an impact on airtightness. No statistically significant relationship was found between the air permeability rate and the other parameters analysed. General trends can be observed, although further analysis and a larger simple should be considered in order to deduce accurate conclusions.

In spite of the fact that the assessed area has a mild climate, the energy impact affects mainly the heating demand. Air infiltration has an energy impact between 2.43 and 16.44 kWh/m^2·year on the heating demand and between 0.54 and 3.06 kWh/m^2·year on the cooling demand. These results are in line with the values previously stated in other studies [5]. A general improvement trend can be observed regarding the implementation of regulations, although a fast expansion of the cities could have probably derived in poor quality construction in the cases of Barcelona and Sevilla during the period 1980 – 2006.

There is currently no limit in Spain regarding the airtightness of the building envelope in buildings (CTE only establishes requirements for windows). Consequently, compliance with the European Directive 2018/844 seems only possible by implementing limitations in this respect applicable both to the design of new buildings and to the renovation of the existing housing stock.

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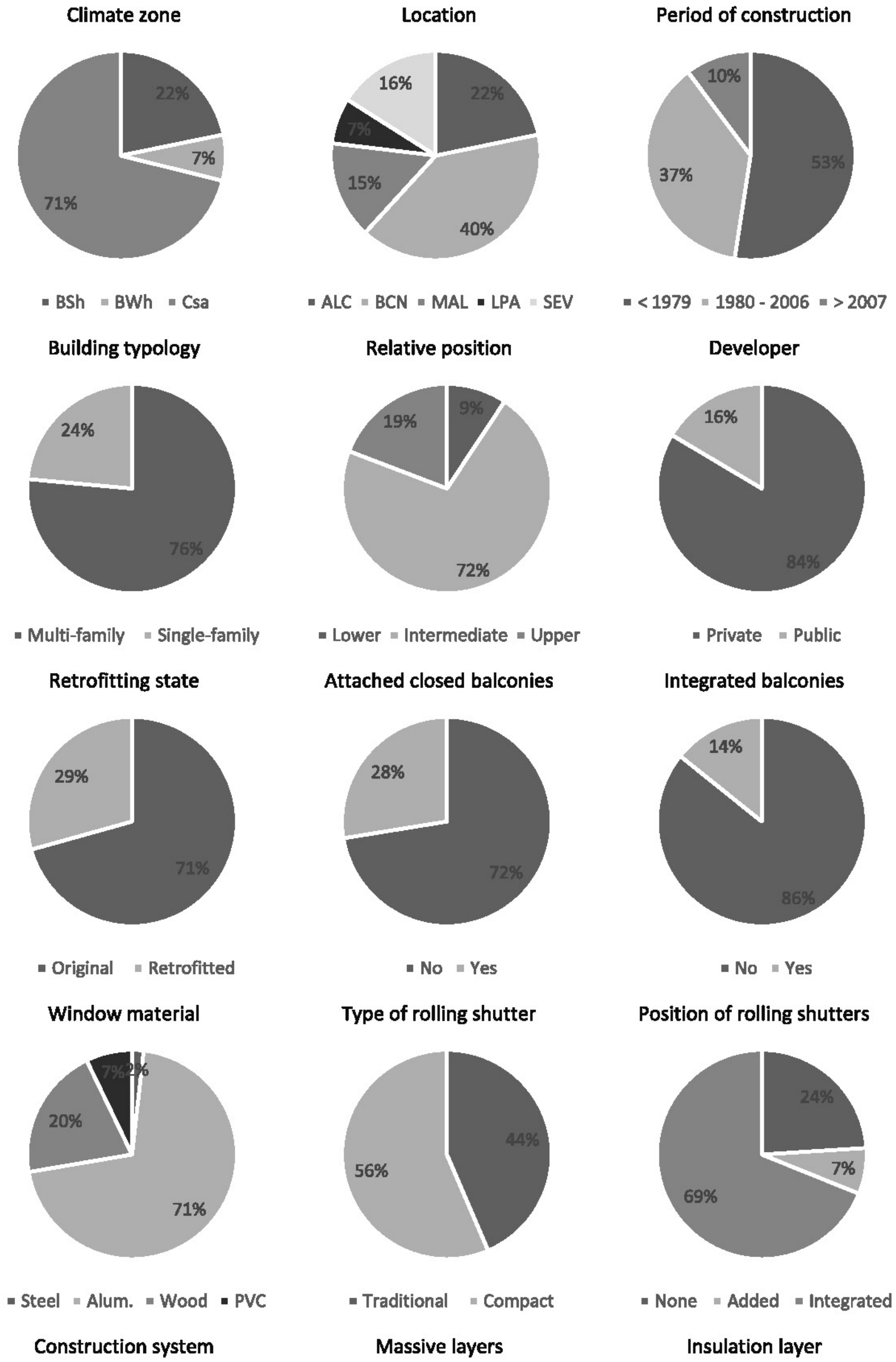
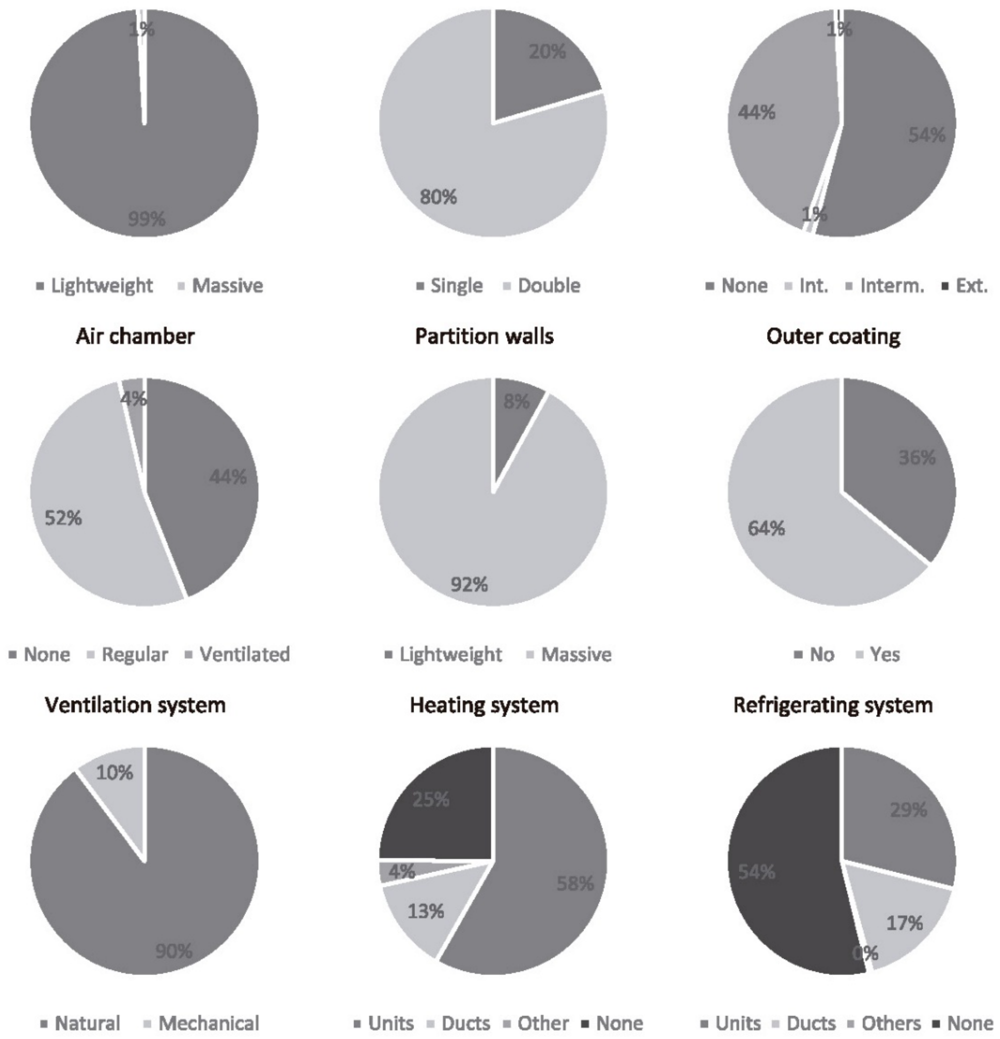
Declarations of interest

None.

Annex. I: Characterization assessment of the sample





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4.4 AIRTIGHTNESS AND ENERGY IMPACT OF AIR INFILTRATION IN RESIDENTIAL BUILDINGS IN SPAIN

Poza-Casado, I., Meiss, A., Padilla-Marcos, M. Á., & Feijó-Muñoz, J.

4.4.1 Abstract

Addressing the airtightness of the building envelope is key to achieve thermal comfort, good performance of ventilation systems and to avoid excessive energy consumption. Previous studies have estimated an energy impact of infiltration on the heating demand between 2 and 20 $kWh/(m^2\ y)$ in regions with temperate climates. In Spain, this issue has not yet been addressed in depth. This study aims to assess the energy impact of uncontrolled airflows through the envelope in residential buildings in Spain. For this purpose, airtightness results of more than 400 blower door tests have been analysed. Multi-family and single-family dwellings built in several periods and located in nine regions with different climate characteristics have been studied. Infiltration was found to have an energy impact in the range 2.43–19.07 $kWh/(m^2\ y)$ for the heating demand, whereas it is not so significant regarding the cooling demand. The obtained results show great potential for energy saving in the country.

Keywords: air leakage; blower door; energy impact; residential buildings; fan pressurization test

4.4.2 Reference

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4.4.3 Contribution of the doctoral candidate

Collaboration in the design of the methodology, analysis of the results, and writing of the manuscript.

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Airtightness and energy impact of air infiltration in residential buildings in Spain

Irene Poza-Casado, Alberto Meiss, Miguel Ángel Padilla-Marcos and Jesús Feijó-Muñoz

GIR Arquitectura & Energía, Universidad de Valladolid, Valladolid, Spain

ABSTRACT

Addressing the airtightness of the building envelope is key to achieve thermal comfort, good performance ofventilation systems and to avoid excessive energy consumption. Previous studies have estimated an energy impact of infiltration on the heating demand between 2 and 20 kW h/(m^2 y) in regions with temperate climates. In Spain, this issue has not yet been addressed in depth. This study aims to assess the energy impact of uncontrolled airflows through the envelope in residential buildings in Spain. For this purpose, airtightness results of more than 400 blower door tests have been analysed. Multi-family and single-family dwellings built in several periods and located in nine regions with different climate characteristics have been studied. Infiltration was found to have an energy impact in the range 2.43–19.07 kW h/(m^2 y) for the heating demand, whereas it is not so significant regarding the cooling demand. The obtained results show great potential for energy saving in the country.

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KEYWORDS
Air leakage; blower door; energy impact; residential buildings; fan pressurisation test

1. Introduction

The European Union is committed to reducing greenhouse gas emissions, establishing a sustainable, competitive and decarbonised energy system by 2050. It is estimated that buildings are responsible for approximately 36% of all CO_2 emissions and that almost 50% of the final energy consumption of the EU is used for heating and cooling. Eighty percent (80%) of it is consumed in buildings (European Parliament, 2018). Therefore, it seems essential to establish strategies that support the renovation of national buildings stocks, facilitating their transformation into nearly zero-energy buildings (nZEB).

In this context, one of the factors that has a great impact is the presence of air infiltration.

In Mediterranean countries, however, airtightness has still not been broadly addressed. The fact that ventilation is not controlled and normally done by manually opening the windows, means that air infiltration is the only continuous air supply. It has already been estimated that the energy impact of air infiltration on the heating demand can account for around 10 kW h/(m^2 y) in regions with a moderately cold climate (2500 degrees-day) (Carrié & Wouters, 2013), or an increase on the heating demand from 5 to 20 kW h/(m^2 y) in countries with temperate climate (Spiekman, 2010).

CONTACT Irene Poza-Casado irene.poza@uva.es GIR Arquitectura & Energía, Universidad de Valladolid, Valladolid, Spain.

National building regulations in Spain are gathered in the National Building Code (CTE), which was first released in 2006 and has been updated several times so far (Ministerio de Fomento del Gobierno de España, 2017). Requirements regarding the limitation of the energy demand in dwellings are gathered in its Basic Document "Energy saving" (DB HE). Concerning airtightness, there is only a limitation on the permeability of windows depending on the climate zone, not considering global airtightness. That means that the energy impact of air infiltration has increased its weight on the overall energy performance of buildings, given the constant improvement of the thermal transmittance of the building envelope without concern on airtightness. A new update of CTE is expected to be released in 2020. Although measures are taken to implement nZEB following European Directive 2018/844 (European Parliament, 2018) on the energy performance of buildings and energy efficiency, no update regarding airtightness is expected.

However, even though regulations in Spain do not include airtightness requirements of the whole building envelope, the official tools for the EPB-requirements verification consider air infiltration as a parameter. Since tests performance is not mandatory, global permeability is calculated based on the permeability of doors and windows (from default values depending on its classification), the permeability of the opaque part of the envelope (from default values depending on building typology) and air inlets (default value).

Given the relevance of airtightness from an energy point of view, the purpose of this paper is to analyse the energy impact of air infiltration in Spain from real airtightness measurements in order to evaluate its importance in the total energy consumption in dwellings.

2. Methodology

2.1. Sample

Since there are no building airtightness requirements in Spain, testing is not mandatory and therefore there is a lack of data in this regard. Tests are only performed to comply with specific energy programmes (Passivhaus, BREEAM, LEED, etc.), by constructors who wish to ensure the quality of construction or as a diagnostic tool in case of poor energy performance of the building or before retrofitting actions. In any case, this data is scarce, not publicly available and belong to a very specific type of buildings, which are not representative of the housing stock of the country. Some studies on airtightness focussed on a specific type of dwelling have already been carried out in Spain so far (Fernández-Agüera et al., 2016; Jiménez Tiberio & Branchi, 2013; Meiss & Feijó-Muñoz, 2015). Recently, another study established a database with more than 400 representative cases (Feijó-Muñoz et al., 2018), which will constitute the sample for this study.

The considered database includes cases in different climate zones, built in several periods of time and gathers both single and multi-family 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.

The most representative climate areas were Mediterranean (209 cases located in Barcelona (BCN), Alicante (ALC), Málaga (MAL) and Sevilla (SEV)) and Continental (129 cases located in Madrid (MAD) and Valladolid (VLL)), but also Oceanic (47 cases located in Bilbao (BIL) and La Coruña (COR)) and the Canary Islands (16 cases located in Las Palmas de Gran Canaria (LPA) were included in the sample). The vintage of the cases tested was proportional to the existing building stock, being the periods 1960–1979 (37%) and 1980–2006 (39.5%) the most representative ones. Concerning typology, 325 cases were apartments (81%) and 76 cases were single-family houses (19%).

2.2. Testing method

The assessment of the building airtightness was approached by means of the fan pressurisation method, according to ISO 9972 (International Organization for Standardization, 2015). Regarding building preparation, any intentional opening in the building envelope was closed or sealed (Method B). The correct calibration of the equipment was ensured to maintain accuracy specifications of 1% of reading, or 0.15 Pa. On the other hand, according to ISO 9972, the overall uncertainty is highly dependent upon the environment during the test, being lower than 10% in most cases in calm conditions.

The infiltration curve is calculated as follows (Equation (1)):

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

where V_{env} is the airflow rate through the envelope of the dwelling (m^3/h), C_{env} the airflow coefficient ($m^3/(h\,Pa^n)$), Δp the induced pressure difference (Pa), n the pressure exponent (–).

In order to compare air leakage rates, the values of the airflow rate were normalised by the building envelope area, A_E (m^2) and internal volume V (m^3), and reported at a normalised pressure difference of 50 Pa, q_{50} ($m^3/(h\,m^2)$) and n_{50} (h^{-1}), respectively, interpolated from measurements.

However, operational pressure differences are typically an order of magnitude around 4 Pa, much lower than 50 Pa (Jones et al., 2015). There have been many studies in this regard so far. The studies that first assessed the relationship between n_{50} and n_{nat} (air change rate under natural conditions) were carried out in the 70′ and 80′ (Kronvall, 1978; Persily & Linteris, 1983). Subsequently, Sherman (1987) reported a linear relationship considering an empirical correction factor N scaling it according to local climate, air leakage path size, dwelling height and shielding (Equation (2))

$$n_{nat} = \frac{n_{50}}{N} \tag{2}$$

This model has been broadly applied in national building codes and standards, although it must be emphasised that the use of a scaling factor is a simplified treatment of a complex reality (Chan et al., 2005).

2.3. Energy impact assessment

Infiltration can contribute significantly to the overall heating or cooling load of a building (Buchanan & Sherman, 1998). Several models have been developed so far but there is no common criterion about the appropriate model to evaluate the energy impact of infiltrations. The energy load was obtained by means of a simplified model using the classical infiltration calculation (Equation (3)).

It is obtained as a product of the air infiltration flow, the volumetric air capacity, and the temperature difference between the inside and the outside of the dwelling. The concept of degree-day was applied, relating the average temperature outside the tested dwelling and the comfort indoor temperature (21 °C for heating and 25 °C for cooling). It is important to note that this estimation is theoretical and real energy consumption depends on the particular temperature conditions of the dwellings (Feijó-Muñoz et al., 2019). Some authors have emphasised that this method might be well acceptable when calculating the load due to concentrated leakage (through large openings, short paths), but it could entail a considerable overestimation of the energy impact in the case of diffuse leakage (small cracks, where heat exchange between the infiltrating air and the wall may occur) (Younes et al., 2012)

$$Q_{inf} = C_p \cdot G_t \cdot V_{inf} \tag{3}$$

where Q_{inf} is the annual energy loss (kW h/y) due to air infiltration for heating Q_{inf-H} and cooling Q_{inf-C}. Annual energy losses are expressed per unit area. C_p is the volumetric heat capacity of the air, which is 0.34 W h/(m^3 K), G_t are the annual degree days (kK h/y), both for heating

(G_{t-H}) with a base comfort temperature of 21 °C, and for cooling (G_{t-C}) with a base comfort temperature of 25 °C. V_{inf} is the air leakage rate (m^3/h), defined according to Equation (4):

$$V_{inf} = n_{nat} \cdot V \tag{4}$$

Furthermore, it is worth mentioning that the non-guarded pressurisation testing method used does not allow to distinguish the origin of air infiltration in the case of apartments in buildings. It has been estimated in previous studies that inter-zonal leakages can account for a wide range between 2% and more than 60% of the total air leakage (Villi et al., 2013). In this case, given that the study is a first approximation to the energy impact of air infiltration in Spain, a simplified model has been addressed and the most unfavourable situation was approached, considering that the whole air infiltration is produced through the surface in contact with the outdoor environment.

3. Results and discussion

Averaged main results sorted by location of the dwellings are shown in Table 1. The energy impact estimation of the air infiltration was obtained, both for the heating and cooling demand (Figure 1). Furthermore, the relative impact of air infiltration on the heating and cooling demand has been approached based on reference demand values used in energy certification of existing buildings (Figure 2). These values were obtained with the software LIDER, using representative typologies and construction systems (IDAE, 2011). Given that reference values are given by typology, they were averaged.

A widespread of the airtightness results was found within the range 1.19–39.42 h^{-1} for the air change rate n_{50} and from 0.96 to 29.92 $m^3/(h\,m^2)$ in the case of the air permeability rate q_{50}. The distribution of the data was found to be non-normal, according to Kolmogorov–Smirnov normality test using the extended tool IBM SPSS Statistics. Considering the air change rate (n_{50}) of the whole sample, a mean value of 7.52 h^{-1}, a median of 6.39 h^{-1} and a standard deviation of 4.91 were found. Maximum values were found in Mediterranean areas such as Barcelona ($n_{50} = 9.73\,h^{-1}$), Sevilla ($n_{50} = 8.88\,h^{-1}$) and Alicante ($n_{50} = 7.78\,h^{-1}$), whereas dwellings with better airtightness performance were located in the north of the country: A Coruña ($n_{50} = 4.61\,h^{-1}$), Bilbao ($n_{50} = 4.67\,h^{-1}$) and Valladolid ($n_{50} = 4.99\,h^{-1}$).

From a regulatory point of view, since, as already mentioned, there are no requirements in Spain, a comparison has been made with other countries' standards. Most of the cases tested would comply with regulations in the UK or Ireland, where limitations have been implemented for new dwellings: $q_{50} < 10$ or 7 $m^3/(h\,m^2)$, respectively. However, results are above regulations in other countries such as Germany ($n_{50} < 3\,h^{-1}$ in buildings with natural ventilation). On the other hand, as it could be expected, the results obtained are in any case far from LEED puncturable values (1.5–4.25 h^{-1}, depending on the climate zone) or Passivhaus airtightness requirement ($n_{50} < 0.6\,h^{-1}$), which seems to have become the target value in some areas like Sweden or

Table 1. Airtightness results and energy impact due to air infiltration.

Parameter	Unit	COR	BIL	VLL	MAD	ALC	BCN	MAL	SEV	LPA
n_{50}	h^{-1}	4.61	4.67	4.99	7.29	7.78	9.73	6.89	8.88	5.43
q_{50}	$m^3/(h\ m^2)$	3.58	3.47	3.76	5.93	6.26	7.49	5.16	6.81	4.60
n	–	0.62	0.62	0.64	0.61	0.61	0.59	0.60	0.58	0.59
A_E	m^2	331.3	235.5	310.3	288.2	296.49	286.1	274.5	275.2	457.2
V	m^3	255.7	176.1	244.6	244.9	250.8	231.3	209.8	226.9	412.2
$G_{t\ H}$	kK h/y	54.89	56.86	80.09	63.48	33.24	44.90	34.46	38.50	9.86
$G_{t\ C}$	kK h/y	0.12	1.32	3.91	8.21	5.30	1.99	3.12	8.30	
$Q_{inf\ H}$	kW h/(m^2 y)	11.10	11.15	16.41	19.07	10.02	16.44	8.61	14.21	2.43
$Q_{inf\ C}$	kW h/(m^2 y)	0.02	0.26	0.80	2.47	1.60	0.73	0.78	3.06	0.54
$\%_{H}$	%	11	11	10	15	18	18	20	25	0
$\%_{c}$	%	0	0	9	12	5	5	2	6	2

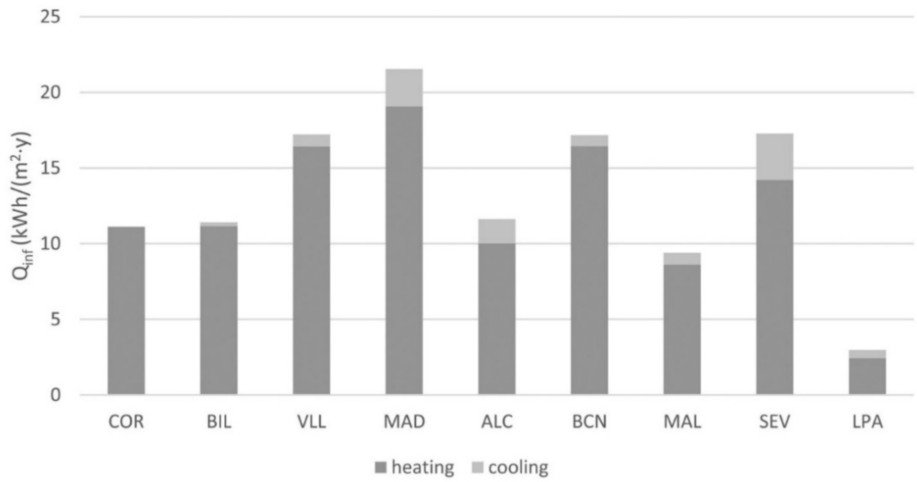

Figure 1. Annual energy impact due to air infiltration.

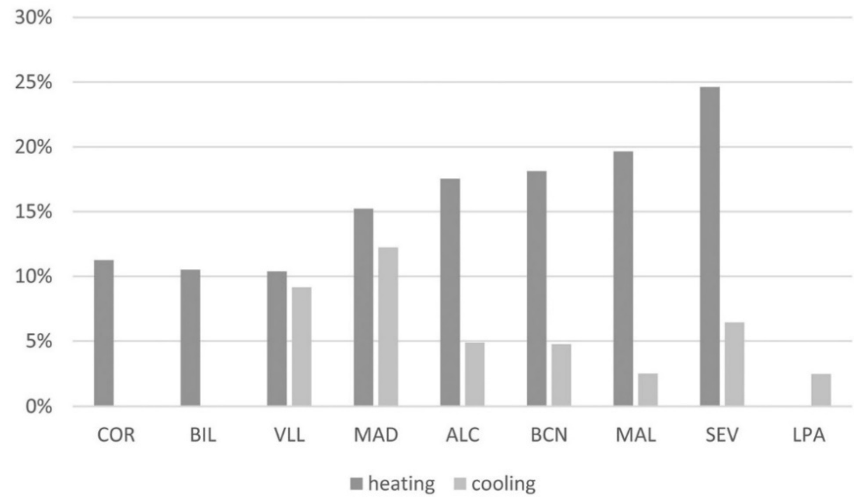

Figure 2. Relative impact of the air infiltration on the heating and cooling demand.

Brussels. However, it must be taken into account that regulations usually refer to new buildings and the scope of this study was to characterise existing dwellings built on different periods.

Considering the energy assessment, air infiltration has a greater impact on the heating demand, especially in cities with a continental climate such as Madrid or Valladolid. Values up to 19.07 kW h/(m^2 y) have been obtained in the case of Madrid, while in cities with a milder climate such as Las Palmas de Gran Canaria, the value is reduced to 2.43 kW h/(m^2 y). In the case of the cooling demand, the energy impact of air infiltration is lower, with maximum values of 3.06 kW h/(m^2 y) in the case of Sevilla. In other locations such as A Coruña or Bilbao, the impact on the cooling demand becomes negligible.

Regarding the relative impact of air infiltration, values up to 25% corresponding to the heating demand in the case of Sevilla or 12% for the cooling demand in Madrid were obtained. These relative values must be interpreted taking into account the airtightness results and the energy demand. In the case of Sevilla or Málaga, the high share of the energy impact of infiltration can be explained given the low heating demand (57.70 and 43.84 kW h/(m^2 y), respectively) and, at the same time, a high air change rate.

4. Conclusions

In Mediterranean countries with mild climates and where ventilation has traditionally been done in a natural way, the concern regarding airtightness is still scarce. However, air infiltration cannot be ignored any more in a context where huge efforts are being made to transform the existing building stock into nZEB. It seems to be time to face a change in building construction traditions and regulations, addressing airtightness properly.

From the results obtained in the present study, it is possible to conclude that air infiltration through the building envelope has an enormous impact in Spain. The impact is greater on the heating demand, while the impact for cooling can be negligible in Atlantic areas. Maximum values up to 19.07 kW h/(m^2 y) for the heating demand have been obtained in the case of Madrid, or up to 3.06 kW h/(m^2 y) in the case of the cooling demand in Sevilla. In relative terms, air leakage entails up to 25% of the heating demand and up to 12% of the cooling demand. These results are in line with the values previously stated in other studies.

Therefore, the energy impact of air infiltration in existing residential buildings of Spain is a matter to consider necessarily given its demonstrated relevance. Consequently, compliance with the European Directive 2018/844 seems only possible by paying special attention to airtightness, implementing limitations in this respect applicable both to the design of new buildings and to the renovation of the existing housing stock.

Nevertheless, a larger sample and a deeper analysis of the data should be considered in order to draw more accurate conclusions.

Disclosure statement

No potential conflict of interest was reported by the authors.

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4.5 RESIDENTIAL BUILDINGS AIRTIGHTNESS FRAMEWORKS: A REVIEW ON THE MAIN DATABASES AND SETUPS IN EUROPE AND NORTH AMERICA

Poza-Casado, I., Cardoso, V. E. M., Almeida, R. M. S. F., Meiss, A., Ramos, N. M. M., & Padilla-Marcos, M. Á.

4.5.1 Abstract

The airtightness of buildings has gained relevance in the last decade. The spread of the regulatory frameworks, the demand of stricter requirements, schemes for testing and quality control, the creation of airtightness databases and its analysis, is proof of this reality. The present review encompasses schemes developed in Europe and North America with regard to these aspects for national residential sectors. A normative framework on requirements and recommendations at the national level is compiled. Whole building airtightness databases are compared based on their structures and measurement data acquisition protocols. Gathered complementary information not directly related to testing is analysed and airtightness influencing factors importance and relationships are discussed. Weaknesses and strengths in the different aspects of the existing database setups are identified. Also, neglected or not entirely undertaken topics are pinpointed together with the suggestion of possible opportunities for future works and changes. Amongst other relevant remarks and discussions, it is concluded that the lack of uniformization in method between countries, the need for a minimum data setup, the lack of data analysis on relating the energy impact with the advancement in requirements of airtightness performance and the implemented setups are some of the main issues to address in the near future.

Keywords: review paper; airtightness; regulation policy

4.5.2 Reference

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4.5.3 Contribution of the doctoral candidate

Collaboration in the conception of the presented idea, gathering of information on airtightness regulations and databases, analysis and discussion, and writing of the manuscript.

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Residential buildings airtightness frameworks: A review on the main databases and setups in Europe and North America

Irene Poza-Casado [a], Vitor E.M. Cardoso [b,*], Ricardo M.S.F. Almeida [b,c], Alberto Meiss [a], Nuno M. M. Ramos [b], Miguel Ángel Padilla-Marcos [a]

[a] RG Architecture & Energy, Universidad de Valladolid, Avda/ Salamanca, 18, Valladolid, 47014, Spain
[b] CONSTRUCT-LFC, Faculdade de Engenharia (FEUP), Universidade do Porto, Rua Dr. Roberto Frias s/n, 4200-465, Porto, Portugal
[c] Polytechnic Institute of Viseu, School of Technology and Management, Department of Civil Engineering, Campus Politécnico de Repeses, 3504-510, Viseu, Portugal

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ABSTRACT

The airtightness of buildings has gained relevance in the last decade. The spread of the regulatory frameworks, the demand of stricter requirements, schemes for testing and quality control, the creation of airtightness databases and its analysis, is proof of this reality. The present review encompasses schemes developed in Europe and North America with regard to these aspects for national residential sectors. A normative framework on requirements and recommendations at the national level is compiled. Whole building airtightness databases are compared based on their structures and measurement data acquisition protocols. Gathered complementary information not directly related to testing is analysed and airtightness influencing factors importance and relationships are discussed. Weaknesses and strengths in the different aspects of the existing database setups are identified. Also, neglected or not entirely undertaken topics are pinpointed together with the suggestion of possible opportunities for future works and changes. Amongst other relevant remarks and discussions, it is concluded that the lack of uniformization in method between countries, the need for a minimum data setup, the lack of data analysis on relating the energy impact with the advancement in requirements of airtightness performance and the implemented setups are some of the main issues to address in the near future.

1. Introduction

For the past decades, the growing interest for airtightness has motivated several studies on this field and the publication of regulations to control and guarantee minimum construction quality [1]. To this end, a high number of measurements were carried out to evaluate building design and construction practices or to demonstrate compliance with regulations. Therefore, some databases with a large number of cases were developed in several countries, gathering information from air leakage tests, as a result of energy policies about the impact of air infiltration in buildings performance. Ongoing data collection and creating representative databases on airtightness levels of a built stock can be useful for several purposes:

- demonstrate the compliance with regulations when they are mandatory [2];
- provide more accurate and reliable input data for buildings energy and ventilation estimations of future construction and weatherised buildings [3];
- gathering information for modelling and designing [4];
- evaluate which factors are the most important for airtightness [5];
- evaluate building design, construction practices and quality [6];
- develop clear guidelines for airtightness best practices [7];
- evaluate the effectiveness of individual measures in improving airtightness [8];
- visualise time trends [9];
- evaluate the progress of the built stock in meeting building energy performance objectives [10];
- compare the building performance with other countries [11].

Abbreviations: nZEB, nearly Zero Energy Buildings; EPBD, Energy Performance Building Directive; USA, United States of America; EWDI, Excessive Winter Death Index; QMS, Quality Management Scheme; EN, European Norm; ISO, International Organization for Standardization; ANOVA, Analysis of Variance; ATTMA, Air Tightness Testing & Measurement Association; LBNL, Lawrence Berkeley National Laboratory; SWOT, Strengths Weaknesses Opportunities Threats.

* Corresponding author.
E-mail address: v.cardoso@fe.up.pt (V.E.M. Cardoso).

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Airtightness databases present themselves as storages of potential knowledge that, through continuous analysis and evolution, can serve as main tools on the progress of this topic towards a more sustainable society. As these practices control occurs at a high authority national level, the approaches are very different among countries. A broader view and analysis of the current setups that take place is missing. A comprehensive review of these efforts should undercover their main differences, existing challenges, and effective actions. The objectives of the present work go according to the following points:

- Explore the main databases on airtightness by identifying the data available, the input scheme, their purpose, the analysis performed, and their overall structure and requirements;
- Systematically compare the databases, discussing their differences and gaps, pinpointing their strengths and weaknesses, and identifying problems in the existing practices as well as opportunities for future actions.

For the achievement of these objectives, the document was structured as follows. Section 2 addresses the regulatory context of airtightness requirements, when existing. Section 3 describes the structure of databases on whole building airtightness measurements. Section 4 analyses instructions, conditions and metrics for measurement data acquisition. Section 5 reports on information gathered on the databases. Section 6 informs on the data analysis performed to these datasets. Finally, in Section 7, the main points are discussed and conclusions are taken in Section 8.

2. Airtightness regulatory context

The need for better energy performance of buildings has led to energy policies that limit the energy use of buildings. For the last few years, the focus on European countries has become the implementation of nZEB, whose framework is set in the Energy Performance of Building Directive (EPBD) [12].

In this context, air infiltration control with airtight envelopes is key to avoid a profound impact on the energy demand of dwellings [13]. However, EPBD does not establish specific requirements or a standard procedure to determine the energy balance [14]. Consequently, discrepancies exist in the regulation on the control of air leakage, which is key for the energy performance of buildings.

In North America the issue ensues similarly, despite detailed requirements and procedures stated in energy codes. Although the states and regions are required to adopt some form of the national energy code, there is no enforcement mechanism.

Therefore, the energy policies adopted in each country, state or region, establish different requirements, or none at all, regarding the airtightness of the building envelope, which differ considerably from one another.

Addressing normative legislation is important to frame the subject, as their criteria and nature are closely related to how and why the current schemes are implemented the way they are.

2.1. Measurement metrics

Regulations in each country use different metrics, so limits cannot often be compared from one country to another, compromising and adding obstacles for joint progress on good practices and corrective measures.

The most common normalised parameters are summarised in Table 1. They derive from the airflow rate at a stablished pressure difference (often 50 Pa) and building dimensions. The comparison of the different measurement metrics for each country is further developed in section 3.

Table 1
Normalised parameters to express building airtightness.

Parameter		Equation	Unit
n_x	**air change rate at x Pa**	V_x/V	h^{-1}
w_x	**specific leakage rate at x Pa**	V_x/A_E	$m^3/h{\cdot}m^2$
q_x	**air permeability rate at x Pa**	V_x/A_F	$m^3/h{\cdot}m^2$

V_x (m^3/h): airflow rate at a pressure difference of x Pa.
V (m^3): internal volume or volume of air inside the measured building.
A_E (m^2): envelope area.
A_F (m^2): net floor area.

2.2. Nature and criteria

The regulatory approach is somewhat different depending on the country: some regulations set limitations on the whole building permeability (e.g., United Kingdom, France), whereas others just set recommendations (e.g., Poland), default values (e.g., Belgium, Finland) or even no consideration at all (e.g., Greece, Hungary) (Table 2). Note that for specific private low energy labelling programs the airtightness requirements are frequently stricter than normative ones at national level.

A trend of more awareness has been observed in countries with colder climate conditions, except for most countries in eastern Europe. On the other hand, most of the Mediterranean countries with milder climates, whole building airtightness has still not been the focus from a regulatory point of view (Fig. 1). Aiming to improve the thermal performance of buildings in countries where air infiltration has a greater impact in energy consumption is expected. However, data shows that excessive winter death index (EWDI) is on average higher in most of the countries that do not have airtightness requirements [47,48]. This fact shows that the issue does not lose relevance with climate factors alone.

It is worth mentioning that in countries with highly decentralised regions, regulations experience different requirements, such as is the case of Belgium [16,42] and Italy [49,50]. In the Flanders and Wallonia regions of Belgium the default values are very unfavorable regarding the energy performance and the only way to improve them is by introducing the actual airtightness values obtained from measurements [51], resulting in a hidden incentive for systematic testing.

In the United States, airtightness requirements get enforced by state governments [52]. Generally, state regulations cannot adopt more tolerant limits than the ones defined at the national level [40,53]. The rationale is the definition of requirements by groups of similar climate zones.

A similar rationale is present in Canada [44], where regions need to comply with the national regulation main guidelines. Airtightness default values are assigned for energy calculation if no measurements are done. Despite no mandatory tests were in force by the end of 2019, there were requirements on the usage of conforming air barrier assemblies [43] and on the provision and compliance of envelope detailing with prescriptive actions. In several countries, no requirements and recommendations for whole building airtightness are in place. Still, specific airtightness class for several envelope building components (windows and doors) is required, and the impact of these on the energy performance of a building is considered (e.g. Portugal) [54]. However, the values refer to laboratory testing and not its real performance. In other words, workmanship is not considered.

Additionally, regulations on airtightness establish different criteria on limits definition, that often encompass:

o Integrated ventilation system type (natural, hybrid, mechanical and, in some cases, considering heat recovery), e.g., Germany [22];
o Dwelling typology (single-family or multi-family buildings), e.g., France [21];
o New or retrofitted dwelling, e.g., Switzerland [38];
o Energy performance label, e.g., Lithuania [28];

Table 2
Regulations regarding residential building airtightness in different countries.

Country	Parameter	Units	Requirements	On-site testing	Comments	Ref.
Airtightness mandatory values						
Austria	n_{50}	h^{-1}	Natural ventilation <3 Mechanical ventilation <1.5	Not mandatory		[15]
Belgium – Brussels region	n_{50}	h^{-1}	<0.6	Not mandatory	New dwellings	[16]
Bosnia	n_{50}	h^{-1}	Natural ventilation < 3 Mechanical ventilation < 1.5	Not mandatory		[17]
Croatia	n_{50}	h^{-1}	Natural ventilation < 3 Mechanical ventilation < 1.5	Not mandatory	Mandatory testing for NZEB	[18]
Czech Republic	n_{50}	h^{-1}	Natural ventilation < 4.5 Mechanical ventilation < 1.5 Heat recovery system <1	Not mandatory	Also, for retrofitted dwellings	[19]
Denmark	w_{50}	l/(s·m²)	A_{env}/A_{floor} < 3: <1 A_{env}/A_{floor} >3: <0.3	Not mandatory	Default value when testing is not conducted: 1.5 l/(s·m²).Random checks are performed.	[20]
France	q_4	m³/(h·m²)	Single-family < 0.6 Multi-family < 1	Mandatory	Alternatively, a certified airtightness quality management approach can be applied.	[21]
Germany	n_{50}	h^{-1}	Natural ventilation < 3 (exceptions with active components < 1.5) Mechanical ventilation < 1.5	Not mandatory	Favorable credits only if testing results comply with the benchmarks. For new and completely renovated buildings.	[22]
Iceland	q_{50}	m³/(h·m²)	<3	Not mandatory		[23]
Ireland	q_{50}	m³/(h·m²)	<5	Mandatory		[24]
Latvia	q_{50}	m³/(h·m²)	Natural ventilation < 3 Mechanical ventilation < 2 Heat recovery system < 1.5	Not mandatory	Mandatory test only in the cases of EU co-financing for construction of new buildings or retrofitting of existing public buildings [25]	[26]
Liechtenstein	q_{50}	m³/(h·m²)	New buildings: Natural ventilation < 2.4 Mechanical ventilation < 1.6 Renovations: Natural ventilation < 3.6 Mechanical ventilation < 2.4	Not mandatory		[27]
Lithuania	n_{50}	h^{-1}	Class C: < 2 Class B: < 1.5 Class A: < 1.0 Class A+ and A++: <0.6	Not mandatory	Mandatory for class A. Classes B and C. Requirements can be calculated, and measurement is only mandatory when there is not compliance.	[28]
Luxembourg	n_{50}	h^{-1}	Natural ventilation < 3 Mechanical ventilation < 1.5 Heat recovery system < 1	Not mandatory		[29]
Monaco	q_4	m³/(h·m²)	Single-family < 0.6 Multi-family < 1	Mandatory	Alternatively, a certified airtightness quality management approach can be applied.	[30]
Montenegro	n_{50}	h^{-1}	Natural ventilation < 3 Mechanical ventilation < 1.5	Not mandatory		[31]
Netherlands	w_{10}	dm³/(s·m²)	<1	Not mandatory		[32]
Norway	n_{50}	h^{-1}	<1.5	Not mandatory	Exceptions for specific typologies and uses	[33]
Russia	n_{50}	h^{-1}	Natural ventilation < 4 Mechanical ventilation < 2	Not mandatory	The developer must conduct mandatory settlement and instrumental control of the standardised energy indicators	[34]
Slovenia	n_{50}	h^{-1}	Natural ventilation < 3 Mechanical ventilation < 2	Not mandatory	Mandatory for buildings > 5000 m²	[35]
Spain	n_{50}	h^{-1}	Compacity V/A_E < 2: <6 V/A_E > 4: <3	Not mandatory	Mandatory test only for dwellings >120 m²	[36]
Sweden	q_{50}	m³/(h·m²)	<0.6	Not mandatory		[37]
Switzerland	q_{50}	m³/(h·m²)	New buildings: Natural ventilation < 2.4 Mechanical ventilation < 1.6 Renovations: Natural ventilation < 3.6 Mechanical ventilation < 2.4	Not mandatory		[38]
United Kingdom	q_{50}	m³/(h·m²)	<10	Mandatory	Notional recommended value: 5 m³/(h·m²)	[39]
USA	n_{50}	h^{-1}	<3 climate zone 3 to 8 <5 climate zone 1 and 2	Mandatory (depending on state level speed of national energy code adoption)		[40]
Airtightness recommended values						
Poland	n_{50}	h^{-1}	Natural ventilation < 3 Mechanical ventilation < 1.5	Not mandatory		[41]
Airtightness default values that can be improved						
Belgium (Flanders and Wallonia)	q_{50}	m³/(h·m²)	12	Mandatory, to improve from default values		[42]
Canada	n_{50}	h^{-1}				[44]

(*continued on next page*)

Table 2 (*continued*)

Country	Parameter	Units	Requirements	On-site testing	Comments	Ref.
			3.2 with basic air barrier specifications 2.5 with extra prescriptive details	Mandatory, to improve from default values	The focus is on the requirements of air barrier assemblies and details [43].	
Estonia	q_{50}	$m^3/(h \cdot m^2)$	Single-family: 6 Other buildings: 3	Mandatory, to improve default values		[45]
Finland	q_{50}	$m^3/(h \cdot m^2)$	4	Mandatory, to improve from default values	New dwellings	[46]
No whole building values suggested or no consideration at all						
Albania **Andorra** **Belarus** **Bulgaria** **Cyprus** **Greece** **Hungary** **Italy (except Trento and Bolzano regions)**						**Malta** **Moldova** **North Macedonia** **San Marino** **Serbia** **Ukraine** **Portugal** **Slovakia**

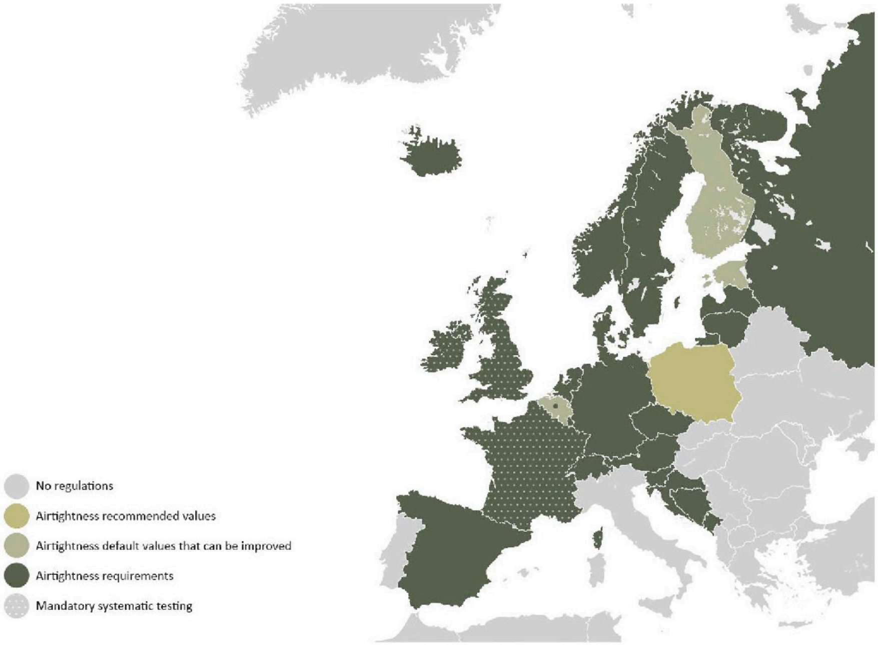

Fig. 1. Airtightness regulatory context in Europe.

o Climate zone, e.g., USA [40];
o Ratios between different geometric properties, e.g., Denmark [20];
o Prescriptive path on air barrier detailing, e.g., Canada [44].

As one can infer from the analysis of Table 2, there are great dissimilarities between each country approach, each with several exceptions to the norm and particular cases demanding strict or stricter requirements and control. The prescriptive and performance nature of the requirements in codes is discussed ahead in this review.

2.3. On-site testing

In most of the countries with airtightness requirements, systematic on-site testing is not required to prove compliance with building regulations. Airtightness is usually estimated based on building characteristics and only random checks undergo. Just in the case of buildings with significant volumes or to reach specific energy labels, buildings get measured. The case is different in countries such as Belgium, where testing is not mandatory, but it is often performed to avoid unfavorable default values in energy performance calculation.

Recently, countries such as the United Kingdom, France, and Ireland, have made systematic on-site testing compulsory to prove compliance with airtightness requirements. This approach has proven to be effective, but it implies higher costs, coordination and quality control for testers.

2.4. Disparities and future trends

The main differences in the North American and European approaches is the leaning of the first towards prescriptive based approaches and the leaning of the second to performance-based ones or a combination of the two, with a small group of countries requiring systematic testing. While prescriptive have its advantages, e.g. generalization of good practices, it leaves several impacting variables unaccounted, e.g. workmanship, and real performance of the envelope remains unknown and just assumed. On the other hand, performance-based approaches established by measurements results portray the reality of the built stock more accurately.

Regulations on airtightness are experiencing fast change in recent years, e.g., recently Spain included airtightness requirements for the first time in its building energy code. In this review, regulation and updates influencing airtightness issues published until December 2019 are analysed.

Despite the uneven guideline adoption by the different member states, as the EPBD requires the compliance of new buildings to be nZEB by the end of 2020, changes on airtightness limits are expected in the building energy codes of European countries in the near future. This further highlights the importance of comparing and evaluating the implemented practices.

A trend for convergence of the practices of the American energy codes to the practices of European ones can be observed. For instance, the revision of the Canadian national energy code by 2020 will require mandatory testing of airtightness performance for all the tiers of energy labelling in the performance-based approach, while for the prescriptive-based approach the testing remains optional. This goes in line with current energy codes in the United States. Still, as with the European countries, the different states and regions of these two countries adopt the established national requirements unevenly, laxly and in some cases not at all.

3. Databases structure

A database on the results of airtightness tests serves as a learning tool of airtightness performance and can provide ground for a sustained evolution of good practices. This section shows an overview of the main existing airtightness databases and their basic functioning, setting criteria and aspects to consider (Table 3)

3.1. Initiative

Airtightness databases are usually managed by regulatory bodies, which are in charge of its maintenance, access control, data privacy, control, and management [55]. On the contrary, some exceptions can be found in countries where no government initiative has been carried out yet (e. g., Czech Republic or Spain). In the latter case, please note that only the academic database *Infiles* has been considered, but it cannot be seen as an open or national database.

3.2. Size

The size of a database relates to its scope, being rather heterogeneous in the considered databases. As can be seen in Table 3, in countries where testing is mandatory, such as France [56] and the United Kingdom [57], among others, databases have had an agile development and account for a high number of cases, mostly new dwellings. On the other hand, in the cases of the USA and Canada, the large amount of gathered information is motivated by weatherisation assistance programs, energy ratings, home performance diagnostics and indoor air quality standards [58] or programs for the energy efficiency retrofit of existing housing stock [59].

The scenario is different in the case of the Flanders and Wallonia regions of Belgium, where very disadvantageous default values for airtightness ($q_{50} = 12\ m^3/(h{\cdot}m^2)$) in the energy performance calculation make airtightness testing implicitly mandatory for new buildings. As a result, at the end of 2016, almost 90% of new residential buildings were tested [60].

In the case of the Czech Republic and Spain, the number of cases gathered in the database is limited, given that they are not the product of an ongoing initiative, but research projects [61] or tests with commercial purpose [1].

3.3. State and update

Two main approaches can be found in terms of the current state of the databases. On the one hand, datasets in countries with airtightness regulations (especially if they imply mandatory testing) favour active datasets. On the other hand, it is challenging to keep databases ongoing when they are the product of one-time efforts [62].

Airtightness datasets in France or the USA that collect air leakage data yearly or occasionally, whereas countries such as the United Kingdom of Belgium experience continuous growth. For that, responsible agencies need to be committed to establishing and maintaining a reporting system [1].

A relevant aspect is the creation of specific software or web-based platform to gather the data associated with each case, which contributes to a uniform approach. In this regard, it is worth mentioning the cases of the United Kingdom [63], where a functional lodgement system has been created, or Spain [61], where the development of a specific software allows for full standardised characterisation and test report of each case.

It is important to note that even though data often get uploaded to an online platform, test results are viewed as private information and are not accessible for the public often due to legal issues of data privacy and data use. Usually, only public reports and scientific papers allow access to trends and results, which hinder global data analysis and comparison between different countries.

3.4. Quality control and tester scheme

One of the problems detected in databases that are open or in which several contractors or agents contribute is the consistency of the data. For that reason, databases need to comply with specific requirements and protocols that allow uniform criteria. Information is more likely to be accurate and complete when specific protocols are followed, like in the cases of France or the United Kingdom. On the other hand, disparities prevail more often when the effort is a compendium of different campaigns or government initiatives, as in the case of the USA.

The reliability of the measurements that integrate databases is a crucial issue. It is necessary to guarantee that the information stored in a database is accurate, and tests have been performed and reported according to the established protocols. To that end, several databases include quality control processes and tester schemes gathered in technical documents beyond the measurement standard, and usually include training programs, examination of testers, equipment control, and evaluation [64]. The database itself can serve as a tool to track suspicious results and to check its consistency [64].

Countries, where testing has become mandatory, have made a great effort in the past few years in order to introduce quality schemes that guarantee the knowledge and know-how of the testers. Testers need official certification in countries such as France [2], Germany [65], United Kingdom [66] and Belgium [60]. In this context, reliability gets addressed by implementing competent tester schemes. In the case of France, the value of the air permeability of the building can also be justified by adopting a quality management scheme (QMS) by legally independent third-party agents [67].

3.5. Sampling scheme

In countries where systematic testing is mandatory, it is sometimes allowed to measure only a sample of the apartments of a building or a development in order to prove compliance. In this regard, France and the United Kingdom have different approaches [68].

For instance, in the United Kingdom blower door tests should be carried out in three units of each dwelling type or 50% of all the dwellings of the development. In France, the minimum number of buildings to be tested depends on the average annual production of buildings, building use and typology [69]. In Germany, there is no

Table 3
Database details and general information by country.

Country	United Kingdom	France	USA	Canada	Czech Republic	Germany	Belgium (Flemish region)	Spain
Initiative	Government	Government	Government	Government	Independent association	Independent association and individuals	Government	Academic
Responsible	Competent Tester Persons: ATTMA and iATS	Cerema (private body)	Lawrence Berkeley National Laboratory – LBNL	Natural Resources Canada	ABD.CZ project (Association Blower Door CZ)	FLiB (independent association)	BCCA, BCQS and the Federal Insurance Company	University of Valladolid
Size	ATTMA - over 500.000 iATS - over 55,000	Over 220,000	Over 150,000	Over 846,000	419	Around 1000	Over 22,000	401
Creation	ATTMA - 2002iATS - 2015	2007	Mid 1990s	2003	2001	2003	2015	2017
Current state	Ongoing	Ongoing	Ongoing	Ongoing	On hold	On hold	Ongoing	On hold
Update	Continuously	Yearly	Occasionally	Continuously	Occasionally	Yearly	Continuously	Occasionally
Platform	Online (https://www.attmalodgement.org, https://iats-lodgement.org.uk)	Offline	Online (http://resdb.lbl.gov/)	Online (https://www.nrcan.gc.ca/)	Offline	Offline	Online (http://dossier.bcca.be)	Offline
Data format	Purpose provided software	Formatted excel spreadsheet	Open-source data management system (PostgreSQL)	Oracle database with an OMNIS 7.8 interface	Formatted excel spreadsheet	Formatted excel spreadsheet	Pdf test report	Formatted excel spreadsheet
Data communication	Online platform upload for test certificate emission	Formatted excel spreadsheet sent yearly to qualification body	Datasets of energy programs get added occasionally	Data files upload to an automated web-based file processor	No clear information	Questionnaire	Online platform where testers upload the test report	Online server upload
Quality control	Auditing both on and off-site by sampling	Auditing both on and off-site by sampling	Dependent on the data source	File processor performs validation and data integrity tests and random file reviews	No	Validation of 5 test reports for recertification every 3 years	Onsite and desktop inspection	Full off-site compliance checks
Tester scheme	Mandatory training program approved by a Competent Tester Person	Qualibat certification	Certified experts for the Energy Star and the Guaranteed Performance programs	Independent certified energy advisors	No	FLiB certification. Training by certified organisations	Quality framework with optional training or mandatory theoretical and practical exam	Mandatory training program
Sampling scheme	Yes	Yes	No	No	No	Yes	No	Yes (quota sampling scheme)
Type of building	Residential and non-residential buildings	Residential and non-residential buildings	Residential	Residential. Pre- and post-energy retrofit	Residential and non-residential buildings	No clear information	Residential and non-residential building	Residential
Predominance	Residential	Single-family	Single-family (92%)	Low-rise dwellings	Single-family	Single-family	Single-family dwellings (78%)	Multi-family

Table 4
Compilation of test standards, guidelines, and methodologies on measurement data acquisition by analysed countries with an established database.

Country	United Kingdom	France	USA	Canada	Czech Republic	Germany	Belgium	Spain
Current test standard	BS EN ISO 9972:2015 [73]	NF EN ISO 9972:2015 [89]	ASTM E779-19 [76] ASTM E1827-11 [75] sp: single point tp: two points	CAN/CGSB-149.10 [78]	ČSN EN ISO 9972:2017 [90]	DIN EN ISO 9972:2018 [70]	NBN EN ISO 9972:2015 [91]	UNE EN ISO 9972:2019 [92]
National guidelines	TSL1:2016 [93]	FD P50-784:2016 [84]	2018 IECC [40]	NBC 2015 [44]	ČSN 73 0540-2:2011 [19]	EnEV 2014 [22] DIN 4108-7:2011 [94]	STS-P 71-3:2014 [95]	None
Test conditions	Wind Temperature Height	Wind Temperature Height	E779: Height Temperature E1827: Wind Temperature	Wind	Wind Temperature Height	Wind Temperature Height	Wind Temperature Height	Wind Temperature Height
Method/ Building preparation	Method 2 on temporary sealing according to method 2 are present in the national guidelines	Method 3 Additional instructions on temporary sealing and guidelines on air leakage location	Permanent and temporary sealing actions in national guideline Additional instructions on the airtightness measurement standard	Permanent and temporary sealing actions in national guidelines Additional instructions on the airtightness test standard	Method 1 or 2 (preferred)No additional instructions on national guidelines	Method 2Instructions on temporary sealing according to method 2 are present in the national guidelines	Method 1 or 2Instructions on temporary sealing according with method 1 or 2 and air leakage location identification are present in the national guidelines	Methods A and B[a]
Minimum initial and final baseline (duration)	10 points (30s)	10 points (30s)	E779: 5 points (10s) E1827:1 point	1 point	10 points (30s)	10 points (30s)	10 points (30s)	10 points (30s)
Minimum test extent (duration)	7 points (-), equal steps < 10 Pa between steps Lowest $\Delta P > 10$ Pa or $5\times \Delta p_0$ 50 Pa $<$ Highest $\Delta P < 90$ Pa	10 points (10s), equal steps < 10 Pa between steps Lowest $\Delta P > 10$ Pa or $5\times \Delta p_0$ 50 Pa $<$ Highest $\Delta P < 100$ Pa	E779: Over 5 points (10s) 10 Pa $< \Delta P < 60$ Pa 5–10 Pa between steps E1827: Repeated sp (5×): 50 Pa Repeated tp (5× each): 12.5 Pa and 50 Pa	8 points (-) 15 Pa $< \Delta P < 50$ Pa 5 Pa between steps	At least 5 points (-), equal steps <10 Pa between steps Lowest $\Delta P > 10$ Pa or $5\times \Delta p_0$ 50 Pa $<$ Highest $\Delta P < 100$ Pa	At least 5 points (-), equal steps <10 Pa between steps Lowest $\Delta P > 10$ Pa or $5\times \Delta p_0$ 50 Pa $<$ Highest $\Delta P < 100$ Pa	At least 5 points (-), equal steps <10 Pa between steps Lowest $\Delta P > 10$ Pa or $5\times \Delta p_0$ 50 Pa $<$ Highest $\Delta P < 100$ Pa	10 points (-), equal steps[a] $11 < \Delta P < 65$ Pa
Regression method	Ordinary least squares	Ordinary least squares	Ordinary least squares	Weighted least squares	Ordinary least squares	Ordinary least squares	Ordinary least squares	Ordinary least squares
Pressure direction	Either or both	Either or both	E779: Both E1827: Either or both	Depress.	Either or both	Either or both	Either or both	Both
Metrics	q_{50} ($m^3.h^{-1}m^{-2}$)	q_4-surf ($m^3.h^{-1}m^{-2}$); n_{50} (h^{-1})	E779: EfLA @ 4Pa (cm^2); N_{50} (h^{-1}) E1827: q_{50} ($m^3.h^{-1}m^{-2}$)	EqLA @10Pa(m^2); NLA ($cm^2.m^{-2}$)	n_{50} (h^{-1})	q_{50} ($m^3.h^{-1}m^{-2}$)	n_{50} (h^{-1}) q_{50} ($m^3.h^{-1}m^{-2}$)	n_{50} (h^{-1}) q_{50} ($m^3.h^{-1}m^{-2}$)
Accuracy of pressure measuring device	±1 Pa	±1 Pa	E779: ±5% or 0.25 Pa, whichever greater E1827 sp: ± 2.5 Pa E1827 tp: ± 0.5 Pa	±2 Pa	±1 Pa	±1 Pa	±1 Pa	±1 Pa
Accuracy of air flow measuring device	±7%	±7%	E779: ±5% E1827 sp: ± 5% E1827 tp: ± 2%	±5%	±7%	±7%	±7%	±7%
Accuracy of temperature measuring device	±0.5 K	±0.5 K	E779: ±1.0 K E1827 sp: ± 2.0 K E1827 tp: ± 2.0 K	±1.0 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K

[a] Methodology used on the dataset of the INFILES project obliged to the standard current at the time: UNE EN 13829:2002 [96].

sampling scheme at the moment, but the sampling protocols currently in a transitioning stage [70] will likely consider rules on a minimum number of dwellings, their location, and a percentage of the total envelope area.

In the particular case of Spain, a quota sampling scheme was applied in order to have a representative sample of the built stock [61,71]. Regarding the type of buildings tested, most of the existing databases focus only on residential buildings, while commercial buildings constitute a minority. Justification could be found on regulations, that usually apply only to dwellings, and because measurement is more feasible in dwelling-size volumes.

Residential buildings are usually divided into single and multi-family housing, given their different characteristics and testing approach. The predominance of a particular building typology tends to reflect the characteristics of the existing building stock. That explains why, for instance, in the USA, single-family houses constitute the majority of the cases [72], whereas, in Spain, it is multi-family dwellings that prevail.

4. Measurement data acquisition

The measurement protocols and standards used to characterise national built stocks differ significantly between regions. In European countries there is a typical measurement framework based on EN ISO 9972:2015 [73], and previously on EN 13829:2000 [74], as the main focus is on the assessment of whole building airtightness. On the other hand, in the USA and Canada different standards can be applied [75–79]. This number of alternatives is related to a greater focus on the details specifications of air barrier assemblies' construction [43], permeability performance [80], and assessment [81] required in the national building codes [40,43].

The systematic comparison of measurement protocols gives useful information on similarities and disparities between current practices. Their discussion and comparison with research in the field provide insight for the scientific community on what may be changed or improved.

4.1. Instructions

Although in Europe, the measurement standards in use have a joint base, the measurement methods adopted by each country differ, which compromise properly built stock characterisation and comparison [82, 83]. Despite the international standard [73] clearly states the actions on sealing and closing of different building components for the different test methods, in most of the countries there are national guidelines with either additional requisites on methodology and building preparation, such as France [84], or checklist documents helping the standard measurement interpretation of specific methods, such as Germany [85]. Future changes should point to convergence on this topic [83], a unified building preparation protocol, in a way that the contribution of ventilation systems and envelope itself are assessed separately in a complementary way of gathering essential data for future analysis, comparison and works.

4.2. Conditions

Table 4 Highlights the relevant information on the different analysed measurement standards. Regarding acceptable test conditions, all the standards establish a combination of rules regarding wind, temperature, and building height. Since all of them influence the measurement quality [86–88], standards should assess them in simultaneous.

Baseline zero-flow pressure readings are required by all the analysed standards, with changing demand on the number of points and reading duration. The latest literature on the topic [97] indicates that more extended measurement periods, especially on high wind conditions, can substantially reduce the impact of zero flow approximation on the uncertainty of the test. Uncertainty is higher for lower pressure stations [98]. These issues add up to the discussion concerning the adequate method for error estimation [98,99]. The consideration of higher numbers of measurement points [100–102] also improves combined uncertainty results.

Certain components and interfaces can suffer a valve effect on one of the directions tested [103]. This effect was found in several studies [58, 102,104,105]. With differences, up to 20% between pressure directions results, the consideration of an average value between them seems to be the most reasonable approach to assess the envelope airtightness performance.

Equipment accuracy experiences differences between European and North American approaches. Research shows that particularly for air pressure differentials and air flow rates this factor has a significant impact on the results reliability [106].

4.3. Metrics

The standards guidelines in North America instruct on the statement of results in several different metrics and at distinct pressure differences, but the national codes require the results for energy certification to be at 50 Pa. As referred in 2.1, the use of different derived quantities can be an additional difficulty, if one intends to make cross country comparisons of performance. In theory, with the direct measurement results, the derived quantities should be interchangeable. However, as they are dependent on building dimensions and despite measurement standards push for normalisation on their quantification, national guidelines still in force include differences in their assessment, which in practice translates in the introduction of errors on the conversion process [1].

Strict and uniform guidelines on measure and report of building dimensions need effective implementation so that additional error does not get introduced in these processes [107].

5. Information gathered

Due to the different purpose, nature of the databases, building codes and standards, substantial differences in the information and the form of data gathered by each one exist [108].

The information required for the construction of a database summarises in some major categories: air leakage measurements, test descriptions, dwelling characteristics, and other related information [1]. Most of the studied databases save the information required by the international standard ISO 9972 [73], and, in some cases, further data gets required by national regulations. The minimum information that a test report should contain are:

- Air leakage measurements: zero-flow pressure differences, temperature, wind speed, corresponding air flow rates for each induced pressure difference, and different values derived from the power-law equation;
- Test descriptions: measured extent, volume, status of the envelope openings, apparatus, procedure, method, standard;
- Dwelling characteristics: address, estimated date of construction and type of heating, ventilating and air conditioning systems.

No further dimensions, building systems nor information are required in the international standard. However, complete and accurate information of the dataset, including not only test results but also characterisation and other complementary data, allows for subsequent data analysis and the study of trends. The lack of precise information could lead to mistreatment of the data and inaccuracies.

5.1. Air leakage measurements

Within this category, all the information from the measurements carried out needs to be included. Beyond the minimum information established in the international standard ISO 9972 [73], some datasets

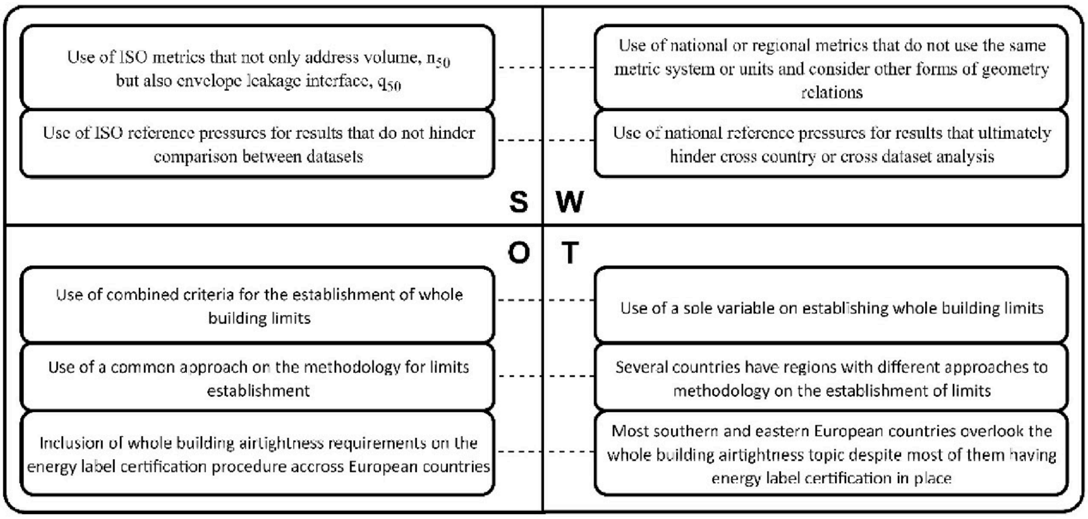

Fig. 3. SWOT scheme on regulatory context.

include leak location information by including thermal imaging when possible, e.g., Spain [61] Canada [59] or Czech Republic [1].

Air leakage location assessment make possible the identification of the most common envelope details [109] for intervention on a renovation scenario and provide awareness and push the search for better design practices in the future on new developments. France [84] and Belgium [95] have established categories of possible leakage paths to allow standardization and ease later analysis [109].

5.2. Test descriptions

Further details regarding the building status at the time of measurement and additional preparations should be specified For example, when national guidelines establish different protocols, as in the United Kingdom where extra possible temporary sealing, is allowed [110].

5.3. Dwelling characteristics

Commonly, databases store identification data on the dwelling, including the year of construction and retrofitting, as well as environmental data such as climate zone, shielding class, and terrain class, e.g. USA database [58]. Additionally, including pre- and post-energy retrofit information can be of great interest, as included in the Canadian database [59].

Typology data usually includes dwelling type or the number of storeys. The location of the unit within the building for multi-family buildings is also often saved [1]. In the case of the United Kingdom or Spain, there is a referral to adjacent unheated spaces, too. Previous

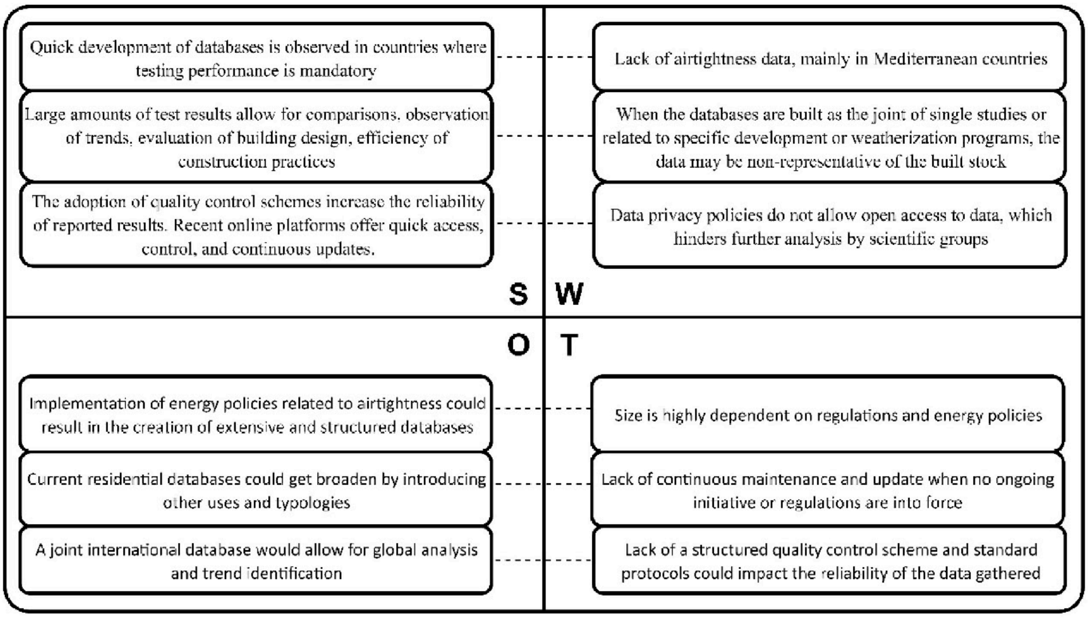

Fig. 4. SWOT scheme on the structure of databases.

studies show that interzonal leakage can be significant and account for up to 68% of the total air leakage rate [111–113]. This information is usually not specified in existing databases, and data only defines the extension of the local measured.

Regarding technology data, databases often require information related to the primary material, construction type, insulation characteristics, ventilation and heating systems, and equipment crossing the building envelope, or presence of distinctive elements influencing airtightness.

5.4. Other related information

Other information gathered in some databases is related to quality control processes, which require specific kinds of information to allow for audition and control. For instance, in the United Kingdom, as part of the quality control process, the operator entity carrying the test must supply its credentials along with manufacturer, model, identifier, and calibration proof on the equipment used [114]. Energy labels and specific certifications on compliance with a quality management scheme, together with operator information, must be included in the report in the case of France. Furthermore, as in Belgium, sometimes pictures of the tested building with the testing equipment installed are also required as part of the quality control [60].

Also, it is of interest to add further information such as, the motivation of the test, the retrofitting actions carried out, when applicable [1], or field evaluation of energy use profiles, included in the case of the EnerGuide for Houses (EGH) database in Canada [59].

6. Data analysis

Data in a national or regional database opens the possibility of analysing how it relates and impacts the airtightness performance of the built stock. Multiple regression analysis [4], Spearman's ranking correlation [115], ANOVA tests [116], and t-tests [117] are among the primary analysis tools for finding significant factors.

The representativeness of the databases is a key factor as some databases do not constitute a representative sample of the building stock because data was collected for a specific purpose or to analyse single issues [118,119]. For instance, when test performance is mandatory for new buildings, the existing building stock is not included, or when they belong to specific energy-related programs, it only focuses on existing dwellings with specific characteristics.

6.1. Geometry and technology

A recent study of almost one million Canadian homes [120] found building age, building volume, building height, climate, and insulation levels to be the best predictors of airtightness levels. An analysis of data on French single-family dwellings [4] concluded that construction type, floor area, number of storeys, insulation type, and age of the building were the main variables influencing airtightness.

A more recent analysis on a big dataset of the established French

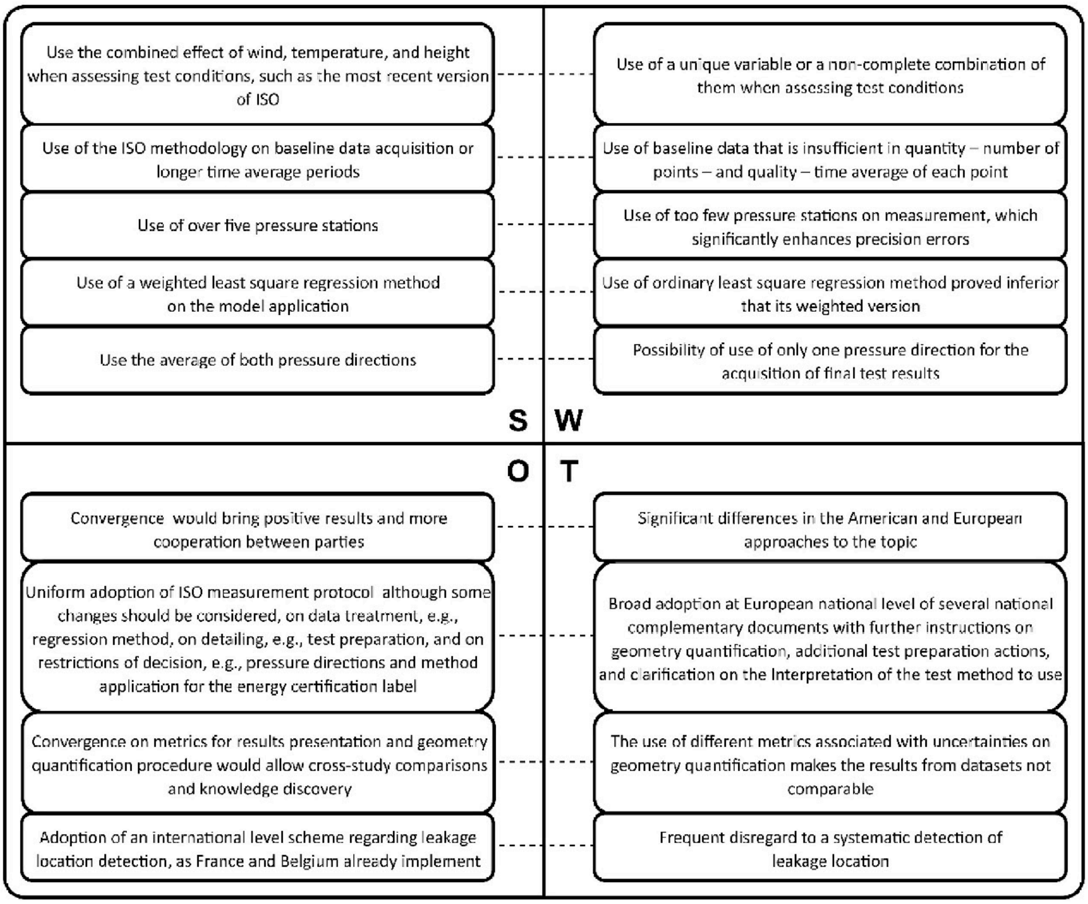

Fig. 5. SWOT scheme on measurement data acquisition.

database [109] found dwelling typology to have significantly different performances, in line with the findings in a Finland study [117]. Insulation characteristics and construction type impact got corroborated. Although more active ventilation systems are associated with tighter envelopes, as requirements already reflect, relevant differences between them were not found in this database contrasting with other findings [51,117]. Construction types of disparate impact is found in data analysis [121,122]. Timber frame dwellings are consistently found less airtight than reinforced concrete ones [57].

Envelope complexity, as defined by the wall, floor, and ceilings joints length divided by the envelope area, was found to be positively correlated to air exchanges in building envelopes [123,124]. The quality management scheme on the French national guidelines address leak detection and establish categories. Crossing floors and walls are the most frequently identified locations of leaks. Rolling shutter casing, ventilation air terminal devices, electrical grids in external walls, and external sliding doors are the other four that complete the top five categories of leak frequency in residential buildings in France.

Air exchanges also correlate to the number of significant envelope penetrations [57] and window frames [118]. Blower door tests on 20 houses in Athens [125] found total frame length to be a relevant factor affecting infiltration in buildings. These findings are in line with the leakage path location assessment also made in a study in Spain [6] and with the LBNL database [62]. The elements that constitute a building envelope should be targeted by dimension factors: areas, lengths, and points [5], as it is a significant concern for results comparison and conclusion drawing [107].

6.2. Workmanship and targets

The post-2006 new-built dwellings showed an average performance with around 6 $m^3/(h.m^2)$ at 50 Pa of pressure difference [57]. The analysis that was carried out included: one-way ANOVA for the impacting factors on air permeability; two- and three-way ANOVA for the assessment of the interactions between factors; and linear regression for the development of a predictive model of air permeability in United Kingdom dwellings. Management context, construction type, and dwelling typology were the most critical factors impacting airtightness and significant interaction between them was also found. As in the French database, the distribution of air permeability performance results of the ATTMA database [110] does not present a defined skewed normal distribution, instead shows abrupt changes in the distribution around the design target values. Two different causes are pointed out for this result: contractors actions are optimised for compliance with upper limits; allowed sealing, by the ATTMA test protocol in force [126], is being voluntarily exceeded during measurements. Design targets, professional supervision and workmanship are often highly correlated to airtightness performance [127–129].

6.3. Durability and climate

The construction ageing factor focuses on the degradation over time of envelope airtightness performance, such as warping of front doors and roof service penetrations [9]. Often asymmetries on building techniques and airtightness regulations are pointed as the causes for different performance evolution over time. Still, new dwellings cannot automatically be assumed as more airtight than older dwellings, since most of the older dwellings sometimes undergo retrofitting works with positive impact in the airtightness performance [123]. Year built and climate were the highest correlated parameters with air leakage in the latest LBNL database analysis [62].

Airtightness ageing variability assessment for new and weatherised homes in the United States estimated an average factor of 15% increase in normalised leakage over ten years [129,130]. Accelerating ageing by hygrothermal cycles in a test room, concluded that airtightness durability is strongly dependent on the sealing techniques and application methods [131]. Tape products had their performance reduced, mainly due to the different shrinking rates of the materials in contact. Since sealants must be able to cope with the movement of the materials, joint sealants density and elasticity were the leading indicators for occurring cracks or shrinkage and consequently airtightness deterioration. However, distinct sealants respond differently to the ageing process [119]. These results are sustained in other literature [132,133].

Even though weather and general climatic conditions having reduced impacts on airtightness measurement results since a high degree of independence gets ensured by test standard rules and guidelines [134], mean values or air change rate at 50 Pa of buildings in different climates differ significantly [62]. These discrepancies are mostly associated with factors of the categories mentioned above, frequently airtightness design consideration, and distinct construction techniques used.

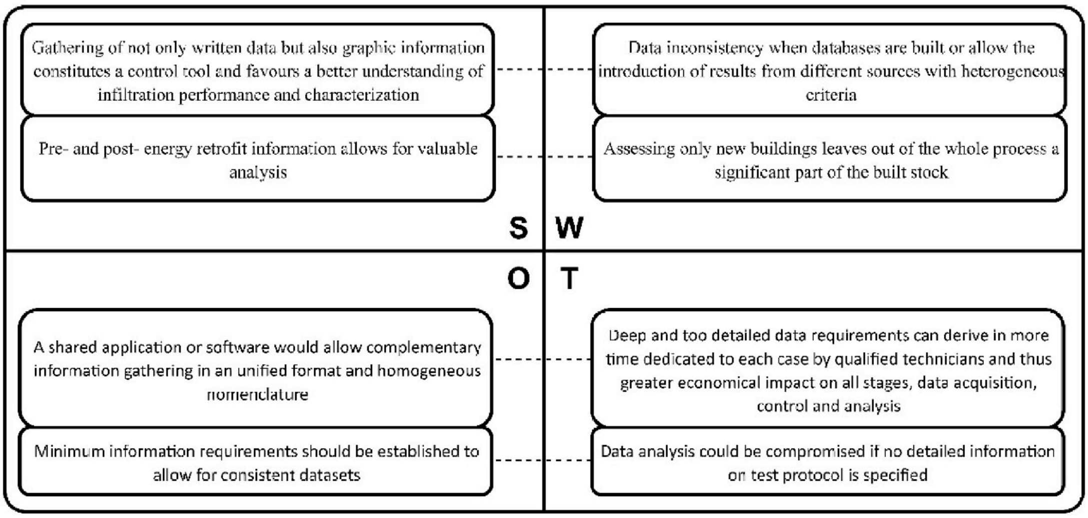

Fig. 6. SWOT scheme on gathered information.

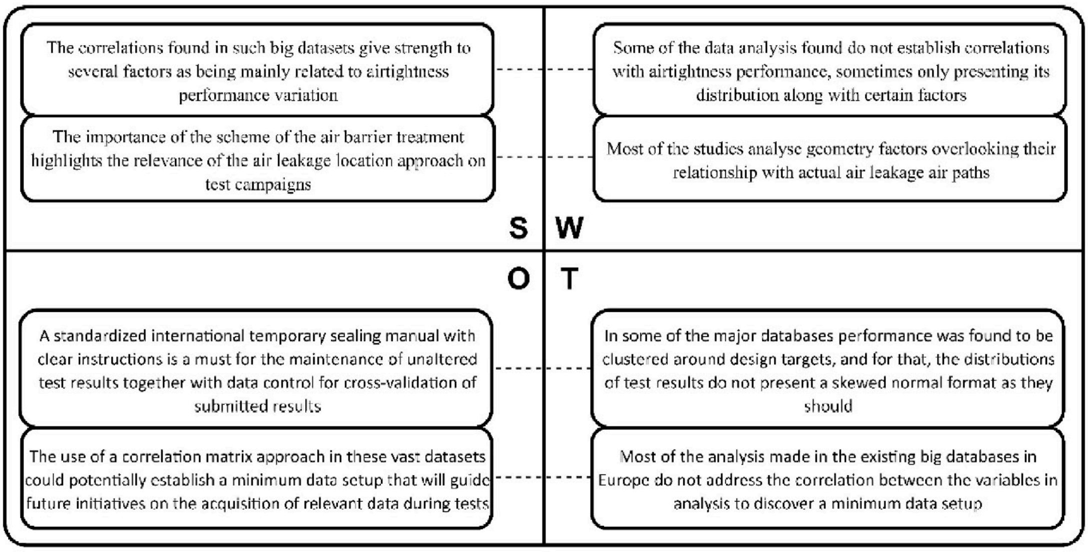

Fig. 7. SWOT scheme on data analysis.

6.4. Primary and secondary factors

Overall, despite some significant correlations found between either the airtightness performance and the identified variables either between the variables themselves, causality relations are rarely addressed. As referred before, the greater awareness towards airtightness concerns in severe climate zones, because of the more significant impact of air leakages in those, leads to seeking and applying more effective building technologies and strategies to cope with it. Climate is, therefore, not a factor by itself but rather a potentiator of others.

One can consider primary factors like the ones that require decisions to happen during the design stage of a building, and that gets directly potentiated by climate. The others are consequences of the first and as so seen as secondary factors (Fig. 2). Primary factors will have different degrees and quantity of interactions between them and with secondary ones.

6.5. Energy impact

While the previous subsections referred to variables influencing airtightness, the energy demand of a dwelling is one of the variables that airtightness influences. The analysis of large airtightness datasets can be useful to estimate the potential benefits of implementing airtightness improvements and the impact of energy policies on the energy performance of dwellings [135].

The energy impact of air infiltration has been a major driver for increasingly stricter building airtightness requirements [136–138]. With emerging large datasets of measurement data, the assessment of the evolution over time of the weight of airtightness on the energy performance of residential sectors can be done with increased accuracy. This increased accuracy accrues from considering test results in such large scales, and not values obtained from a prescriptive approach, either default, recommended or tabulated by components checklists.

While simulation scenarios, on the improvement and compliance with the most up to date energy codes, present theoretical ranges of energy savings [135], direct analysis of this evolution with real measurements from databases is not available.

Studies of these datasets clearly indicate that the transition to mandatory requirements, and the reduction of the stated limit by approximately half, significantly improved airtightness levels stabilising on the new limit in a period of few years [56,109].

Other studies assess this evolution indirectly, concluding differently. In an analysis of a dataset from the USA [62], latter buildings were found to be more airtight than older ones. Despite associating the majority of the disparities to the ageing of the building, it is recognised that different building practices and stricter requirements in building energy codes may partly justify them. On the other hand, other authors studied the correlation between airtightness levels and different energy performance regulations, in Spain, in which airtightness was not a requirement [6]. No significant improvement was observed over time. If one assumes that ageing is associated with airtightness deterioration, these results hint for higher air leakage rates in newer buildings. The general disregard for the issue during the installation of building systems is pointed as the most probable cause.

7. Discussion

The systematic analysis of existing airtightness databases allows for a discussion concerning their Strengths, Weaknesses, Opportunities and Threats (SWOT). This method allows for a structured mind map of the reviewed literature while paving the way for the proposal of future works. Therefore, in each topic, a SWOT scheme is presented with the main conclusions.

7.1. Regulatory context

From a regulatory point of view, the weak points are mainly related to the adoption of different metrics on the expression of measurement results between countries (Fig. 3). Additionally, the reference pressures used for the results are often not coincident between countries. The use of the metrics dependent on pressure differences within measurement range, such as 50 Pa, based on geometry data that allows straightforward comparisons, such as volume, and based on building leakage interfaces, such as envelope area, are the ones recommended.

There is not a single common variable defining performance limits between countries, and occasionally disparities at a regional level in the same country are present. All of them use a one-variable approach.

A combination of several variables already in use with others affecting the performance of natural and adventitious ventilation systems would be a better approach. Southern and eastern European countries with predominantly naturally ventilated dwellings would benefit the most. These are also the countries that often overlook whole building airtightness performance. Including limits on these countries and attaching them to energy label certification procedures would be a big step in the nZEB pursuit.

7.2. Databases structure

There are some common trends regarding the structure of databases and their general functioning. Recent initiatives in European countries such as France or the United Kingdom seem to constitute examples of good practice that could serve as a basis for further initiatives (Fig. 4). These databases have experienced a quick development for the last few years, implementing structured functioning, including quality control schemes that guarantee the reliability of the data.

The main weaknesses detected are related to the lack of data in some regions and the representativeness of the whole building stock. Thus, it seems critical – an opportunity – the further implementation of universal and international energy policies that favours airtightness performance tests, not only for residential buildings but also for other typologies and uses. Despite administrative, regulatory, and data privacy obstacles, a common framework, structure wise, would constitute a powerful tool for easy data analysis and control. The inclusion of other uses and typologies, e.g. institutional, commercial, would require frameworks to adapt, especially regarding requirements, to reconcile the needs of users, and data acquisition protocols, as larger and more complex envelopes often require different techniques for proper testing [139,140].

7.3. Measurement data acquisition

On measurement data acquisition, the weaknesses are related to the procedures established in the measurement protocols. North American measurement protocols do not include the combined effect of wind, temperature, and height on the assessment of test conditions and only a non-complete combination of them, in contrast with the ISO standard (Fig. 5).

Literature indicates that baseline data points (zero flow pressure measurements) should have increased time average for higher measurement precisions. Other recommendations indicate the need to increase the number of pressure stations during the tests, to use the average of both pressure directions, and to apply the weighted line of organic correlation regression method in opposition to the ordinary least square one. Some of these points are better implemented in a few of the analysed test protocols, and some in others. The ISO standard is slightly loose on these procedures, leading to the national adoption of different guidelines. These guidelines include the adoption of several complementary documents with further instructions on geometry quantification, additional test preparation actions, and clarification on the interpretation of the test method to use. Disparities in geometry quantification are especially deterrent of comparisons between datasets of countries with different setups. Efforts should focus on the restriction of these processes.

The authors emphasize that the further detailing of current practices may be counterproductive for implementation. Therefore, a path of uniformization on use of the most promising validated methods of different protocols should be pursued. A convergence between American and European protocols would open significant possibilities for results comparison.

Additionally, most countries disregard the systematic detection of leakage location. The embracing of a framework at the international level regarding this issue, as France and Belgium already implemented, would be a big step forward on the topic awareness. Qualitatively, the location of air leakages does not impose an extra significant amount of labour on the tester part, and methods are well established [141]. Quantitatively, the additional work could make the systematic assessment economically unfeasible, and the accuracy of the obtained results presents itself as an additional issue.

7.4. Information gathered

Regarding the information gathered in the existing databases, all of them contain the necessary airtightness information as recommended in ISO 9972 (Fig. 6). However, it is often heterogeneous and lacks characterisation information, not only among different databases but also among different cases of the same dataset. The reason is that different agents feed the databases, and protocols and criteria are not always uniform. This scenario constitutes, by contrast, an opportunity to set a common framework with a unified platform that would accelerate information processing and control.

Characterising the building does not seem to be an essential issue when only performance results need to be justified to comply with specific regulations. Nevertheless, it is useful and necessary in order to identify trends and factors that impact the airtightness of the envelope. A similar situation is present in the case of pre- and post-retrofit tests.

Another critical issue is the establishment of the minimum information required in a database. The more data acquired for each case, the more analysis and conclusions can be derived. However, too detailed data requirements can also be a threat due to the time required, that could affect the normal use of the building and testing efficiency, deriving in an undesired economic impact. Thus, a balance should be pursued.

7.5. Data analysis

Data analysis shows that some of the studies do not try the establishment of correlations between the variables themselves and between them and airtightness performance (Fig. 7). The research that makes this type of analysis either give strength to suspected factors or uncover misled conceptions on their relation to airtightness performance variations. Further testing correlation between variables would allow the obtention of a minimum complementary data setup. This type of analysis could be performed within the existing massive datasets with a high number of additional data categories. A minimum complementary data setup could guide future initiatives.

Some of the problems found in these analyses feature airtightness performance bunching around design targets and not presenting precise skewed distribution like expected. This hints to a potential misinterpretation of results. In residential buildings, standardised international temporary sealing rules with clear instructions for no second interpretation is a must for the maintenance of unaltered test results together with data control for the cross-validation of submitted results.

Additionally, subsequent estimation of the energy impacts of the obtained airtightness database results should be generalized as it gives additional insight on the built environment. However, it is important to note that airtightness values in databases must be transformed into air infiltration values, considering the building envelope and the driving forces. This issue can be difficult to address, and a mean heating season infiltration rate is commonly inferred from an air leakage rate, although simplified models have been developed, and have proven to obtain accurate estimations even at a population scale [138,142].

8. Conclusions

Regulation wise, a trend of increasingly stricter requirements is observed over time, primarily on the grounds of the push for nZEB implementation. Additional challenges maintaining adequate air change rates for indoor air quality are expected in the future, especially on the design and retrofitting of adventitious and naturally ventilated dwellings.

Compliance by testing remains circumscribed to a few countries and mainly to performance paths. The reliance on prescriptive approaches to meet airtightness requirements leaves a significant number of variables influencing the final performance unaccountable, mainly workmanship and quality of construction. Throughout the studied countries,

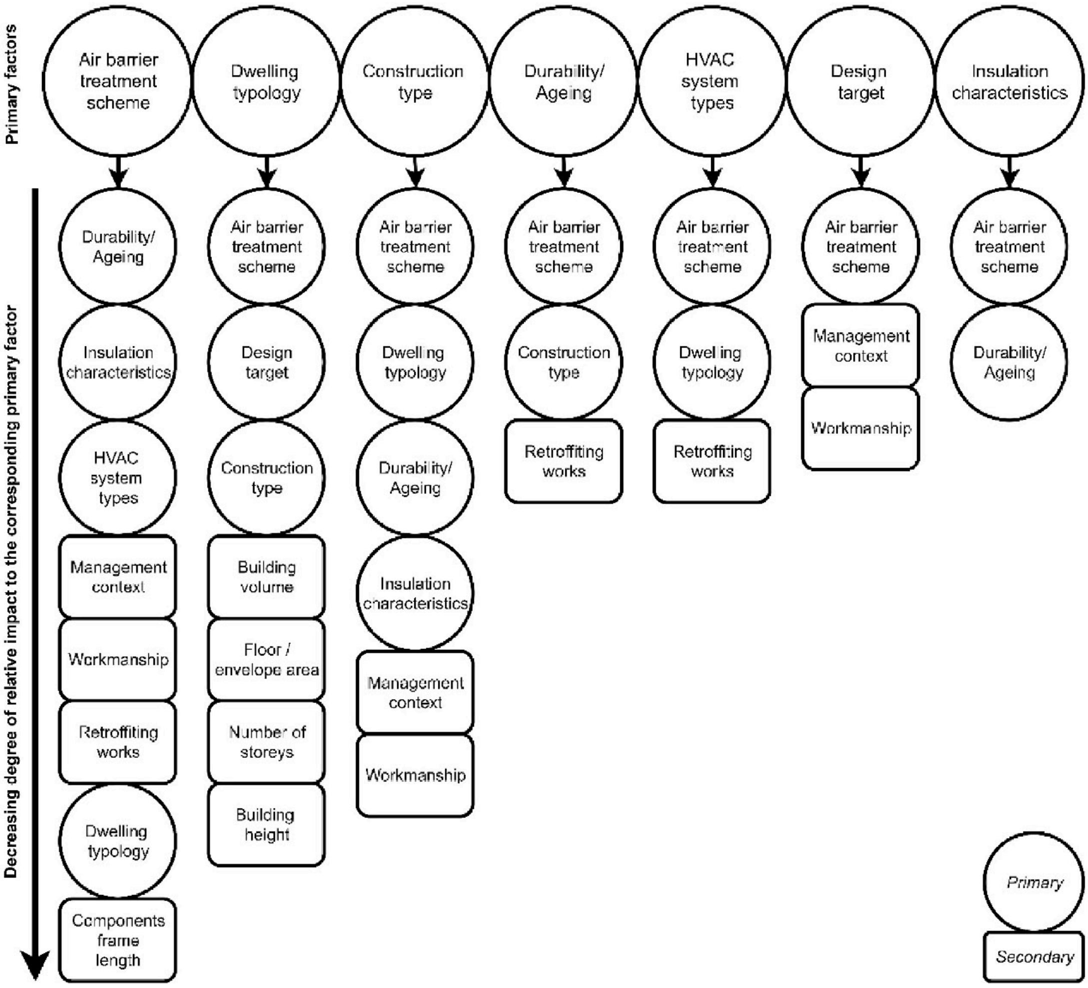

Fig. 2. Primary and secondary factors related to whole building airtightness performance.

preferring performance approaches over prescriptive are trending.

Due to more severe climates, countries in North America and northern and central Europe have more demanding regulatory frameworks than southern European ones, that generally overlook the issue. As shown in section 2.2, in addition to the relevance in the implementation of nZEB, not only energy related issues are associated to airtightness performance. This represents a window of opportunity to implement proper practices in these latter countries.

The setups revised experience significant disparities, regarding structure, information gathered, and data acquisition during measurements. This is the most influential setback in cross data analysis. After a detailed analysis of the different main approaches, a common framework should be based on the:

- Creation of a user friendly, accessible web-based platform for data communication between regulating bodies and practitioners: easing data communication facilitates data storage and further treatment
- Application of an unambiguous quantitative measurement procedure regarding dwelling preparation, data acquisition and presentation of results: validates cross-analysis between results of the same scheme and between different ones in different countries or regions. Seemingly a non-issue by the adoption of ISO codes, it was shown that countries define additional rules
- Comprehensive gathering of dwelling information on visual inspection: many of the factors influencing airtightness are known, but their relative impact and comparison between datasets are hindered by the type of analysis or lack of structured data. Analysis of huge structured datasets may provide insight on the characteristics of particular built environments and even develop reliable prediction tools
- Consideration of applying qualitative tests such as thermography or smoke tracer: this encompasses a specific visual inspection that requires additional instrumentation. Still, identifying particular contributors to the overall performance, and their respective prevalence in a building sector, paves the way for the consideration and application of specific correction measures
- Implementation of a QMS, including procedures for tester training, results control and production sampling for test: such a practice, as a national airtightness database, is only possible when these three aspects are clearly prepared by the supervising bodies.

Even though the uniformization of aspects of structure and data gathered is recommended in this work, it points to the form and method and not to the specific content. The reality of each country or region, regarding average building quality, and particular construction technologies and design principles, may require adaptations that translates in different limits and airtightness solutions.

Establishing building airtightness requirements that bind with energy efficiency labelling, either with mandatory or penalty-reward setups, has been proven to be the origin of solid and long-lasting databases. Airtightness databases are key to allow the characterisation of the residential built stock and give knowledge on what issues to tackle next regarding airtightness performance and control.

Additionally, accurate data on airtightness performance allows more reliable estimation of its relative impact on the energy performance and verifying the repercussion of introducing or changing requirements.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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5 RESULTS

The main results of this Thesis are gathered within the related papers that are the core of this work.

In ***Paper 1***, the Methodology for the characterisation of the building envelope in Spain was presented. The main outcome was the methodology itself, which included the sampling method proposed for the selection of a sample of representative dwellings and their distribution, the adopted measurement method using whole building pressurisation tests and specific guidelines regarding building preparation, the method proposed for the location of leakage paths, and the input required for the whole characterisation of the cases by means of a specific tool. Additionally, the methodology was applied to a case study for its validation, and the airtightness results were put into context and compared with the dataset available to date.

The results obtained from the characterisation of 129 cases in the Continental climate zone of Spain were gathered in ***Paper 2***. General airtightness results of the most significant parameters can be checked, as well as the distribution of the permeability results, and typical leakage paths were identified using IR thermal imaging. To conclude, a statistical analysis was performed in order to identify the influence of different parameters in the airtightness of the cases, also graphically shown through box-plot graphs.

In line with ***Paper 2***, ***Paper 3*** describes the main results obtained from the sample of 225 cases in the Mediterranean area of Spain. The main airtightness results were shown, both for the whole sample and itemised by different building characteristics. The statistical significance of the results was presented as well. Finally, the energy loss associated with the air infiltration was estimated and results were presented.

The main outcomes reached in ***Paper 4*** are related to the estimation of the energy impact of air infiltration of the previous paper. This time, the whole database was assessed. In addition, the relative impact of leakage on the heating and cooling demand was approached, sorted by the location of the dwellings.

Paper 5 makes reference to the exploration of the main databases on airtightness. After the identification of available data and their functioning, results were related to their analysis and comparison, pinpointing their strengths and weaknesses, and identifying problems in the existing practices as well as opportunities for future practices.

Complementary results are gathered in other published papers, conference papers and posters, book chapters, and other dissemination formats listed in Annex I: Scientific dissemination. Annex IV: Test reports contains the full characterisation details and measurement data of each case assessed. The detailed main general results and statistical analyses can be checked in Annex V: Test results.

6 CONCLUSIONS

The conclusions derived from the results obtained in this work are closely related to the objectives proposed. Specific conclusions and further details are available in each of the papers that compose this Thesis.

In ***Paper 1***, after the identification of key knowledge gaps and needs (Objective 1: *To understand the existing information and data to be obtained for the evaluation of the airtightness of residential buildings*), the main conclusions derived from the validation of the proposed methodology to characterise the airtightness of the building envelope of dwellings in Spain were presented (Objective 3: *To identify the procedures for cataloguing airtightness phenomena*). The basis of a replicable airtightness database at a national level was established.

The first conclusions resulting from the analysis of dwellings in the Continental climate zone of Spain were presented in ***Paper 2***. The conclusions mainly focused on the location and type of the main leakage paths (Objective 6: *To identify typical leakage paths using proven and viable techniques*), the global airtightness performance of the dwellings tested (Objective 4: *To quantify the airtightness of the building envelope of residential buildings in Spain* and Objective 5: *To analyse the current state of the building stock in terms of airtightness according to the indicators and building characteristics*), and identified trends concerning the influence of several construction characteristics (Objective 7: *To study the main factors that define the degree of air permeability of buildings*).

Further partial results of dwellings tested in the Mediterranean area of Spain were discussed in ***Paper 3***. The main conclusions were related to the characterisation of the airtightness of the building envelope (Objectives 4, and 5) and the statistically significant relationship of different parameters (Objective 7). In addition, the impact of air infiltration on the energy demand by city and related to the regulations in force was assessed, and the conclusions reached were discussed (Objective 8: *To evaluate the energy impact of air infiltration in residential buildings*).

Paper 4 further discussed the global performance of the building envelope in Spain in terms of airtightness (Objectives 4 and 5), and the energy implications of uncontrolled airflows on the heating and cooling demand in Spanish dwellings (Objective 8). Conclusions highlighted the necessary air infiltration limitation in the current national and international context, where huge efforts are being made to reduce energy use towards the accomplishment of a decarbonised building stock.

To conclude, ***Paper 5*** presented the conclusion derived from the analysis of the main frameworks at an international level regarding airtightness measurement protocols (Objective 2: *To gather, evaluate, and study international procedures and methods for the determination of the air permeability of buildings*), databases (Objective 3), regulations, and data analysis (Objective 1). The main trends in this context were identified, as well as strengths, weaknesses, opportunities and threats of the current practices. Finally, some general guidelines for a common setup were presented as a conclusion of the review carried out (Objective 3).

General conclusions were reached from a global point of view from the work carried out in this Thesis:

In line with Objective 1, the state of the question was assessed both at a national and international scale in order to identify the knowledge gaps regarding the airtightness of the building envelope. Section "State of the art" broadly addresses this issue.

A growing interest in airtightness characterisation in dwellings was identified in North America and European countries for the past 40 years. This fact is reflected in different manners, both in the broad published literature in this field, and in the increasingly stricter requirements encouraged by the push for nZEB (see ***Paper 5***). Northern European and North American countries have led this trend for many years, probably as a result of the major impact of air infiltration on energy loss in severe climates. However, the necessary growing ambition towards the reduction of pollutant's emission and, thus, energy loss, involves the reduction of uncontrolled airflows through the building envelope, even in countries with a mild climate like Spain.

The lack of knowledge in this field in Mediterranean countries, and, specifically in Spain, is undeniable (see ***Paper 1*** and Section "Background on the study of airtightness in Spain"). Given the traditional dependence of air renewal needs on air infiltration, airtightness has been mostly ignored so far. However, the changing scenario towards the implementation of nZEB makes it essential to address this issue. With that in mind, the importance of airtightness as the main feature that conditions air infiltration is highlighted, and, thus, the need to evaluate the airtightness performance of buildings opens a window of opportunities to implement proper practices.

Regarding the analysis of international procedures and methods for the evaluation of the air permeability of the building envelope (Objective 2), a review of the main airtightness measurement methods is presented in Section "Airtightness measurement". After the assessment of the different available technologies and current practices, the DC pressurisation method was considered the most fitting approach to meet the objectives of this work. In spite of the drawbacks of this method, e.g., the pressure gradient is not representative of natural conditions and, therefore, air infiltration is not measured, the induced pressure difference minimises the impact of weather-driven forces.

Among other motives, it seemed reasonable to adopt already proven and widespread protocols, and a method with acceptable uncertainty in order to guarantee data comparison. However, significant disparities among the protocols adopted in different countries were identified, mostly related to building preparation, measurement protocols (pressure stations, regression method, etc.), and geometry quantification (see ***Paper 5***).

Therefore, seeking uniformity, a measurement protocol was established based on the International Standard UNE-EN 13829 (see ***Paper 1*** and Section "Determination of the air permeability"). Particular construction technologies and designed principles made it necessary to set additional fully compatible guidelines: both pressurisation and depressurisation modes were required, 10 measurement points at different pressure stages, building preparation according to both Method 1 and Method 2, specific sealing instruction for typical envelope elements, etc. In addition, leakage location was implemented by means of IR thermal imaging, which most international measurement protocols disregard.

Objective 3 was accomplished by the development of a procedure for cataloguing airtightness phenomena. The main airtightness databases in Europe and North America were studied as a starting point to identify weaknesses and opportunities to learn from good practices and avoid mistakes made (see ***Paper 5*** and Section "Airtightness databases"). Some common trends concerning their structure and their general functioning were identified. In general terms, recent initiatives such as the ones found in France and the UK were seen as successful examples given their quick development experienced for the past few years. Their structured functioning, quality control schemes, and data reliability seem to offer great opportunities for further initiatives.

On the other hand, weaknesses were identified in other examples. The main shortages were related to the lack of data in some regions and the lack of representativeness of the whole building stock in order to draw conclusions regarding the performance of the building envelope. Uniformity issues, and administrative and data privacy obstacles prevent a common framework at an international level, which would constitute a powerful tool for easy data analysis and control.

In this scenario, an airtightness database was created for the characterisation of the performance of the building envelope in Spain. A new procedure according to the needs of this work was determined in order to gather the necessary data in a coordinated, systematic and efficient way, which would allow ultimately valuable and accurate data analysis from the results obtained. For this purpose, a replicable sample scheme was designed with the aim of determining the minimum representative cases to be analysed (see ***Paper 1*** and Section "Determination of the sample"). Some limitations were found in this regard, given the difficulties found for the assessment of certain dwellings, but overall, the method proposed was validated and was sufficient to draw general conclusions.

The data management was performed with a specific tool developed with the aim of gathering full characterisation information of each case: *infilAPP*. It allowed the performance of standardised tests and data systematisation that enabled objective results analysis (see ***Paper 1*** and Section "Characterisation of the dwellings"). In spite of some problems found related to the need for too wide characterisation data, which was found sometimes difficult to assess, its use was found useful and, therefore, its extended practice would allow the construction of a national database developed by multiple agents. Moreover, its basis could be replicable in other scenarios such as other areas with a lack of knowledge on this field.

Compared to other databases, the Spanish example was a one-time effort initiative that worked as a pilot. It can be seen as a learning initiative that could mean the origin of a public initiative resulting from airtightness requirements. In this regard, it is important to note that efforts should be done to implement quality management schemes and training programs to guarantee data reliability, following the example of other countries.

The quantification of the airtightness of the building envelope of dwellings in Spain (Objective 4) was addressed by performing pressurisation tests in a representative sample of the building stock (see Section "Tested dwellings"). First, the physical principles of the airtightness phenomena were addressed (see Section "Airtightness of the building envelope"). The distribution of the permeability results obtained followed a non-normal distribution in a wide range: the air change rate at 50 Pa (n_{50}) was between 1.19 to 39.42 h^{-1} with a median value of 6.39 h^{-1} (***Paper 2***, ***Paper 3***, ***Paper 4***).

The airtightness results obtained allowed the analysis of the current state of the building stock in Spain (Objective 5). The median is below but close to average values of 7.5 h^{-1} reported in European surveys that assessed samples of existing building stocks (Laverge et al., 2014).

The airtightness performance was dependent on the location and climate zone of the dwellings, with significant differences among building stocks. Clearly better performance was found in the Oceanic and Continental climate zones, whereas dwellings located in Mediterranean areas were leakier. This could be derived from the extreme winter temperature conditions in the Continental area, which significantly differ from mild Mediterranean climate areas. In the case of the Canary Islands, the reduced sample did not allow to draw clear conclusions (see ***Paper 4***).

The analysis of the results obtained showed that the airtightness of the building envelope has not led to a significant improvement over time. New buildings had better airtightness performance than older ones, but only within a tight range, even though construction technology and regulations have experienced great development. The entry into force of NBE-CT-79 (Ministerio de Obras Públicas y Urbanismo. Gobierno de España, 1979) and CTE regulations (Ministerio de Vivienda. Gobierno de España, 2006c) concerning the energy performance of buildings could have urged a slight improvement (see Section "Airtightness of the building envelope in Spain", ***Paper 2*** and ***Paper 3***). However, the fact that none of them considers airtightness nor establishes any limitation could explain that building systems and construction is done carelessly regarding this aspect.

It seems clear that the performance of new buildings in terms of airtightness is still far from current practices in other European countries. There is a scarce concern related to the impact of air infiltration due to the lack of airtightness. Therefore, whole building airtightness requirements and demonstrated compliance could be the only path towards the tightening of the building envelope.

The wide dispersion of the results hinders the identification of trends and comparison to current buildings airtightness requirements in Spain (maximum n_{50} of 3 to 6 h^{-1} depending on the compacity, see Section “Airtightness requirements in Spain”). Implementing real target values that condition building design and construction is key to accomplish good performance. In any case, limit values seem easily reachable if airtightness is taken into account from the design stage and also workmanship, both for new and renovated dwellings. Still, workmanship and the lack of awareness remain the main challenges to overcome in the near future. The recent implementation of whole building airtightness requirements does not enable the analysis of its impact yet.

The quantification of the airtightness of the building envelope also enabled the understanding of the dependence of naturally ventilated dwellings on air infiltration, although this issue was not specifically addressed (see Sections “Impact of air infiltration on ventilation” and “Ventilation strategies in Spanish dwellings”). Therefore, deep building renovation in line with EPBD towards the transformation of existing buildings into nZEB should not overlook the risk of poor IAQ if retrofitting actions do not encompass ventilation systems implementation.

Typical construction discontinuities and defects of specific building systems were identified according to Objective 6. Leakage paths were located using IR thermal imaging during the depressurisation stage of the airtightness tests performed in the selected cases (see Section “Leakage location” and ***Paper 2***). Climate limitations made IR thermal visualisation difficult in some cases when there was not enough temperature gradient. Therefore, the use of alternative methods is suggested for future experiences when the minimum thermal conditions are not met.

Discontinuities of the building envelope were confirmed mostly in window frames and rolling shutters, but also in pipe and duct paths, and construction joints. Even in the case of dwellings with airtight windows that complied with regulations, poor workmanship and joint design led to window-wall discontinuities (see Section “Leakage paths on the Spanish building envelope”).

In recent dwellings, poor design of the lightweight inner layer of the envelope combined with an air chamber and a discontinuous or inexistent air layer were the main reasons for inadequate performance. Workmanship and poor design were, therefore, pointed out as the main reasons that explained the presence of air leakage paths.

The flow exponent n obtained from the pressurisation tests performed provided information regarding the type of openings of the building envelope. Mean and median values of 0.60 mean that infiltrating airflows tend to be turbulent through punctual and direct cracks. Thus, the commonly accepted value n = 0.65 in other countries (Orme et al., 1994) is not accurate for the existing residential building stock in Spain. This fact can be explained given the different building systems used in the country, where massive construction prevails, and workmanship plays an important role.

The identification of the main leakage paths constitutes an opportunity in the current context for the development of specific building systems and solutions that overcome the main troublesome points from the design stage, as well as for efficient renovation works.

Objective 7 was approached through the statistical analysis of the data to identify the main factors that define the degree of air permeability of buildings. Even though the limitations of the sample size did not enable the development of a detailed airtightness model (see Sections “Development of predictive models” and “Airtightness estimation in Spain”), or drawing more accurate conclusions, general trends were revealed. The great variability of the workmanship quality and the difficulties found to evaluate it were also pointed out as one of the reasons why more precise conclusions could not be reached.

Regarding construction systems, window material, rolling shutters’ position, and retrofitting state were found to be relevant factors concerning the airtightness of the building envelope (see ***Paper 2***, and

Paper 3). The impact of different window materials was assessed. Aluminium and PVC windows prevailed in the sample, with better results obtained for PVC windows. Associated with window characteristics, rolling shutters play an important role in airtightness. Against all odds, dwellings with no rolling shutters were not statistically the most airtight. This could be explained because most of the dwellings without rolling shutters were the oldest ones and often were in an original state. Integrated rolling shutters seem to perform better than traditional non-integrated systems.

The improvement of retrofitted dwellings with regard to original ones may be explained by the indirect impact on the airtightness of the thermal insulation of the envelope. Thus, airtightness improvement could be greater if it was considered, and specific measures were taken during the retrofitting process. This information is essential for the optimisation of design and renovation decisions.

Lastly, the energy impact of air infiltration through the building envelope in Spanish dwellings was assessed, according to Objective 8 (see ***Paper 3*** and ***Paper 4***). First, the phenomenon of air infiltration as a result of the lack of airtightness and the action of driving forces was addressed (see Section "Air infiltration"). Then air infiltration rates were estimated from the airtightness results obtained (see Section "Air infiltration rate estimation"), and finally, the energy impact of air infiltration on the energy demand of the dwellings was calculated (see Section "Energy impact assessment").

The results obtained are in line with the values previously stated in previous studies (Spiekman, 2010). The energy impact of leakages was found significant, mostly on the heating demand, even in areas with a mild climate. Air infiltration is responsible for up to 25% of the heating demand, and 12% of the cooling demand. It must be noted, though, that these figures considered the total infiltration airflow and, thus, the necessary air renewal flow was not deducted. In any case, it is possible to conclude that air infiltration through the building envelope has a significant impact on the energy demand of dwellings, and, thus, this issue necessarily needs to be considered given its demonstrated relevance. Consequently, compliance with European Directives seems only possible by paying special attention to permeability limitations. The quantification of potential energy-saving will be crucial for the implementation of future energy policies and strategies in a realistic way.

All things considered, the airtightness characterisation of the building envelope of existing dwellings in Spain was fulfilled through this work, accomplishing, therefore, the General Objective of this Thesis. The assessment of the different features according to the secondary objectives contributed to filling the identified knowledge gap. The conclusions reached regarding the airtightness performance of the building envelope of the existing residential stock will be essential to approach building design and deep renovation strategies. This will enable the responsible agents to prioritise the efforts towards renovation strategies and policies towards a decarbonised building stock in the near future.

6.1 FUTURE RESEARCH LINES

The work carried out within this Thesis has found a number of limitations and certainly has opened research paths that could be approached in the future.

Creation of a national airtightness database.

With the lessons learned from the methodology proposed in ***Paper 1*** and the analysis of existing databases carried out in ***Paper 5*** as a starting point, the creation of a national airtightness database could constitute a useful tool to offer valuable information on the building stock. The development of an adequate testing protocol, sampling method, determination of the data gathered, the establishment of a quality management scheme and certification requirements, and the creation of an easy and accessible platform are the main challenges to overcome.

Expansion of the sample and cases of the database.

The sample of dwellings characterised for the purposes of INFILES Project was designed from a statistical point of view to be representative of the main typologies and characteristics of the building stock. However, a broader sample would be needed in order to draw more accurate results and avoid possible distortions caused by non-representative cases. Furthermore, the database should be completed with other underrepresented areas, such as some regions and dwellings located in rural areas, where buildings could perform differently. Ideally, the database would be complemented by airtightness and characterisation results performed by other agents who are involved in renovation and certification processes. This can be considered a realistic option after the recent whole building airtightness requirements set by regulations.

Estimation of the energy impact of the air infiltration at a building stock scale by means of dynamic models.

For the purposes of this work, the estimation of the energy impact associated with air infiltration was approached by means of a simplified procedure that cannot be considered accurate since only annual mean infiltration rates were considered, and latent heat was not taken into account. It was only a first estimation, but, doubtlessly, a more specific method should be applied in order to obtain more accurate results to consider regarding energy policies and strategies definition.

Interzonal air leakage assessment between units in multi-family dwellings.

Another limitation of the present work, which will be addressed in the future, is the assessment of interzonal air infiltration. This can be easily approached by means of guarded-zone pressurisation tests, among other options. The contribution to this knowledge gap would provide valuable information, which is key for the study of the energy performance and pollutants' transmission between different units.

Estimation of the impact of air infiltration on ventilation.

Although this topic was beyond the scope of this Thesis, the study of the contribution of air infiltration on air renewal is a closely related issue, which can be easily approached from the airtightness characterisation data obtained. The estimation of the relationship between airtightness and ventilation is crucial when facing and proposing renovation measures given the dependence on air infiltration as an air renewal source in the building stock analysed.

Development of a predictive model to estimate the airtightness of the building envelope in Spanish dwellings.

Further analysis of the available collected data can be subject of future research, going beyond descriptive statistics. Inferential statistics using univariable and multivariable analyses will be performed in order to identify relationships and trends in the data, which can be of great interest to provide further understanding of the airtightness performance of the building envelope in Spain.

In addition, airtightness predictive models offer valuable information (see Section "Development of predictive models"). However, models proposed in other contexts do not apply to the Spanish building stock. Therefore, a deep analysis of the database, ideally completed with further cases, could result in the proposal of a realistic model that, among other applications, would improve the airtightness estimation required by regulations when a pressurisation test is not performed.

Proposal of standardised airtightness values as input data for simulation and certification models.

A methodological guide could be developed in order to incorporate airtightness and infiltration airflow values in building simulation and energy certification software. This will enable more real values when airtightness pressurisation tests have not been performed.

Development of retrofitting verified solutions to improve the airtightness of the building envelope.

The component evaluation of typical building solutions in Spain that constitute the main leakage paths (windows, rolling-shutters, joints, etc.) will be necessary to address energy-efficient renovations in the existing building stock. The analysis of different building systems and the weaker points can be a starting point in the proposal, development, and verification of airtight solutions.

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NOTATIONS

Symbol	Definition	Unit
A	leakage area	$[m^2]$
a	coefficient representing the turbulent part of the quadratic law	$[Pa\ s/m^3]$
A_0	sum of areas of the opaque thermal building envelope	$[m^2]$
A_E	envelope area	$[m^2]$
A_{ET}	sum of areas of the thermal building envelope with heat exchange with the outdoor air	$[m^2]$
A_F	net floor area	$[m^2]$
A_h	sum of the area of the doors and windows of the thermal building envelope	$[m^2]$
ACH	average annual air change rate	$[h^{-1}]$
ACH_{K-P}	average annual air change rate of the K-P model	$[h^{-1}]$
b	coefficient representing the laminar part of the quadratic law	$[Pa\ s^2/m^6]$
B	length of the crack	$[m]$
B'	Specific buoyancy flux	$[m^4/s^3]$
c	optional constant representing the zero-flow pressure difference in the quadratic equation	$[Pa]$
C	Concentration	$[-]$
CDD	Cooling Degree-Days	$[°C - day]$
C_0	airflow coefficient of the opaque part of the thermal envelope	$[m^3/h\ m^2]$
C_d	discharge coefficient of the opening	$[-]$
C_f	climatic factor	$[-]$
C_h	permeability of doors and windows on the thermal building envelope at a reference pressure of 100 Pa	$[m^3/h\ m^2]$
C_L	air leakage coefficient	$[m^3/(h\ Pa^n)]$
C_p	pressure coefficient	$[-]$
c_p	specific heat of air	$[Wh/kg\ K]$
C_{po}	internal pressure coefficient that balances inflows and outflows summed over all leakage sites	$[-]$
$C_{p,v}$	volumetric heat capacity of the air	$Wh/(m^3\ K)$
cf_1	height correction factor of the building	$[-]$
cf_2	site shielding correction factor	$[-]$
cf_3	leakiness correction factor	$[-]$
d_h	hydraulic diameter	$[m]$
e	margin of error	$[-]$

$E_{conduction}$	conductive heat loss	$[W]$
E_{heat}	heating load	$[W]$
E_{inf}	infiltration heat loss	$[W]$
$E_{inf-H/C}$	infiltration seasonal heat loss (for heating/cooling)	$[kWh/year]$
ELA	effective leakage area	$[cm^2]$
ELA_E	specific effective leakage area per the building envelope area at 50 Pa	$[m^2/m^2]$
ELA_F	specific effective leakage area per the floor area at 50 Pa	$[m^2/m^2]$
$EqLA$	equivalent leakage area	$[cm^2]$
f_s	infiltration stack parameter	$[m/s\,K^{1/2}]$
f_w	infiltration wind parameter	$[-]$
g	acceleration of gravity	$[m/s^2]$
G_t	Annual degree hours	$[kKh/year]$
G_{t-H}	Annual heating degree hours	$[kKh/year]$
G_{t-C}	Annual cooling degree hours	$[kKh/year]$
h	level height	$[m]$
h_o	neutral level height	$[m]$
$h_{o,s}$	neutral level height for stack pressure	$[m]$
HDD	Heating Degree-Days	$[°C-day]$
$HIDD$	Heating Infiltration Degree-Days	$[°C-day]$
k	Leakage infiltration ratio of the LBNL model	$[-]$
L	depth of the crack in the airflow direction	$[m]$
n	airflow exponent	$[-]$
n_{50}	air change rate at 50 Pa	$[h^{-1}]$
N	population size	$[-]$
N_i	population size of stratum i	$[-]$
q	volume airflow rate through the leakage site	$[m^3/s]$
q_{50}	specific leakage rate per the building envelope area at 50 Pa	$[m^3/h\,m^2]$
q_{100}	specific leakage rate at 100 Pa	$[m^3/h\,m^2]$
q_m	mass flow rate of infiltration	$[kg/s]$
Q	total volume airflow rate	$[m^3/s]$
Q_{50}	air leakage rate at 50 Pa	$[m^3/h]$
Q_E	airflow to outside	$[m^3/h]$
Q_I	airflow to the staircase	$[m^3/h]$
Q_L	lateral airflow to a neighbouring zone	$[m^3/h]$
Q_M	measured airflow	$[m^3/h]$
Q_{pr}	airflow rate at a reference pressure difference	$[m^3/h]$
Q_s	stack flow rate	$[m^3/s]$
Q_v	ventilation airflow	$[l/s]$
Q_w	wind flow rate	$[m^3/s]$
s	specific infiltration	$[m^3/h\,cm^2]$
s_0	average specific infiltration	$[m^3/h\,cm^2]$
s_a	typical annual average specific infiltration	$[m/s]$
S	sample size	$[-]$
S_i	sample size of stratum i	$[-]$
T^h_{base}	base temperature during the heating season	$[°C]$
T_{in}	indoor air temperature	$[°C]$
T_{out}	outdoor air temperature	$[°C]$
$T_{out-daily}$	outdoor air temperature when it is below 20°C	$[°C]$

V	internal volume of the deliberately conditioned space of the dwelling	$[m^3]$
v	windspeed	$[m/s]$
w_{50}	specific leakage rate per the floor area at 50 Pa	$[m^3/h\, m^2]$
Z	critical value which depends on the confidence interval	$[-]$

Greek letters

$\Delta p_s(h)$	change in stack pressure with height caused by buoyancy	$[Pa]$
Δp_w	wind pressure difference	$[Pa]$
Δp_r	reference pressure difference	$[Pa]$
Δp	pressure difference across the leakage site	$[Pa]$
ΔT	temperature difference	$[K]$
ε	infiltration heat recovery effectiveness ($IHRE$)	$[-]$
λ	envelope conductivity	$[W/K]$
σ	population standard deviation	$[-]$
ρ_{out}	outdoor air density	$[kg/m^3]$
ρ	density of the air	$[kg/m^3]$
μ	absolute viscosity of the air	$[Pa\, s]$

ABBREVIATIONS

AC: alternating
AIM-2: Alberta Infiltration Model
AIDA: Air Infiltration Development Algorithm
AIVC: Air Infiltration and Ventilation Centre
ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM: American Society for Testing and Materials
BGBI: Bundesgesetzblatt (German Federal Law Gazette)
CEN: European Committee for Standardization
CGSB: Canadian General Standards Board
CIBSE: Chartered Institution of Building Services Engineers
CTE: Código Técnico de la Edificación (Spanish Technical Building Code)
DB: Documento Básico (Basic Document of CTE)
DC: steady state
DOI: digital object identifier
EN: European Standard
EPB: energy performance of buildings
EPBD: Energy Performance Building Directive
EPR: energy performance regulations
HE: ahorro de energía (energy saving)
HS: salubridad (healthiness)
HVAC: heating, ventilation, and air conditioning
IAQ: indoor air quality
ICC: International Code Council
IR: infrared
ISO: International Organization for Standardization
LBNL: Lawrence Berkeley National Laboratory
NBE: Norma Básica de la Edificación (Spanish Construction Basic Norm)
NL: normalised leakage
nZEB: nearly zero-energy building
OLS: ordinary least square
PVC: polyvinyl chloride
EU: European Union
UK: United Kingdom
UNFCC: United Nations Framework Convention on Climate Change
USA: United States of America

ANNEX I: SCIENTIFIC DISSEMINATION

SCIENTIFIC PAPERS OF THE THESIS

Poza-Casado, I., Cardoso, V. E. M., Almeida, R. M. S. F., Meiss, A., Ramos, N. M. M., & Padilla-Marcos, M. Á. (2020). Residential buildings airtightness frameworks: A review on the main databases and setups in Europe and North America. Building and Environment, 183, 107221. https://doi.org/10.1016/j.buildenv.2020.107221

Building and Environment				
JCR Year	**Impact factor**	**JIF Rank**	**JIF Quartile**	**Category**
2020	6.456	6/136	Q1	Civil Engineering
		6/66	Q1	Construction & building technology
		12/54	Q1	Environmental engineering

Poza-Casado, I., Meiss, A., Padilla-Marcos, M. Á., & Feijó-Muñoz, J. (2020). Airtightness and energy impact of air infiltration in residential buildings in Spain. International Journal of Ventilation. https://doi.org/10.1080/14733315.2020.1777029

International Journal of Ventilation				
JCR Year	**Impact factor**	**JIF Rank**	**JIF Quartile**	**Category**
2020	1.595	98/114	Q4	Energy & fuels
		50/66	Q4	Construction & building technology

Feijó-Muñoz, J., Pardal, C., Echarri-Iribarren, V., Fernández-Agüera, J., Assiego de Larriva, R., Montesdeoca Calderín, M., Poza-Casado, I., Padilla-Marcos, M. Á., & Meiss, A. (2019). Energy impact of the air infiltration in residential buildings in the Mediterranean area of Spain and the Canary islands. Energy and Buildings, 188–189, 226–238. https://doi.org/10.1016/j.enbuild.2019.02.023

Energy and Buildings				
JCR Year	**Impact factor**	**JIF Rank**	**JIF Quartile**	**Category**
2019	4.867	5/134	Q1	Civil Engineering
		7/63	Q1	Construction & building technology
		31/112	Q2	Energy & fuels

Feijó-Muñoz, J., González-Lezcano, R. A., Poza-Casado, I., Padilla-Marcos, M. Á., & Meiss, A. (2019). Airtightness of residential buildings in the Continental area of Spain. Building and Environment, 148, 299–308. https://doi.org/10.1016/j.buildenv.2018.11.010

Building and Environment				
JCR Year	**Impact factor**	**JIF Rank**	**JIF Quartile**	**Category**
2019	4.971	4/134	Q1	Civil Engineering
		6/63	Q1	Construction & building technology
		12/53	Q1	Environmental engineering

Feijó-Muñoz, J., Poza-Casado, I., González-Lezcano, R. A., Pardal, C., Echarri, V., Assiego De Larriva, R., … Meiss, A. (2018). Methodology for the Study of the Envelope Airtightness of Residential Buildings in Spain: A Case Study. Energies, 11(4), 704. https://doi.org/10.3390/en11040704

Energies				
JCR Year	**Impact factor**	**JIF Rank**	**JIF Quartile**	**Category**
2018	2.707	56/103	Q3	Energy & fuels

COMPLEMENTARY SCIENTIFIC PAPERS

Meiss, A., Jimeno-Merino, H., Poza-Casado, I., Llorente-Álvarez, A., & Padilla-Marcos, M. Á. (2021). Indoor Air Quality in Naturally Ventilated Classrooms. Lessons Learned from a Case Study in a COVID-19 Scenario. Sustainability, 13(15), 8446. https://doi.org/10.3390/su13158446

Sustainability				
JCR Year	**Impact factor**	**JIF Rank**	**JIF Quartile**	**Category**
2020	3.251	60/125	Q2	Environmental studies
		124/274	Q2	Environmental Sciences
		6/9	Q3	Green and sustainable science & technology
		30/44	Q3	Green & sustainable science & technology

Poza-Casado, I., Gil-Valverde, R., Meiss, A., & Padilla-Marcos, M. Á. (2021). Impact of Air Infiltration on IAQ and Ventilation Efficiency in Higher Educational Classrooms in Spain. Sustainability, 13(12), 6875. https://doi.org/10.3390/su13126875

Sustainability				
JCR Year	**Impact factor**	**JIF Rank**	**JIF Quartile**	**Category**
2020	3.251	60/125	Q2	Environmental studies
		124/274	Q2	Environmental Sciences
		6/9	Q3	Green and sustainable science & technology
		30/44	Q3	Green & sustainable science & technology

Gil-Valverde, R., Tamayo-Alonso, D., Royuela-del-Val, A., Poza-Casado, I., Meiss, A., & Padilla-Marcos, M. Á. (2021). Three-dimensional characterisation of air infiltration using infrared thermography. Energy and Buildings, 233, 110656. https://doi.org/10.1016/j.enbuild.2020.110656

Energy and Buildings				
JCR Year	**Impact factor**	**JIF Rank**	**JIF Quartile**	**Category**
2020	5.879	9/136	Q1	Civil Engineering
		9/66	Q1	Construction & building technology

		36/114	Q2	Energy & fuels

Meiss, A., Padilla-Marcos, M. Á., Poza-Casado, I., & Álvaro-Tordesillas, A. (2020). A Graphical Tool to Estimate the Air Change Efficiency in Rooms with Heat Recovery Systems. Sustainability, 12(3), 1031. https://doi.org/10.3390/su12031031

Sustainability				
JCR Year	**Impact factor**	**JIF Rank**	**JIF Quartile**	**Category**
2020	3.251	60/125	Q2	Environmental studies
		124/274	Q2	Environmental Sciences
		6/9	Q3	Green and sustainable science & technology
		30/44	Q3	Green & sustainable science & technology

CONFERENCE PAPERS

Poza-Casado, I., Gil-Valverde, R., & Padilla-Marcos, M. Á. (2021). Permeabilidad al aire y tasa de infiltración en dos aulas universitarias. In Fundación 3CIN (Ed.), VII Jornadas de Investigadoras de Castilla y León, 45.

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ANNEX II: INTERNATIONAL MENTION

This Thesis aims at obtaining the International Mention according to art. 15.1.a of Real Decreto 99/2011. Part of the research work was carried out at the Faculdade de Engenharia of Universidade do Porto for 4 months (1st of February to 31st of May 2019). The candidate collaborated with the Research Group CONSTRUCT - Instituto de I&D em Estruturas e Construções. LFC – Laboratory of Building Physics, and Professor Nuno Manuel Monteiro Ramos (Department of Civil Engineering) was the responsible person of the host institution.

This international stay was possible thanks to the competitive grant *UVa-Santander Iberoamérica Investigación España*, which provided the funding that covered the expenses that the mobility involved. The program, promoted by Banco Santander and Universidad de Valladolid, intended to reinforce the mobility and exchange of young professors, researchers and doctoral students among Ibero-American universities and research centres, in order to advance towards the construction of an Ibero-American space of socially responsible knowledge.

The international mobility at FEUP was encouraged by the common interest and research lines of the host Research Group and the candidate, who is an associate member of the Research Group Architecture & Energy of Universidad de Valladolid. Both teams carried out intense research on airtightness and air infiltration in dwellings for the past few years. It meant an undeniable enrichment of the research work developed, the trainee of new methods and techniques, and also broadened the candidate's knowledge in the field of airtightness. In addition, it established the collaboration between both research groups and contributed to the internationalisation of Universidad de Valladolid.

Proof of this collaboration and as a result of the work carried out by the authors during and after the mobility of the candidate, one of the scientific papers that are part of this Theses was published:

Poza-Casado, I., Cardoso, V. E. M., Almeida, R. M. S. F., Meiss, A., Ramos, N. M. M., & Padilla-Marcos, M. Á. (2020). Residential buildings airtightness frameworks: A review on the main databases and setups in Europe and North America. Building and Environment, 183, 107221. https://doi.org/10.1016/j.buildenv.2020.107221

U. PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

SICC - COOP
COMUNICATION AND COOPERATION SERVICES
COOPERATION UNIT

STATEMENT

To whom it may concern, we declare that **Irene Poza Casado**, student from Universidad de Valladolid (Spain), was a mobility student at the *Faculdade de Engenharia da Universidade do Porto*, in the academic year 2018/19, performing a Santander Workplan from the 1st of February to the 31st of May 2019.

Porto, FEUP, 31st May 2019

FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Patricia Martins
INcoming Mobility Officer

RUA DR. ROBERTO FRIAS, 4200-465 PORTO - PORTUGAL | NIF 501 413 197 | TELEFONE +351 22 508 1479 | FAX +351 22 508 1440 | sicc@fe.up.pt | www.fe.up.pt

ANNEX III: TESTING PROTOCOL

The testing protocol developed for the purposes of INFILES project in order to characterize the building envelope specified the correct execution of the experimental procedures and data capture step by step, proposing unified procedure and criteria, which could be easily applicable to other countries with analogous objectives. It is available (in Spanish) at this link:

https://bit.ly/2UWYNjo

ANNEX IV: TEST REPORTS

The reports of all the characterised cases (in Spanish) including whole characterisation data and pressurisation test results are available at this link:

https://bit.ly/3i53HUf

ANNEX V: TEST RESULTS

The main outcomes of the cases assessed were gathered in:

Poza-Casado, I. (2019). Resultados. In A. Meiss & M. Á. Padilla-Marcos (Eds.), Permeabilidad al aire de los edificios residenciales en España. Estudio y caracterización de sus infiltraciones (pp. 46–86). Ediciones Asimétricas.

An extract of this book is available (in Spanish) at this link:

https://bit.ly/37ifvwx