Improving building envelope knowledge from analysis of 219,000 certified on-site air leakage measurements in France

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Abstract

The French air leakage testers' scheme led to the development of a national database, which includes about 219,000 airtightness measurements, mainly from residential buildings built since 2010. This paper first presents the measurement methodology and the requirements of the testers' scheme regarding the reliability of the data included in the database. Different analyses are then presented, to:

- give a general overview of the new French building stock;
- analyse several factors, including insulation, ventilation systems, and main building materials, that may significantly impact building leakage measurement results;
- identifying levers to improve the practices of building construction stakeholders and testers.

These analyses reveal influential factors, such as the main material of the building, the thermal insulation technique and the type of ventilation system. The most frequently identified leaks and the most influential leaks have been identified, in order to improve building airtightness. The common use of last-minute correction has also been identified, despite the impact on airtightness durability. Finally, these analyses confirm that the multi-point testing method fits well with the French context, buildings and climates.

Keywords: building envelope; airtightness; measurement; database

1. Introduction

Controlling and reducing building envelope air leakage have become one of the major levers to reduce the energy used by buildings, especially for heating needs. By 1975, Tamura had estimated that heat loss due to envelope air leakage may represent 40% of the total heat loss from buildings [1]. More recent studies have estimated that infiltrations are responsible for up to 30% of heating demand [2], [3], [4], [5], [6], [7]. Poor building airtightness may also have a significant impact on indoor air quality and occupant comfort, and may be a significant source of noise transmission [8]. In order to improve knowledge of existing envelope performance regarding air leakage, many experimental studies have been conducted from measurements performed on dwellings [9] (20 Italian residential buildings), [10] (9 Irish single-family houses), [11] (170 single-family houses and 56 apartments in Finland) and [12] (129 Spanish dwellings). Analyses of airleakage measurement results on these samples of buildings have made it possible to identify the most critical causes of envelope leakage, such as windows and chimneys without sealing [9], pipe and duct paths [12]. The first airleakage database to be developed and analysed is the LBNL's residential diagnostics database (ResDB) including from 70,000 airleakage data across the United States in 2005 [13], to 134,000- 175,000 data in 2013, [14] [15]. This database has been used to build a predictive model, even though the variability of measurement results and building characteristics makes this prediction very difficult and highly uncertain.

Nowadays, many countries include requirements for building airtightness in their current national regulations or energy-efficiency programmes, mainly to reduce building energy losses due to air leakage [16]. In some cases, the minimum requirement for building airtightness has to be justified by an airtightness test performed by accredited testers. In France, the current energy performance regulation RT2012 [17] requires that all new residential building must comply with a limit value for the French indicator q_{a4} ($Q_{4Pa\text{-}surf}$ in French: air leakage rate at 4 Pa divided by the loss surface area excluding the basement floor): 0.6 $m^3.h^{-1}.m^{-2}$ for single-family houses (i.e. around n_{50}=2.3 h^{-1})[1] and 1.0 $m^3.h^{-1}.m^{-2}$ for multi-family buildings. Compliance is justified either by an airtightness test performed by a qualified tester or by applying a certified quality framework [18]. The same justification is required for non-residential buildings if the Energy Performance calculation takes into account a better-than-default value. Moreover, the EP programme Effinergie [19] imposes a more demanding limit for residential buildings and requires a measurement for small non-residential buildings (floor area below 3000 m²). As for the regulation, in the context of Effinergie, the test has to be performed by a qualified tester.

In this context, the reliability of the building airtightness test is a key issue, as it is increasingly used for compliance checks and it may result in severe penalties [20]. Firstly, the uncertainty of the measurement results has become a key concern in several countries over the past years. Studies have been conducted regarding the impact of wind and temperature differences [21], [22] and [23]. These studies propose different methodologies to estimate the uncertainties, based on numerical evaluations. Others studies deal with the impact of the mathematical model used in the fan pressurization method [15] and [24]. They investigate the impact of the flow exponent of the power-law n value approximation, the zero-flow pressure correction and the unweighted correlation. They propose some changes to the measurement methodology in order to reduce the uncertainty of the result. Finally, the seasonal variation of the measurement result has been investigated [25] and [26]. In these studies, the significant impact of the weather on

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[1] The equivalence is calculated for a generic two-story house with an internal volume of 320 m^3 and a loss surface area excluding basement floor of 224 m²; and considering a flow exponent n=2/3

airleakage measurement has been identified for wooden houses. Secondly, this context has led to the development of instruments such as competent tester schemes [27], calibration rules and testing guidelines [28]. In particular, standard ISO 9972 [29] requires periodic calibration of the measurement system and gives threshold values regarding the accuracy of the pressure-measuring device, the air flow rate measuring system, and the temperature-measuring device. Moreover, in France, the associated standard FD P50-784 [30] gives the calibration frequencies for each device. The competent tester schemes have made it possible to collect hundreds of thousands of data from in-situ measurements: this is the case in the UK [31] (192,731 records in 2017) and in France [32] (219,000 measurements). The purpose of this paper is to:

- Give the measurement and collection methodology used, in order to significantly increase the reliability of the measurement results;
- Explore the database in order to get a general overview of the new building stock;
- Analyse several factors that can significantly impact building leakage measurement results;
- Identify levers to improve the practices of building construction stakeholders and testers.

2. Methodology

The French EP-regulation RT2012 requires that each airtightness test has to be performed by a qualified tester according to EN ISO 9972 and the French standard FD P50-784, as described by Leprince et al. [33]. The fan pressurization method described in EN ISO 9972 is a multi-point testing method that uses the power-law equation given in equation 1.

$$Q = C.\Delta P^n \qquad \text{Eq. 1}$$

where:

Q is the volume flow rate [$m^3.h^{-1}$]

ΔP is the indoor-outdoor pressure difference [Pa]

C is the air leakage coefficient [$m^3.s^{-1}.Pa^{-n}$]

n is the flow exponent [-].

In order to determine the air leakage for a specific pressure difference, EN ISO 9972 requires at least five equally spaced pressures differences and measurement of the associated airflow rates in order to determine values of C and n from a regression analysis in logarithm scale. The airflow rate can then be extrapolated to a reference pressure difference (in France: 4 Pa). Moreover, FD P50-784 requires that measurements shall be performed according to method 3 of EN ISO 9972 and specifies how the building must be prepared. More specifically, only the ventilation openings included in the EP-calculation are sealed, and all windows, doors, and trapdoors on the envelope are closed. The French testers' scheme was developed in 2008. The certification body Qualibat annually assess qualified testers. To be qualified, a tester has to:

- Undergo state-approved training,
- Pass the training examination (the theoretical part, with a state-approved multiple choice questionnaire; and the practical part, with a real test performed with a qualified tester);
- Provide proof of sufficient testing experience with a minimum of 10 tests performed.

Once qualified, every tester is subjected to yearly follow-up checks, organized by the certification body. The follow-up checks include an analysis of some reports to verify their compliance with applicable standards and guidelines. The certification body can check the testers based on the documentation sent every year, but also on site, in particular, in case of complaints or doubts about their work. A committee involving stakeholders is in charge of delivering qualification, re-issuing qualification or handling complaints. The follow-up checks require provision of a professional standard form giving information on all airtightness measurements performed within the year (the professional measurement register). As of December 2018, 884 testers were qualified. Collected registers are annually compiled in a national database which is composed of 39 data fields as follows:

- general building information: owner, location, use (single-family for a building with one or two apartments, multi-family for a building with more than two apartments, several subcategories for non-residential buildings such as schools and office buildings), year of construction, year of rehabilitation;
- special requirements: label, certification;
- main building characteristics: main material, construction type (frame structure, bearing walls, combined or lightweight facade), insulation type, ventilation system, heating system;
- measurement protocol: operator, date of measurement, measurement device, time of measurement (construction phase of the building), method;
- measurement input data: envelope area (excluding low floors), floor area, volume;
- measurement results: air leakage coefficient C_L, flow exponent n, q_{a4}, n_{50}, uncertainties (the uncertainties are calculated according to Annex C of ISO 9972. FD P50-784 requires that the uncertainty on q_{a4} is below 15%);
- detected leakage locations: leakages being classified into 46 standardized categories.

Data are checked to ensure their accuracy, completeness, and reliability regarding the specifications of standards ISO 9972 and FD P50-784, in particular:

- the entries of multiple-choice data are consistent with the given lists of choices;
- the values for q_{a4} and for n_{50} are consistent with the values for C_L and n, and the values for the envelope area and internal volume;
- the value of the coefficient of determination r^2 of the linear regression is between 0.98 and 1.00;
- the value for the flow exponent n is between 0.5 and 1.0;
- the uncertainty on q_{a4} is below 15%.

The database is fed annually with consolidated data from all collected registers, removing duplicates, irrelevant data, and incomplete recordings. Currently, more than 219,000 measurements performed between 2009 and 2016 have been recorded in the database. Data from around 63,000 tests are expected each year. However, it takes about 2 years to collect registers and perform data analysis. Therefore, this paper analyses data up until December 2016.

3. Results

3.1 Overview of new French building stock

Almost all measurements recorded in the database were performed on new buildings: 87% of buildings tested were built after 2008. Most of the measurements were performed on residential buildings, with 64% coming from single-family houses and 32% from multi-family dwellings (Table 1). The sample of non-residential buildings included in this database is not yet big enough to be representative of their diversity. All results presented in this paper apply therefore only to residential buildings. 88% of these measurements were performed at the commissioning stage when all works that could alter building airtightness are carried out and 11% were performed during the construction stage (Table 2). However, in order to make relevant comparisons, all data and analyses presented in this paper concern only measurements performed at the commissioning stage.

Table 1: Number of airtightness tests in the database according to the use of the building

Use of the building	Single-family houses	Multi-family dwellings	Non-residential buildings	Total
Number of tests	140,542	70,632	8,023	219,197
Distribution	64.1%	32.2%	3.7%	100%

Table 2: Number of airtightness tests in the database according to the construction phase

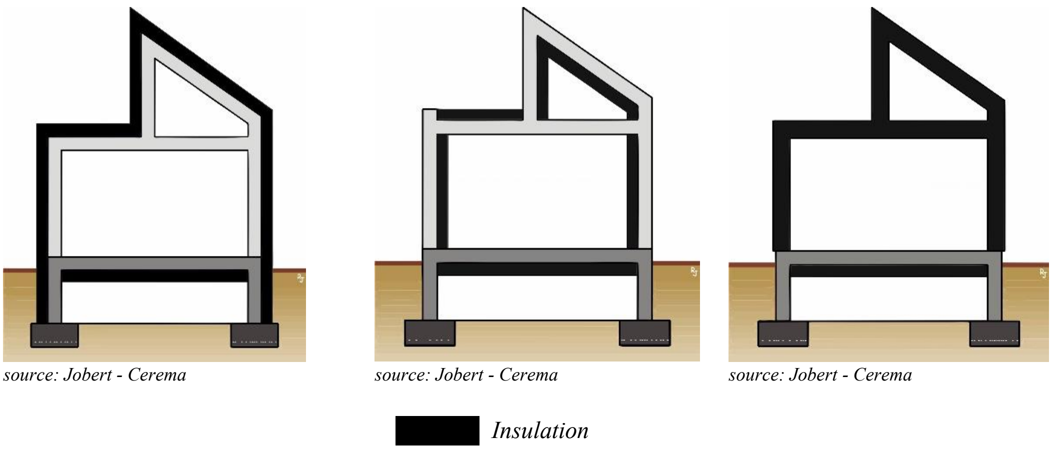
Construction step	At commissioning	During construction	Before retrofitting	No information	Total
Number of tests	192,846	23,745	969	1,637	219,197
Distribution	88.0%	10.8%	0.4%	0.7%	100%

The database includes information regarding ventilation systems types that are described in Table 3. The context in France, regarding ventilation, has remained the same since the 1982 regulation [34]: mandatory general and permanent ventilation of residential buildings with threshold values for exhaust airflows. Therefore, for more than 30 years, almost every building has been equipped with a mechanical ventilation system. These systems include exhaust air terminal devices in humid rooms, and either supply air terminal devices or air inlets in dry rooms. 90% of the buildings tested were equipped with a single-exhaust ventilation system and 6% with a balanced ventilation system. The “other” category includes ventilation “by window opening”, “on-off” systems and single-supply ventilation systems.

Table 3: Number of airtightness tests in the database depending on the type of ventilation system for residential and non-residential buildings

Type of ventilation system		Single-exhaust ventilation	Balanced ventilation	Other or none	Total
Single-family houses	**Number of tests**	116,847	6,736	3,257	126,840
	Distribution	92.1%	5.3%	2.6%	100%
Multi-family dwellings	**Number of tests**	57,049	1,142	630	58,821
	Distribution	97.0%	1.9%	1.1%	100%
Non-residential buildings	**Number of tests**	1,933	2,311	935	5,179
	Distribution	37.3%	44.6%	18.1%	100%

The database includes data regarding insulation types that are described in Figure 1. Table 4 gives the distribution of the insulation types depending on how the buildings are used. Traditionally, internal insulation walls are used in residential buildings (84% for multi-family dwellings and 64% for single-family houses). The category "distributed thermal insulation" includes wood-frame buildings with insulation between studs, lightweight insulating concrete, etc.



(a) External thermal insulation (ETI)

(b) Internal thermal insulation (ITI)

(c) Distributed thermal insulation (DTI)

Figure 1: Insulation types used in French buildings

Table 4: Number of airtightness tests in the database according to the type of insulation for residential and non-residential buildings

Type of insulation		Internal thermal insulation (ITI)	External thermal insulation (ETI)	Distributed thermal insulation (DTI)	Other or no information	Total
Single-family houses	**Number of tests**	107,544	2,975	6,171	10,150	126,840
	Distribution	84.8%	2.3%	4.9%	8.0%	100%
Multi-family dwellings	**Number of tests**	38,394	14,622	2,597	3,208	58,821
	Distribution	65.3%	24.9%	4.4%	5.5%	100%

Figure 2 shows the distribution of the main construction materials for residential and non-residential buildings. Most single-family houses in the database are built of brick (46%), concrete (30%) and wood (9%). For multi-family dwellings, concrete is the main material (48%), followed by brick (27%) and wood (2%).

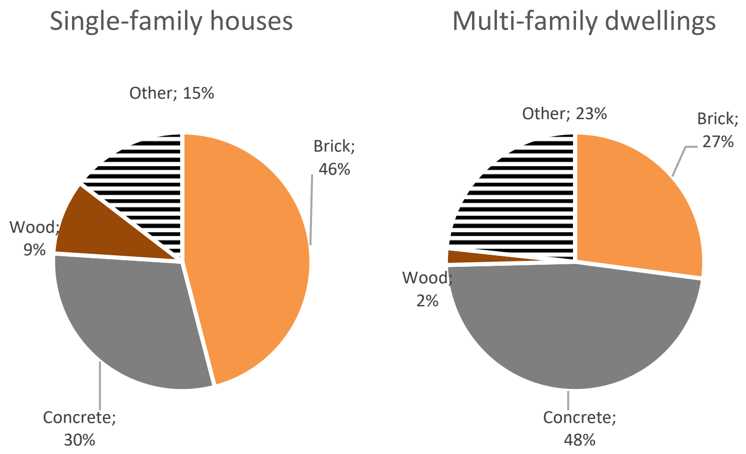


Figure 2: Main materials for residential buildings

3.2 Identification of factors impacting building airleakage and measurement results

3.2.1 Changes over recent years

As two key issues, Figure 3 illustrates the number of tested buildings and the air leakage median value per year from 2000 to 2016. There are two major factors responsible for the changes shown in Figure 3: the EP label launched in 2007 and the current EP regulation (RT2012) applicable for residential buildings commissioned in 2014-2015. Therefore:

- before 2007: there are very few tests performed;
- between 2007 and 2013: the Effinergie label has led to a progressive increase in tests from fewer than 100 per year up to almost 20,000 per year in 2013;
- from 2014: the first RT2012 buildings were tested leading to more than 50’000 tests per year.

Regarding the air leakage median value, the implementation of the EP label requirements in 2007 clearly led to a significant decrease in the median value of q_{a4} for residential buildings measured (mostly buildings applying for the label were tested). In 2011, half of the single-family houses measured had reached q_{a4}=0.42 $m^3.h^{-1}.m^{-2}$ and half of the multi-family dwellings measured had reached q_{a4}=0.58 $m^3.h^{-1}.m^{-2}$. However, a small improvement was evident for houses with a median value of 0.38 $m^3.h^{-1}.m^{-2}$ in 2016 and no improvement for multi-family buildings. This may be due to the use of a new limit value of 0.4 $m^3.h^{-1}.m^{-2}$ in the EP label for single-family houses. From 2015 the median value become representative of all new residential buildings as the test has become mandatory for all new residential buildings.

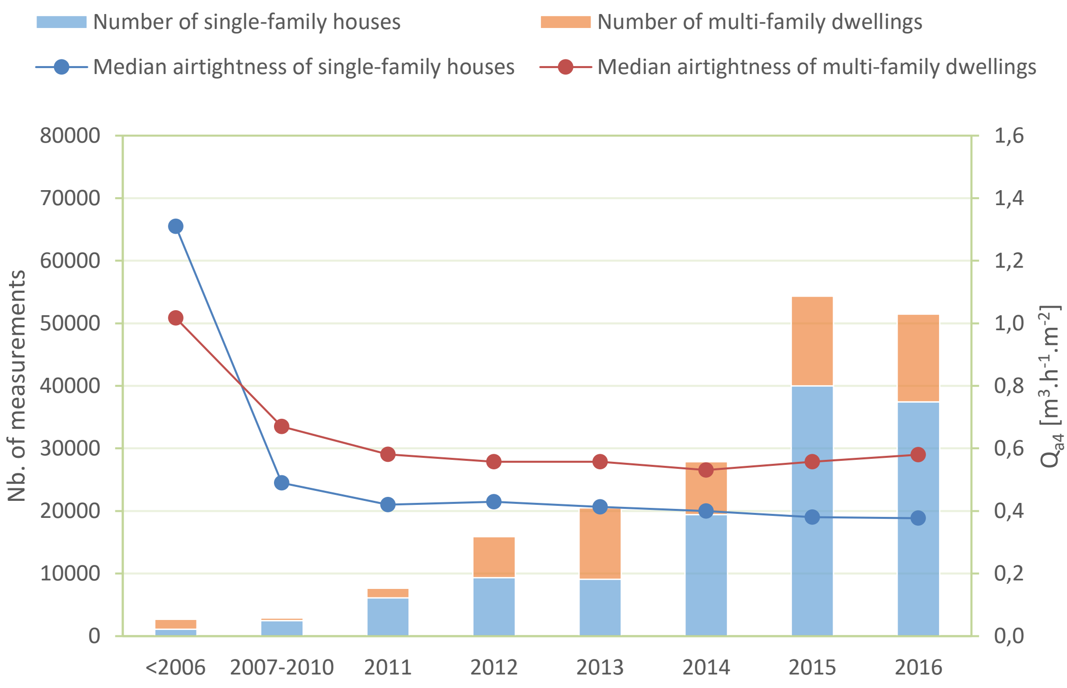


Figure 3: Number of building airtightness tests and their results according to the year of construction of the building

3.2.2 Impact of the construction method on air leakage

As the database includes various information regarding building characteristics, the following paragraphs provide an analysis of correlations between air leakage and:

- Main material;
- Insulation type;
- Ventilation system.

A previous analysis of this database [35] has shown that there is no significant correlation between the volume and envelope airtightness. This paper does not therefore provide any further analysis regarding volume impact.

3.2.2.1 Impact of main material on air leakage

The database includes a large variety of main construction materials. This is due to the materials used in old buildings. In order to perform analysis on significant sub-samples, only data from residential buildings built since 2010 with brick, wood, and concrete are detailed; all other types of material (steel, clay, stone, hemp, and straw) are grouped together in the "other" category. Figure 4 gives the distribution of q_{a4} results depending on the main material for measurements performed on single-family houses and Figure 5 on multi-family buildings. In this paper, the box width represents the amount of material in the database, the median is represented by the central mark, the lower and upper edges of the box are the 25th (1st quartile) and 75th percentiles (3rd quartile) respectively. The whiskers extend to the most extreme data points not considered outliers (±2.7 times the standard deviation). The outliers are not plotted. The dashed line represents the median for the whole sample $q_{a4,med,sample}$. For single-family houses, the median air leakage varies from 0.38 $m^3.h^{-1}.m^{-2}$ for concrete-houses to 0.44 $m^3.h^{-1}.m^{-2}$ for wooden houses, through 0.40 $m^3.h^{-1}.m^{-2}$ for brick-houses (Figure 4). For multi-family dwellings, the median air leakage varies from 0.54 $m^3.h^{-1}.m^{-2}$ for concrete buildings to 0.65 $m^3.h^{-1}.m^{-2}$ for wooden buildings, through 0.62 $m^3.h^{-1}.m^{-2}$ for brick-buildings (Figure 5). According to these figures, wooden buildings are slightly less airtight than concrete and brick buildings; however, the difference is low. Field surveys have shown that wooden buildings can be very airtight if there is a vapour barrier and if it is properly fitted. Nevertheless, there is a lack of experience in France on wood construction that may lead to the vapour barrier being incorrectly fitted, thereby explaining the results for wooden buildings.

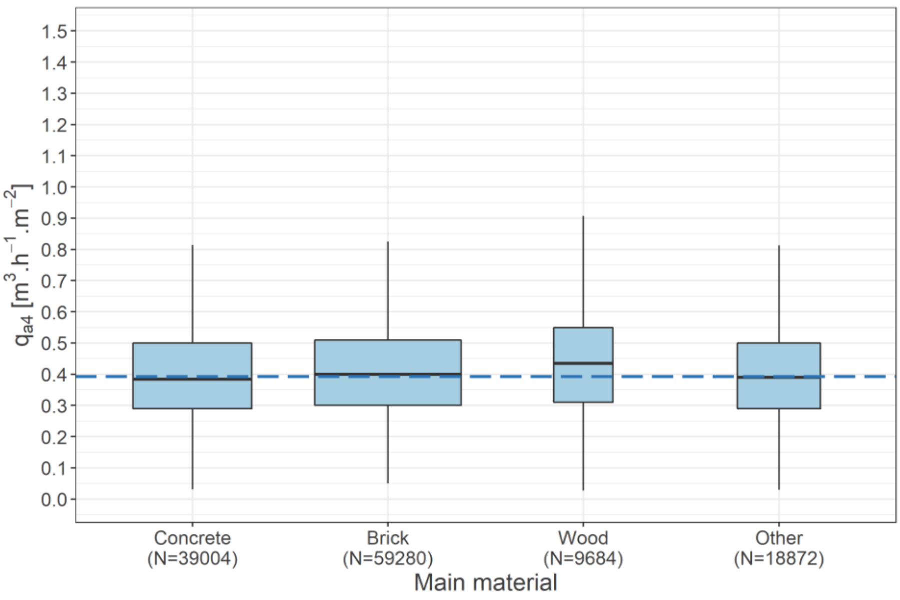


Figure 4: Impact of the main material on envelope airtightness for 170,028 single-family houses ($q_{a4,med,sample}$ =0.39 m^3.h^{-1}.m^{-2})

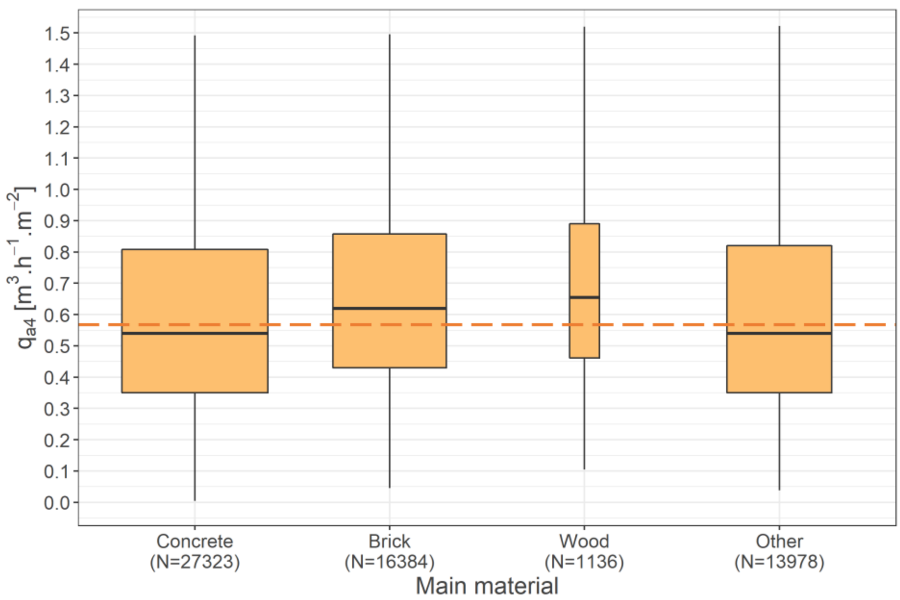


Figure 5: Impact of the main material on envelope airtightness for 57,224 multi-family buildings ($q_{a4,med,sample}$ =0.57 m^3.h^{-1}.m^{-2})

3.2.2.2 Impact of insulation method on air leakage

Figure 6 provides the distribution of q_{a4} results according to insulation method (ITI= Internal thermal insulation, ETI=External thermal insulation, DTI= Distributed thermal insulation) for measurements performed on single-family houses and multi-family dwellings. For single-family houses, the air leakage seems to be slightly higher for the ETI. The ETI is not often used for single-family houses (only 2.3% of houses in the database) and requires a different technique to make the envelope airtight. The lack of experience of stakeholders with this type of building might explain the poorer result for ETI. Conversely, external insulated multi-family dwellings represent a significant percentage of the buildings in the database (24,9%) and are more airtight than internal insulated buildings. Probably because multi-family buildings are made with shuttered concrete which is naturally airtight, while single houses are mostly made with brick and concrete blocks that are not airtight. However, the distinction between shuttered concrete and concrete blocks is not made in the database so we cannot confirm this assumption. The results for DTI are similar to the result for ITI for both houses and multi-family dwellings.

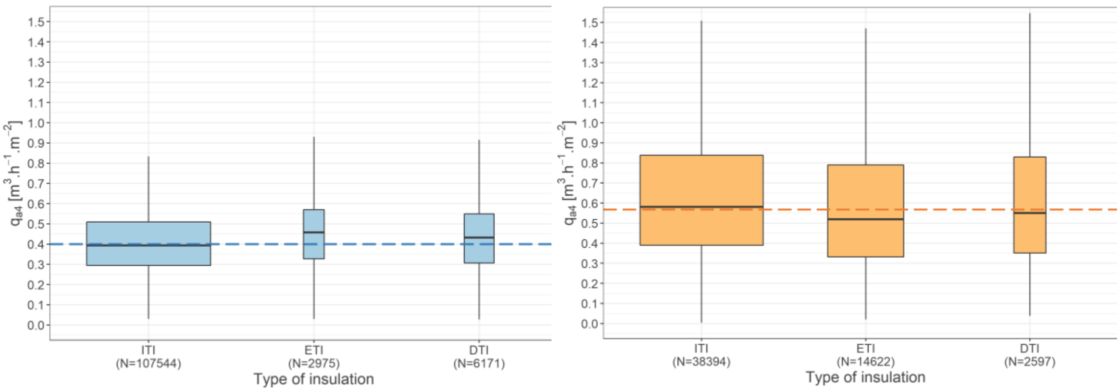


Figure 6: Impact of type of thermal insulation on envelope airtightness for single-family houses (left) and multi-family dwellings (right)

3.2.2.3 Impact of ventilation system on air leakage

Figure 7 provides the distribution of q_{a4} results according to the ventilation system for measurements made on single-family houses and multi-family dwellings. For single-family houses, as the variability of the results for balanced ventilation systems is higher than for exhaust ventilation systems and the median values are not significantly different, and so no conclusion can be drawn regarding the impact of the type of ventilation system on envelope airleakage. For multi-family dwellings, the balanced ventilation system shows lower air leakage. For this type of building, the use of balanced ventilation systems is very often part of a global quality approach to the building. The better results for balanced ventilation systems are probably therefore due to the awareness of the stakeholders.

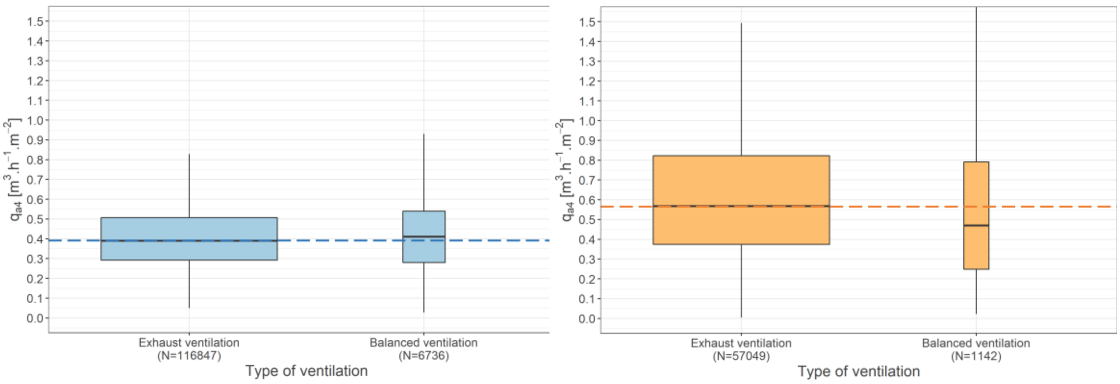


Figure 7: Impact of type of ventilation system on envelope airtightness for single-family houses (left) and multi-family dwellings (right)

3.2.3 Seasonal variation

Several studies dealing with uncertainties in envelope airtightness measurements look at seasonal variations. ISO EN 9972 sets recommendations only on temperature difference over the thermal envelope and on the wind speed limit. Nevertheless, the significant impact of seasonal change has been evaluated at between 5% and 120% [26], [36] and [37]. Analysis of the variation in the distribution of measurement results for each season makes it possible to detect a seasonal variation. Single-family houses measured in France have been therefore been classified into categories according to the treatment of airtightness. The two main categories are:

- wood structure houses where airtightness is provided by the vapour barrier;
- heavy structure with interior insulation where the air barrier is provided by plasterboard and mastic on the inside facing of the walls.

They were then classified regarding the climate of the region according to the three climatic zones of the French EP-regulation: continental climate (H1), oceanic climate

(H2), and Mediterranean climate (H3). WIN=Winter; SPR=Spring; SUM=Summer; AUT=Autumn

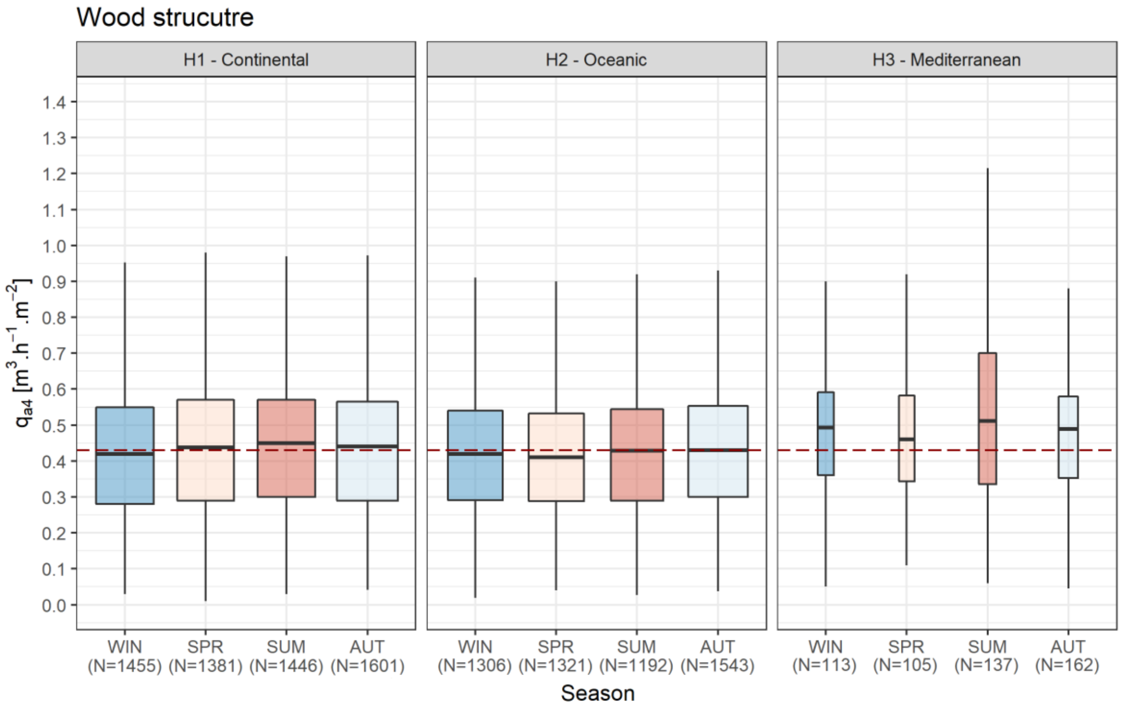
Figure 8 and Figure 9 show the seasonal variations of air leakage in single-family dwellings for the two categories of airtightness treatments. For wooden houses, Figure 8 shows no seasonal variation for continental and oceanic climates (less than 5%). These variations are higher for the Mediterranean climate but the samples are too small to enable any conclusions to be drawn. This result contradicts the findings of Walhgren [38] and Domhagen et al. [26] who found that in winter, Swedish wooden buildings were 8-10% leakier than in summer.

For heavy structure houses with internal insulation (Figure 9), the results do not show seasonal variations as well (less than 3%).

Others results of this analysis concern the impact of the climate and the type of structure. For the Mediterranean climate, higher values for all seasons are observed with average values being between 7 and 19 % higher than all the wooden sample ones, and between 7% and 13% higher than all the heavy structure sample ones. Lower heating needs in this climate may induce less concern regarding airtightness and thus explain these differences. Nevertheless, further investigations need to be performed to confirm these results because the samples are quite small and the differences are not significant enough.

Finally, the comparison of Figure 8 and Figure 9 shows that wooden houses are leakier that heavy structure houses, which is consistent with previous analyses of Figure 4.

Wood structure



WIN=Winter; SPR=Spring; SUM=Summer; AUT=Autumn

Figure 8: Variation of air leakage for wood structure houses according to climate and season ($q_{a4,med,sample}$ =0.43 $m^3.h^{-1}.m^{-2}$)

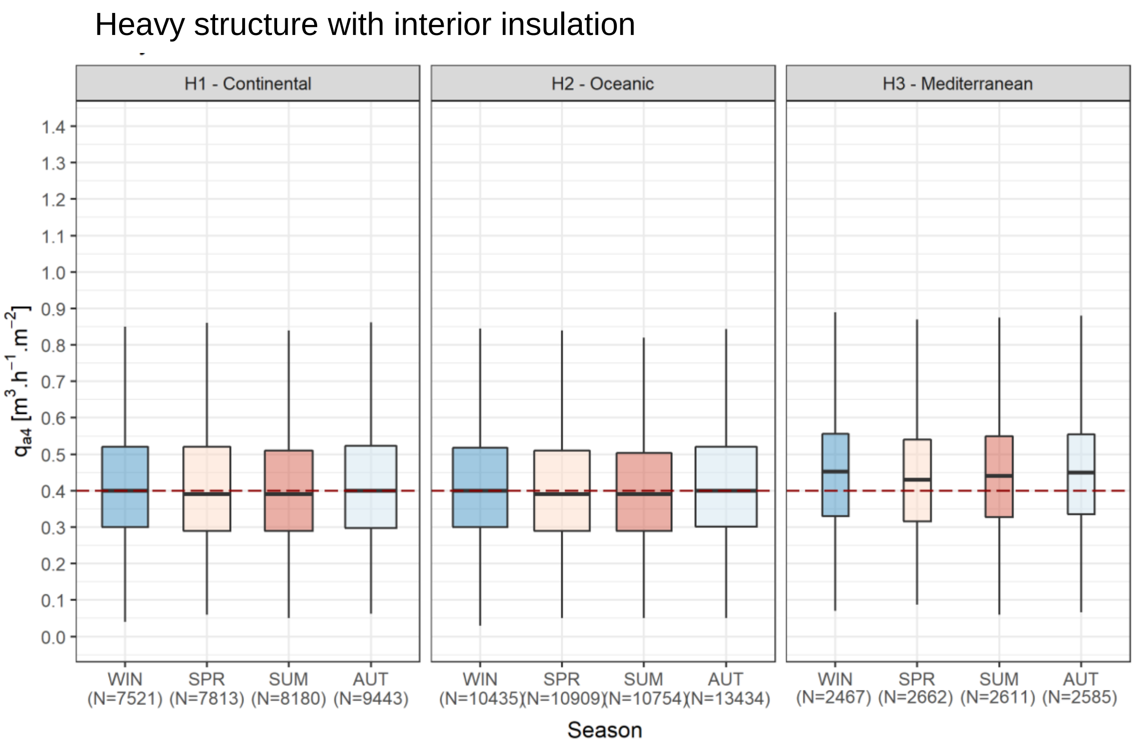


Figure 9: Variation of air leakage for heavy structure houses (with interior insulation) according to climate and season ($q_{a4,med,sample}$ = 0.40 $m^3.h^{-1}.m^{-2}$)

3.2.4 Distribution of the flow exponent n values

Figure 10 and Figure 11 show the distribution of the flow exponent n for single-family houses and multi-family dwellings. For single family houses in the database, the average exponent is 0.668. This figure matches the commonly used default value (n=0.67). It is also consistent with the mean value n=0.65 for the houses included in the LBNL database [15]. The standard variation (0.051), which represents the variability of n values, is also consistent with the standard deviation of the LBNL database (0.057). As the French indicator is calculated from an extrapolated airflow at 4 Pa, the variability of n values confirms the relevance of the multi-point testing method compared to the one-point testing method which considers a default value for n. This conclusion also applies to multi-family dwellings, as the standard variation of n value is even higher (0.066).

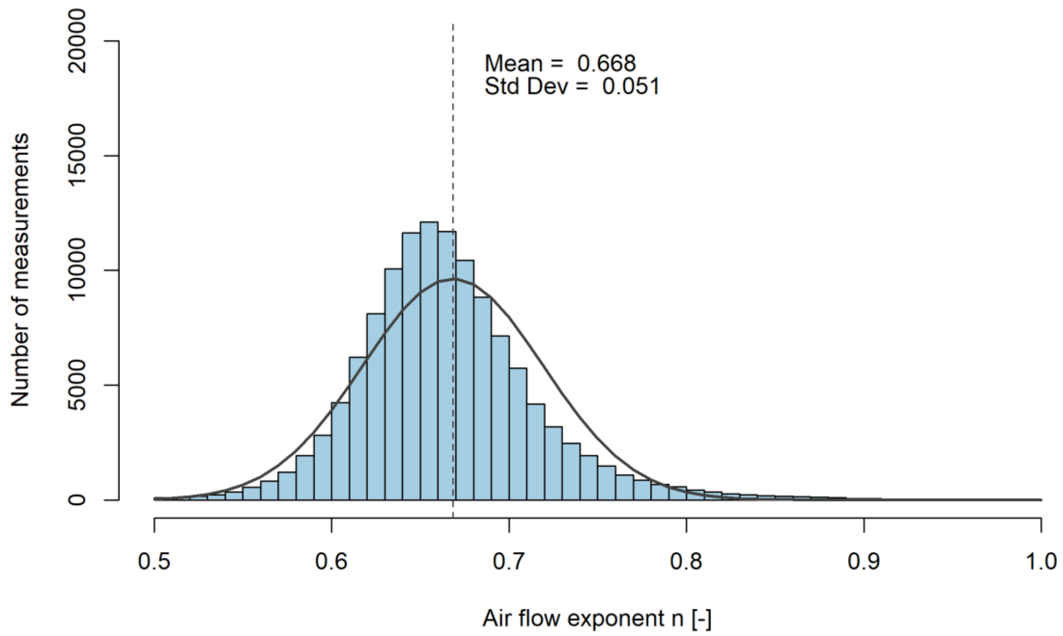


Figure 10: Distribution of flow exponent n for single-family houses

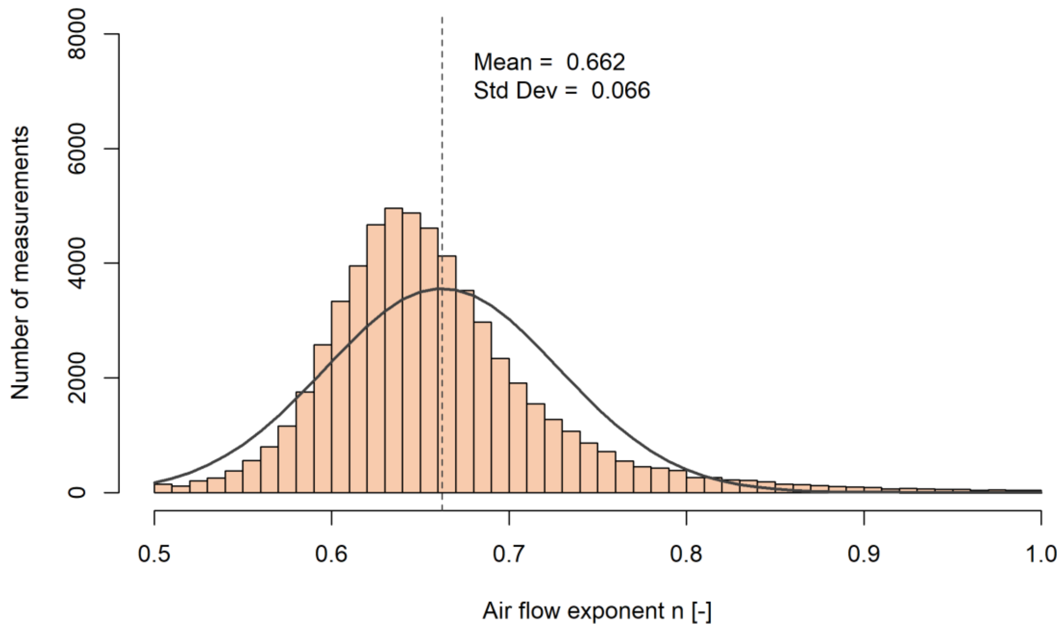


Figure 11: Distribution of flow exponent n for multi-family dwellings

3.3 Identifying areas of improvement for building construction stakeholders and measurement testers

3.3.1 Leaks distribution analyses

According to the French guide FD P50-784 and the French tester's scheme, for each measurement, the tester has to detect major envelope leaks. Each leakage identified has to be described and located during the measurement and reported in the professional register according to the classification given in the FD P50-784. These categories include leaks detected on:

- Main envelope area;
- Wall, roof and floor junctions;
- Doors and windows
- Building components penetrating the envelope
- Trapdoors
- Electrical components
- Door/wall and window/wall junctions
- Wood-burners, chimneys, elevators, cooker hoods, etc.

The leaks are identified according to ISO 9972 – Annex E using either an infrared thermo viewer, smoke or an air velocity meter. For each measurement recorded in the database, one or more leaks are declared according to the 46 subcategory classification. For each subcategory, Table 5 presents the occurrences in the database according to the building use. On average, 6 different leak locations per building are declared. For multi-family dwellings, the three most frequently identified leak locations are "D3: Crossing floor and walls and/or partitions" (57% of dwellings), "C8: Rolling shutter casing" (55%), and "D4: Ventilation air terminal devices" (47%). For single-family houses, the three most frequently identified leak locations are "D3: Crossing floor and walls and/or partitions" (53% of houses), "F3: Electrical grids built on the external walls" (52%), and "C6:

External sliding doors" (50%). For non-residential buildings, the most frequently identified leak is also "D3: Crossing floor and walls and/or partitions" (54% of buildings), followed by others leaks: "C2: Window and French window: frames" (49%) and: "C1: Other leaks on doors and windows" (37%).

Table 5: Leak categories and occurrences

Categories	Subcategories	Occurrences		
		Multi-family dwellings 54,304 measurements	**Single-family houses 109,224 measurements**	**Non-residential buildings 4,247 measurements**
A: Main envelope area	A1: Other leak on main envelope area	6%	9%	16%
	A2: Vapour barrier membrane (or similar complex): adhesive junction between strips, puncture or tear	3%	4%	9%
	A3: Liaisons mortar/glue between masonry blocks, panels between doublings	3%	4%	7%
	A4: Opening (e.g.: wall plug) or not sealed junctions between panels	5%	8%	11%
	A5: False ceiling slabs	3%	4%	15%
B: Wall, roof and floor junctions	B1: Other leak on wall, roof and floor junctions	5%	7%	10%
	B2: Junction between two vertical walls	4%	5%	12%
	B3: Junction between wall base and floor	15%	22%	17%
	B4: Junction between wall and high floor or pitched roof	4%	6%	12%
	B5: Vapour barrier membrane (or similar complex): Attachment defective smooth with sill, intermediate floor, and top floor	3%	3%	6%
C: Doors and windows	**C1: Other leaks on doors and windows**	**25%**	**28%**	**37%**
	C2: Window and French window: frames (no seals or compression default of seals)	**30%**	**26%**	**49%**
	C3: Window and French window: junction between glass and frame defective seal)	9%	8%	22%
	C4: Landing door or fire door: poor compression of seals (excluding threshold bar)	4%	19%	28%
	C5: Landing door or fire door: absent or ineffective threshold bar	4%	16%	32%
	C6: Sliding door: Excessive space between window portions of sliding frame, and/or top and bottom of frame	**10%**	**50%**	**19%**
	C7: Sliding door: Evacuation of condensates	4%	14%	9%
	C8: Rolling shutter casing	**55%**	**17%**	**19%**
	D1: Another element through a wall	13%	15%	14%

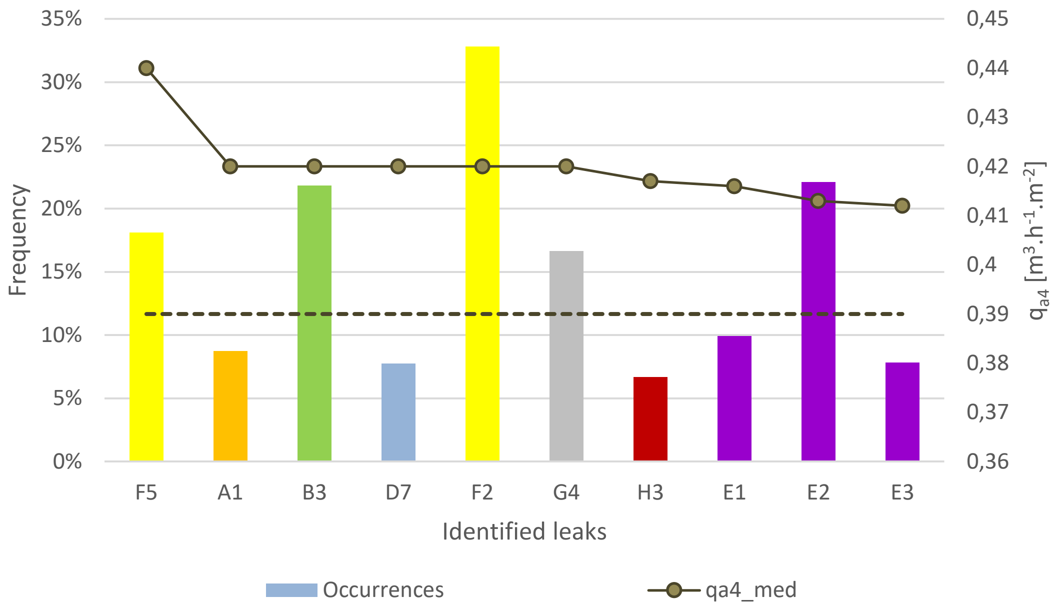
D: Building component penetrating the envelope	D2: Vapour barrier membrane (or similar complex) through which duct, pipe, beams, hatches	4%	5%	10%
	D3: Crossing Floor and walls and/or partitions (any type of plumbing pipes and electrical conduits ...)	**57%**	**53%**	**54%**
	D4: Ventilation air terminals: leaks at periphery of exhaust or supply air vents	**47%**	**23%**	**21%**
	D5: Beams: Linking beams or joist with walls	4%	6%	9%
	D6: Beams: Liaison with ceiling beams or joists or floor	3%	5%	7%
	D7: Stairs: Junction flooring / stairs or vertical walls / stairs	3%	8%	6%
E: Trapdoor	E1: Another trapdoor	12%	10%	10%
	E2: Trapdoor to attic (absent or ineffective seal)	5%	22%	11%
	E3: Trapdoor to vertical technical duct (absent or ineffective seal)	18%	8%	11%
F: Electrical component	F1: Another equipment	7%	11%	11%
	F2: Electrical board	**45%**	**33%**	**26%**
	F3: Grids built on the exterior walls	**36%**	**52%**	**31%**
	F4: Grids built on the internal partition walls	24%	23%	18%
	F5: Lighting components	7%	18%	14%
G: Door/wall and windows/wall junctions	G1: Another leak on walls/doors and windows junction	4%	6%	9%
	G2: Junction between walls and windows or French windows	12%	8%	16%
	G3: Junction between walls and landing door or Fire door	4%	5%	9%
	G4: Junction between internal panels and window and French window	20%	17%	17%
	G5: Junction between internal panels and landing door or Fire door	5%	6%	7%
	G6: Junction between vapor barrier membrane and door or window	3%	3%	5%
H: Wood-burner, chimney, elevator, cooker hood…	H1: Another leak	10%	20%	16%
	H2: Wood-burner, fireplace insert or boiler, or combustion-air air vent	7%	13%	8%
	H3: Extractor hood with external evacuation	3%	7%	8%
	H4: Trapdoor for smokes evacuation	3%	3%	13%
	H5: Zenithal lighting roof lights	3%	3%	10%
	H6: Elevator door (frame - connecting door ...)	3%	2%	14%
	H7: Arrival air extraction or not described in the thermal calculation	3%	2%	7%

The sample of single-family houses analysed in this section is statistically significant: each leak has been identified in at least in 2,000 houses. For each of the 46 subcategories, a subsample of all the houses where this particular leak has been identified was constituted. For each subsample, the median value for q_{a4} was then calculated from measurement results from all houses within this subsample. These 46 values of median q_{a4} are compared to the median value of the entire sample of houses (121,478 houses):

$q_{a4,med,sample}$ = 0.39 $m^3.h^{-1}.m^{-2}$. This comparison gives clues regarding the correlation between leak locations and airtightness levels in single-family houses. This is so because when the median value of the subsample is higher than the median value of the entire sample, the leak identified in the subsample can be considered has having a significant impact on house air leakage. Figure 12 shows the results for the 10 subcategories with the highest median value of q_{a4}. For each of these 10 subcategories, Figure 12 presents both the median value of q_{a4} for the subsample and the frequency of identification of the leak.

It should first be noted that the most frequent leak locations previously identified (F3, D3, and C6) do not appear in Figure 12. This result indicates that even if these leaks are the most frequently identified in houses, they are not significantly responsible for high air leakage results. Secondly, one leak which seems to have a significant impact on house air leakage: houses with leaks due to lighting components (F5) have a median q_{a4} 13% (+0.05 $m^3.h^{-1}.m^{-2}$) higher than the $q_{a4,med,sample}$. Moreover, this leak is frequently identified: for 18% of the 109,224 houses of the sample. Thirdly, the leak due to the electrical board (F2) is both frequently identified and seems to have a significant impact on q_{a4}. For this leak, the median q_{a4} is 8% higher than the $q_{a4,med,sample}$ and has been identified in 33% of the houses of the sample. For the eight other leaks in the graph, impacts on q_{a4} are lower, between 6 and 8 %, with lower observation frequencies (7-22%).

Such information can be very useful to improve envelope airtightness, during both the design stage and on-site construction.



A	Main envelope area
B	Wall, roof and floor junctions
C	Doors and windows
D	Building component penetrating the envelope
E	Trapdoor
F	Electrical component
G	Door/wall and window/wall junctions
H	Wood-burner, chimney, elevator, cooker hood…

Figure 12: Number of observations for 10 leaks identified on single-family houses with the highest median q_{a4} value (from the sample of 121,478 measurements on houses)

Analysis based on leak location identification has, however, two limits. Firstly, the tester does not provide any information on the extent of the leakage. Secondly, not every leakage may be detected, especially when the targeted airtightness level is met, in which case the tester often does not perform any detailed leak location study. Nevertheless, the average of 6 leak locations identified per building in this database indicates that testers perform this identification scrupulously.

3.3.2 Threshold effect in the distribution of test results due to regulatory limit values

Figure 13 gives the number of measurements by airtightness level interval for multi-family dwellings and Figure 14gives those for single-family houses in order to analyze the impact of the implementation of a threshold value in more detail. For multi-family buildings, the distribution is regular and is close to a skew-normal distribution. Figure 13 shows no threshold effect around the regulatory value of 1.0 $m^3.h^{-1}.m^{-2}$. 86% of measurements are below this threshold, and 73% below the threshold of EP-label "Effinergie+" 0.8 $m^3.h^{-1}.m^{-2}$. Note that most tests are performed by sampling, so in most cases, only dwellings are tested and not common parts. The test results analyzed here are the air leakage of the dwellings. In addition, the threshold value applies to the average value of the sample of dwellings and not to each dwelling in the sample. For single-family houses, Figure 14 clearly illustrates the threshold effect of the mandatory requirement of the EP-regulation for single-family dwellings (0.6 $m^3.h^{-1}.m^{-2}$) which creates a discontinuity in the distribution of the measured values of the air leakage. This might be due to last-minute corrections on building envelopes during the commissioning test to force the measured air leakage below the regulatory threshold. Thus 93% of the measurements are below 0.6 $m^3.h^{-1}.m^{-2}$. Also, more than half (53%) are below the threshold of EP-label "Effinergie+" 0.4 $m^3.h^{-1}.m^{-2}$. Much field feedback indicates that mastic is used on the wall surface as a last-minute correction just after the first measurement in order to comply with the regulatory threshold. Moreover, these corrections are most of the time made without a backer rod. Wingfield, Bell, Miles-Shenton, South, & Bob (2009) [39], have shown that after a few weeks of heating, mastics used without backer road may begin to shrink. This practice may therefore have an impact on the durability of envelope airtightness, and highlights the need for improvement in practices to comply with the airtightness threshold using durable solutions. This practice has also been identified in the UK. As a similar sharp peak is observed in their graphs, they suspect that the first measurements are performed but not recorded, and that refinement of air permeability is done before the recorded test. [31].

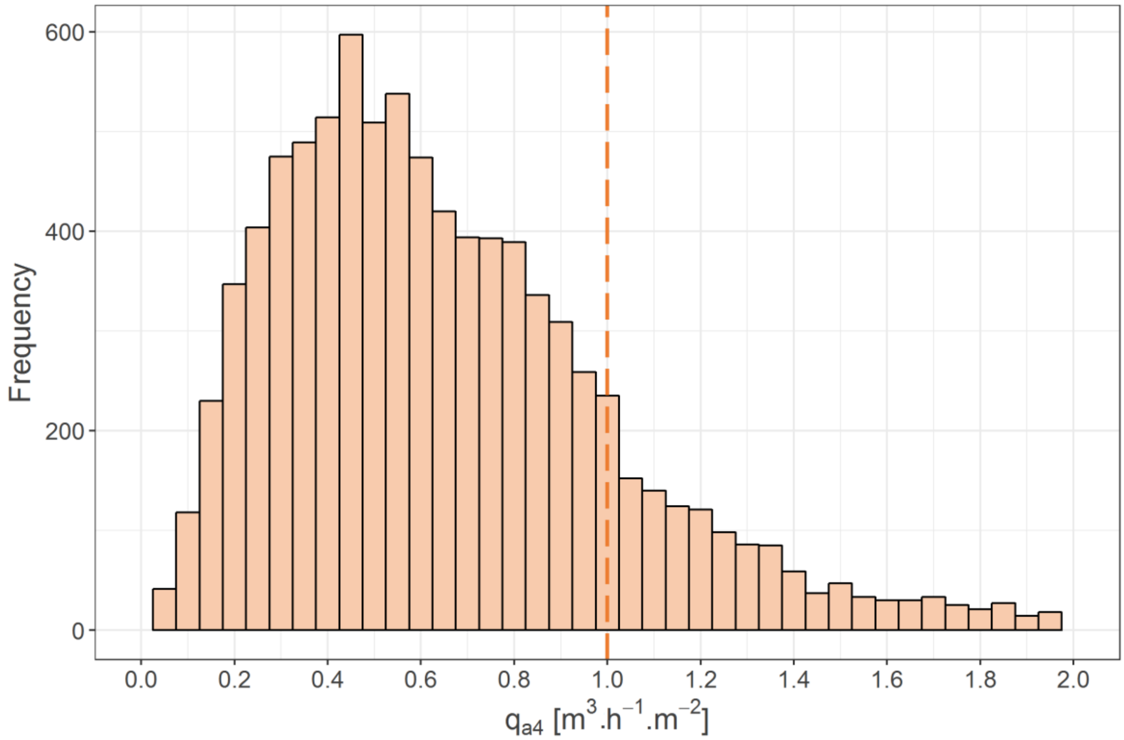


Figure 13: Airleakage test result distribution for multi-family dwellings (58,225 dwellings)

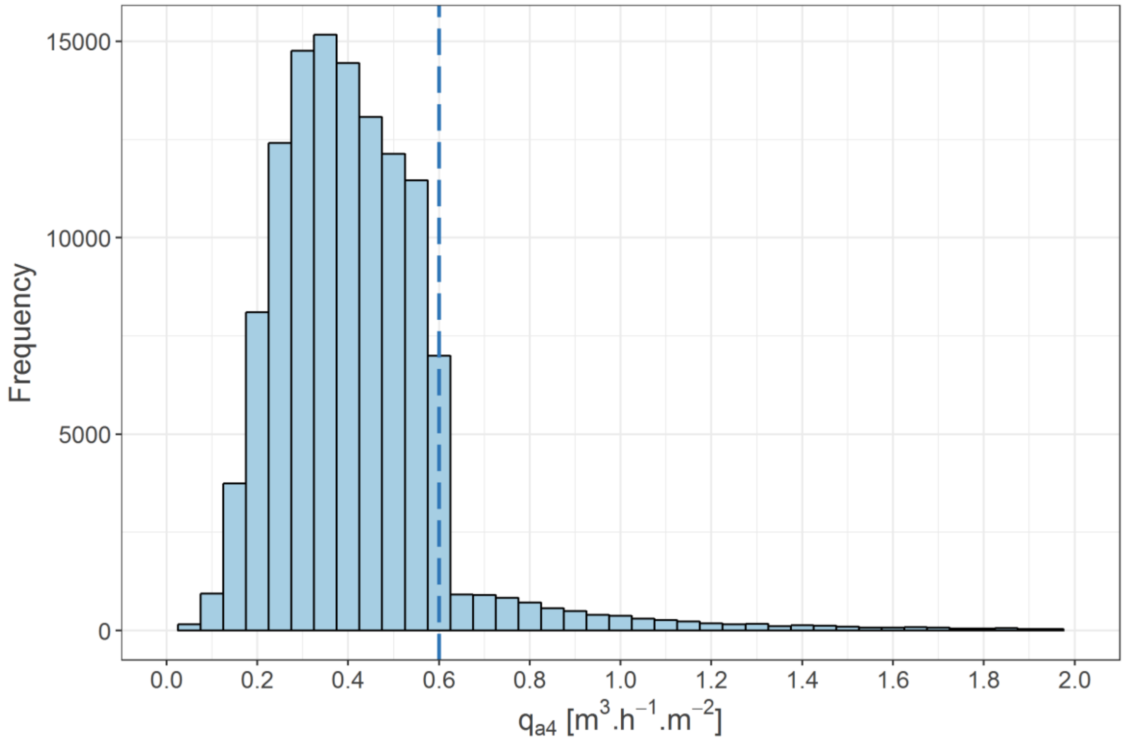


Figure 14: Airleakage test result distribution for single-family houses

4. Discussion

4.1 Barriers in comparison with other databases

This paper references two other very large databases: the LBNL database, which in 2013 included 72% of detached houses, 6% of multi-family dwellings and 21% of mobile homes, and a large percentage of the dwellings in this database consist of existing and retrofitted (social) houses through weatherization programmes [15], and the UK database, which includes dwellings without distinction between houses and multi-family dwellings. The French database includes all types of buildings but essentially new buildings. Comparisons have been made regarding the flow exponent distribution and the threshold effect of limit values. Nevertheless, this paper does not provide further comparisons due to the following barriers:

- the air leakage measurements are made using different protocols, including different testing methods: either the one-point testing method or the multi-point method, different building preparations for the measurements: some envelope components are sealed in France and not in the UK or in the US, for example; etc.
- the indicators are different: q_{a4}, q_{50} and NL. It is not possible to calculate the equivalence between these indicators from the French database because it does not include information regarding the floor area, the building height or the total envelope area;
- the type of buildings included in the databases are different: the LBNL database includes only existing social houses before retrofitting; the UK database includes dwellings without distinction between houses and multi-family dwellings, and the French database includes all types of buildings but essentially new buildings.

4.2 Feedback to testers and stakeholders

The analyses presented in this paper and the previous one have been presented in France both to testers and to stakeholders. Each year, during the national conference for testers organized by the qualification body, Cerema presents updated data analyses to over 200 testers. This presentation promotes the work of the testers and reminds them of the importance of providing reliable data. The discussions during this conference led to the sharing of feedback regarding field practices in order to improve and adapt the testers' scheme requirements. During this meeting, testers also provide valuable information to explain the results of the analysis. The stakeholders are also consulted, especially through the dissemination of these studies during national meetings regarding airtightness issues organised by the Ministry in charge of Construction. This is an important way to communicate these results and help them to improve the envelope airtightness of future buildings, especially through analysis of leak distribution.

4.3 Improvement of databases in France and throughout the world

The analyses performed on the database over the last few years regularly led to changes in the professional registers through feedback from the testers regarding the arrival of new heating, cooling and ventilation systems in buildings, or new constructional techniques, and regarding the difficulties that they might have to complete certain fields in the register. Other fields are modified or added in order to perform more detailed analyses. Moreover, the experience shared with other people in charge of national databases has led to the definition of a framework in order to:

- share experience regarding the creation and management of building airtightness databases;
- consider some standardisation method to enable cross-analysis between countries.

This last work was introduced during the TightVent Airtightness Associations Committee meetings and is still on-going.

Conclusions

The development of competent tester schemes provides a great opportunity to collect a number of reliable air leakage measurement results: up to 219,000 measurements in the French database. The analyses performed on the French database led to the identification of several factors that can significantly impact building airtightness. Firstly, wooden buildings have been found slightly less airtight than concrete and brick buildings, due to lack of field experience in France for this type of construction. Secondly, while there is no significant impact of the thermal isolation technique for single-family houses, external insulated multi-family buildings are generally more airtight. This observation may be explained by the use of naturally airtight shuttered concrete for this type of building. Similarly, the choice of ventilation system does not impact envelope airtightness for single family dwellings, whereas better results are observed for balanced ventilation than for exhaust ventilation for multi-family buildings. This tendency may be due to a global quality approach for buildings where balanced ventilation systems are used.

Analysis of the French database has also led to the identification of levers to improve the practices of building construction stakeholders and testers. Firstly, the leakage location analyses have led to the identification of the most common leaks, both for single-family houses and multi-family houses. Moreover, influent leaks on envelope airtightness have been identified. These results can be very useful to improve envelope airtightness, during both the design stage and on-site construction. Secondly, the threshold effect of the mandatory requirement of the EP-regulation for single-family dwellings reflects the implementation of last-minute corrections. As this practice may have an impact on the durability of envelope airtightness, it highlights the need for practice improvements to comply with the airtightness threshold by using durable solutions.

Finally, some results presented in this paper confirm that the multi-point testing method can be used during all seasons in France. No significant seasonal variations have been identified, either for wooden buildings or for heavy structure buildings. Moreover, the distribution of the n value for French buildings confirms the need for multi-point testing for an indicator extrapolated at 4 Pa.

This database will grow and change in the next few years, through feedback from the field and international sharing, which will lead to more analyses and comparisons in order to improve building performance.

Acknowledgments

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