French building airtightness database after 10 years of operation: statistical analyses of about 500,000 measurements

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ABSTRACT

With the constant evolution of the French EP-regulations, good building airtightness has become mandatory to reach required energy performance. More than 60,000 airtightness tests are performed each year since 2015. Each measurement performed by a qualified tester must be recorded in a national database that is therefore growing fast (more than half million in 2020).

Following RT2012, the new EP-regulation RE2020 came into force on January 1, 2022. It has strengthen the requirements for the air permeability of residential buildings. Moreover, this new regulation goes beyond the energy performance of buildings by requiring the commissioning of ventilation systems to ensure that new dwellings are ventilated right. The inspection schemes for ventilation systems is similar to the building airtightness one (tester qualification scheme, national database), additionally an on-line observatory will be created.

After a brief introduction regarding the French regulatory context for building air permeability and ventilation, this paper gives an overview of the building airtightness database followed by a detailed presentation of the results including: 1) impact of buildings' characteristics on building airtightness level; 2) the evolution of the air permeability (French indicator Q4Pa-Surf, and n50) in new and renovated buildings depending on the building use; 3) the frequency of detected leakages and their impact on the air leakage rate.

In new single-houses, the mean air permeability is 0.38 m3/(h.m²) at 4 Pa which is significantly below the mandatory threshold value (0.6 m3/(h.m²)) and 94% of all houses meet the mandatory requirement. In new multi-family buildings, the mean air permeability is 0.63 m3/(h.m²) at 4 Pa which is significantly below the mandatory threshold value (1.0 m3/(h.m²)) and 98% of all buildings meet the mandatory requirement. In new non-residential buildings, for which there is no mandatory test, the airtightness has improved over the years and is now equivalent to the new multi-family buildings level. In renovated buildings (no mandatory test), more measurements are needed to improve the knowledge regarding the changes in airtightness before and after renovation. The analyses of detected leakages enable us to identify the most critical leakages that are not always the most frequent ones.

KEYWORDS

Building airtightness, measurements, database, field data

1 INTRODUCTION

With the constant evolution of the French EP-regulations, good building airtightness has become mandatory to reach required energy performance. The EP-regulation RT2012 introduced for the first time in 2013 minimum requirements for building airtightness in all new residential buildings. The air permeability, expressed by the he French indicator q_{E4} ($Q_{4Pa\text{-}surf}$ in French: air leakage rate at 4 Pa divided by the loss surface area excluding the basement floor)

must be lower than 0.6 $m^3.h^{-1}.m^{-2}$ for single-family houses (i.e. around n50 = 2.3 h−1) and 1.0 $m^3.h^{-1}.m^{-2}$ for multi-family buildings. In addition to the regulatory requirement, The EP-labels of French association Effinergie (BBC, BEPOS, and BEPOS+ Effinergie 2017) set higher requirements for residential buildings: 0.4 $m^3.h^{-1}.m^{-2}$ for single-family buildings and 0.8 $m^3.h^{-1}.m^{-2}$ (instead of 1.0 $m^3.h^{-1}.m^{-2}$) for multi-family buildings in case of measurement by sampling. Compliance must be justified either by an airtightness test performed by a qualified tester or by applying a certified quality framework. Thanks to this requirement, more than 60,000 airtightness tests have been carried out each year since 2015. Each test performed by a qualified tester is recorded in the French database on building airtightness, which is therefore growing rapidly (more than half million in 2020).
Following RT2012, the new EP-regulation RE2020 came into force on January 1, 2022. It has strengthen the requirements by:

- introducing a new minimum requirement for non-residential (a limit value of 1.7 $m^3.h^{-1}.m^{-2}$ for office building and schools of less than 3000 m² of surface);
- and adding penalties for measurements by sampling (final result multiplied by 1.2) or tests performed before the completion of all work impacting the envelope air permeability (final result incremented by 0.3 $m^3.h^{-1}.m^{-2}$).

Moreover, this new regulation goes beyond the energy performance of buildings by requiring the commissioning of ventilation systems to ensure that new dwellings are ventilated right. The inspection schemes for ventilation systems is similar to the building airtightness one (tester qualification scheme, national database), additionally an on-line observatory will be created.
This paper summarizes the recent results of the French database regarding buildings' characteristics, the evolution of air permeability, and the frequency of detected leakages and their impact on the air leakage rate.

2 DATABASE OVERVIEW

The French database of building airtightness was created in 2007 following the implementation of the national qualification scheme for building airtightness measurement. The measurements of the qualified testers are collected annually according to a standardized form and are implemented in the database. The structure of the database is presented by Mélois (Mélois *et al.*, 2019). It is composed of 39 data fields on the building, the measurement procedure and the test results.
Figure 1 shows the evolution of the number of building airtightness measurements and the percentage of measurements depending on the use of the building.
The database currently contains about 570,000 measurements. It takes into account the measurements made in France until 2021 (incomplete data for 2021, with measurements from two-thirds of qualified measurers being collected at present). The implementation of the regulatory requirement of the former EP-regulation RT2012 has initiated since 2013 a strong increase in the annual number of tests that fluctuates today between 65000 and 80000 approximately.
Residential buildings account for almost all of measurements (68% for single-family dwellings with 388,442 tests, and 28% for multi-family buildings with 157,469 tests). Only 4% of tests are carried out in non-residential buildings (35,958 tests). This is due to the mandatory requirement that applies only to residential buildings. With the new requirement in the current regulation RE2020 regulation for non-residential buildings, we can expect to see a large increase in the number of tests in office buildings and schools in the coming years, similar to residential buildings.

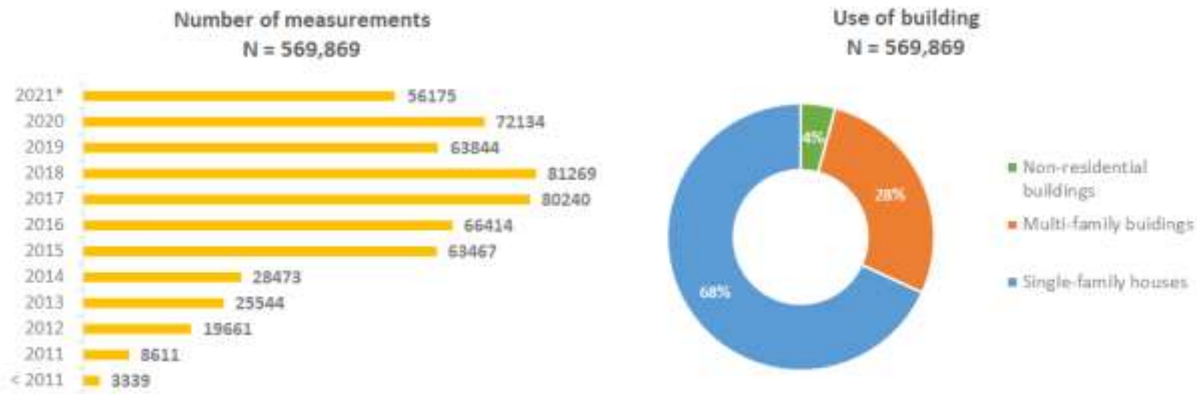

Figure 1: Evolution of the number of building airtightness test in France (left) and percentage of measurements depending on the use of the building. (*The data for 2021 is not complete and corresponds to measurements made by around two-thirds of qualified measurers. The rest will be implemented later)

Figure 2 presents the distribution of the measurements number depending on the measurement time and the measured extent of building. The majority of tests in the database are performed at building completion (commissioning test to justify compliance with the mandatory requirement). Only 5-13% of tests are performed during construction in residential buildings, and 23% in non-residential buildings. Although testers are expected to complete all measurements performed, those performed during building construction may not be consistently completed.

Regarding the measured extent of the building, almost all measurements in single-family dwellings are performed on the whole building. Conversely, more than 90% of the measurements in multi-family buildings are carried out on a part of the building (a sample of apartments). In non-residential buildings, more than 75% of measurements are performed on the whole buildings. This results are in accordance with the compulsory measurement protocol which allows measurements based on a sampling method for multi-family buildings over 10m in height (AFNOR, 2015, 2016).

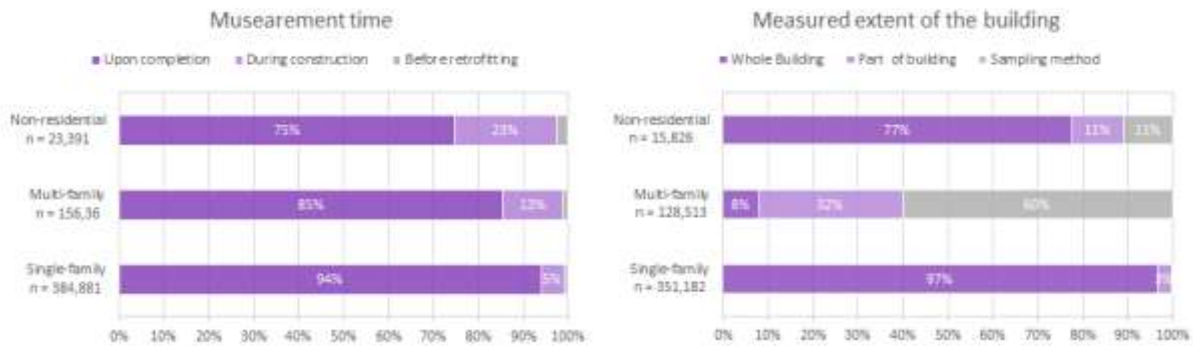

Figure 2: Number of building airtightness measurements depending on the measurement time (left) and the measured extent of building (right)

3 RESULTS

3.1 Main characteristics of buildings

Figure 3 presents the characteristics of buildings regarding main construction material and the type of thermal insulation for single-family, multi-family and non-residential buildings. The majority of single-family houses are built of masonry, mainly with brick (44%) followed by concrete (40%). Wooden houses account for 6%. For Multi-family buildings, concrete is the main material (55%), followed by brick (29%). Wood accounts only for 2%. For non-residential building, concrete is also the main material (36%), followed by brick (20%) and wood (11%). Regarding the thermal insulation, internal insulation walls are still the most used technique in particular in single-family buildings (94%, against 75% around in multi-family and non-residential buildings). The use of external insulation walls is larger in multi-family and non-residential buildings (20% and 15% respectively against 2% in single-family dwellings). The category "distributed thermal insulation" includes in particular wood-frame buildings with insulation between studs. It is important to note that the airtightness of concrete and brick constructions is treated in the same way in France, in most cases it is made through plasterboards and mastics at the inside facing of the walls. The wooden constructions are mainly wood frame structure, and the airtightness is ensured by the vapour barrier.

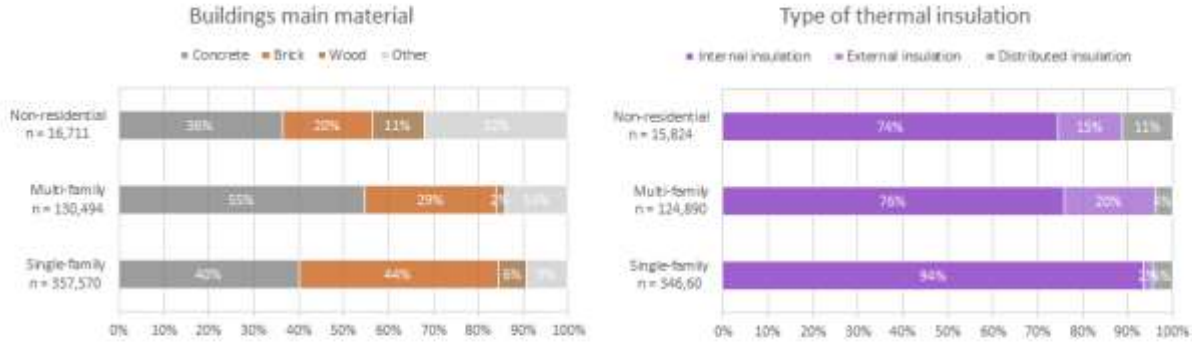

Figure 3: Number of building airtightness measurements depending on the buildings main material (left) and the type of insulation (right)

3.2 Changes of air permeability in the last decade

The results presented here are expressed according to the air permeability French indicator $Q_{4Pa\text{-}surf}$, as explained in section 1, and the air change rate at 5 Pa n_{50}. Only measurements performed upon completion are analysed hereafter in order to perform relevant comparisons. Figure 4 presents the change over the last decade of building air permeability and its distribution.

For single-family dwellings, the air permeability values decrease quickly in the first years and both median and mean values of $Q_{4Pa\text{-}surf}$ stabilize around 0.4 $m^3.h^{-1}.m^{-2}$ (median and mean values of n_{50} are 1.70 and 1.86 h^{-1} respectively) from 2015, clearly below the limit value of the mandatory requirement (0.6 $m^3.h^{-1}.m^{-2}$).

For multi-family buildings, the air permeability values also decrease quickly in the first years and then increase slightly from 2015. This is probably because every new building is now tested and not only exemplary ones that were applying for an EP-label. Indeed, the application of the mandatory requirement in multi-family buildings has been delayed by two years compared to single-family dwellings. The median and mean values of $Q_{4Pa\text{-}surf}$ tend to stabilize around 0.65 and 0.8 $m^3.h^{-1}.m^{-2}$ respectively (median and mean values of n_{50} are 1.43 and 1.78 h^{-1} respectively). They are both clearly below the limit value of the mandatory requirement (1.0 $m^3.h^{-1}.m^{-2}$). The discrepancy between the median and the mean values are probably because of the heterogeneity of the sample, due to the measurement method. As we can see on Figure 5, the air permeability values measured on the whole building are higher than those obtained when the measurement is performed on a sample of apartments or a part of the building. Unlike the whole building measurement method, the other methods do not account for leakages in common areas that represents 24% up to 67% of the air leakage of the whole building (Moujalled *et al.*, 2011).

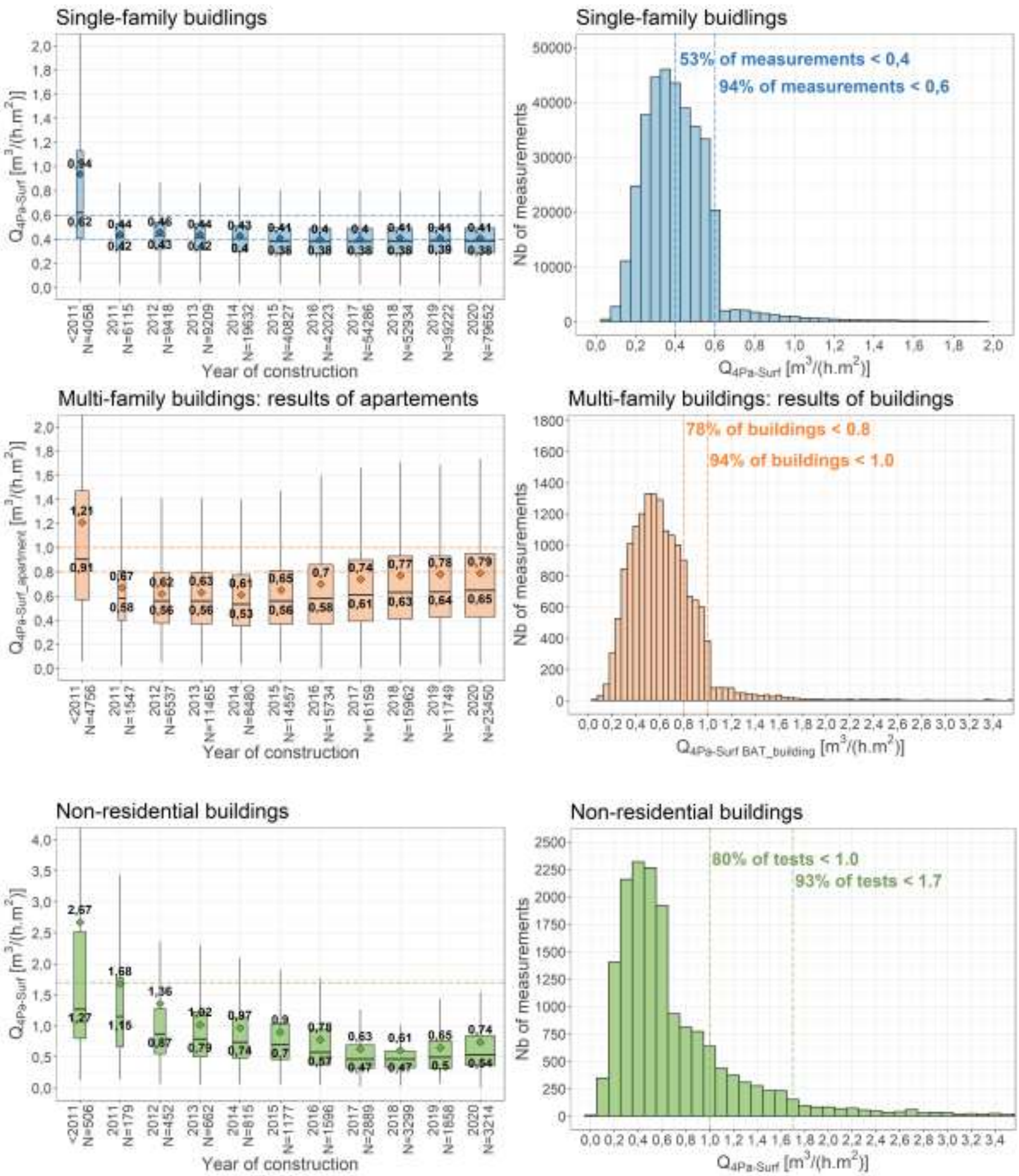

Figure 4: Boxplot of the building air permeability according to the year of construction (left) and its distribution (right) in single-family (top), multi-family (middle) and non-residential buildings (bottom)

For non-residential buildings, as seen above, the number of measurements is much lower. However, results show an annual increase in the number of measurements since 2011, with more than 3,000 non-residential buildings tested in 2020. As for the multi-family buildings, air permeability drops rapidly during the first years, then begins to increase slightly over the last three years as the number of buildings measured increases. The median and mean values of $Q_{4Pa\text{-}surf}$ tend to stabilize around 0.55 and 0.75 $m^3.h^{-1}.m^{-2}$ respectively (median and mean values of n_{50} are 1.82 and 2.38 h^{-1} respectively). The discrepancy between the median and the mean values is also because of the heterogeneity of the sample of non-residential buildings that cover a larger variety of building use (Figure 6). 93% of the tested buildings are better than the default value of the RT 2012 (1.7 $m^3.h^{-1}.m^{-2}$), knowing that the latter is set as limit value for the new mandatory requirement of the RE2020 for office and school buildings. This requirement will help to increase the number of office and school buildings measured and thus provide a better representation of the air permeability of these buildings.

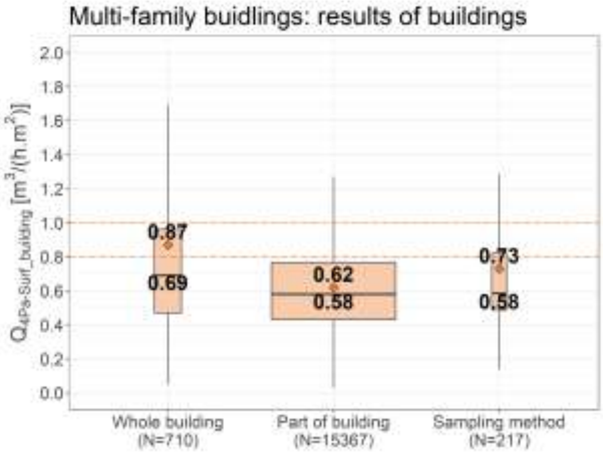

Figure 5: Boxplot of the whole building air permeability in multi-family buildings according to the measurement method. When the measurement is performed on a part of the building or a sample of apartments, the equivalent air permeability of the whole building is calculated as a weighted average of the air permeabilities of the tested apartments by their envelope surfaces according to FD P50 784(AFNOR, 2016, p. 50).

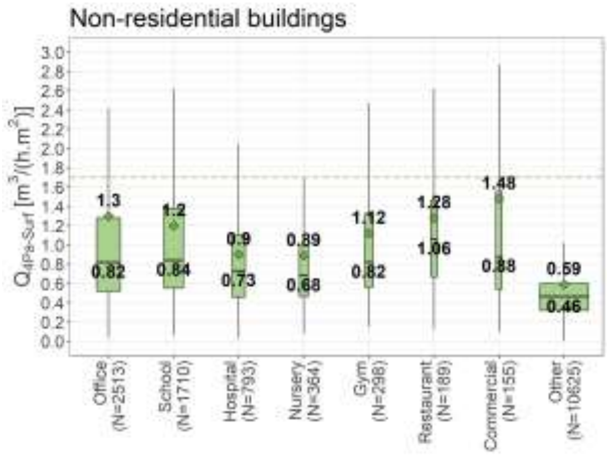

Figure 6: Boxplot of the air permeability in non-residential buildings depending on the building use

3.3 Changes of air permeability in existing buildings

Figure 7 presents the change of building air permeability in existing buildings depending on the moment measurement: before retrofitting (initial), during construction, and upon completion (after retrofitting).

First, we can observe the relatively small numbers of measurements in existing single-family, multi-family and non-residential buildings compared to new buildings. In the absence of a mandatory requirement for existing buildings, the measurements in these buildings are carried out at the will of the owner or in the framework of a label. Overall, the results show that the air permeability of existing buildings after retrofitting is better than that of buildings before retrofitting. However, it is difficult to draw general conclusions from these observations due to the small number of buildings measured. It is necessary to increase the measurements in existing buildings in order to improve the knowledge of the air permeability in these buildings and how it is impacted by the renovation works.

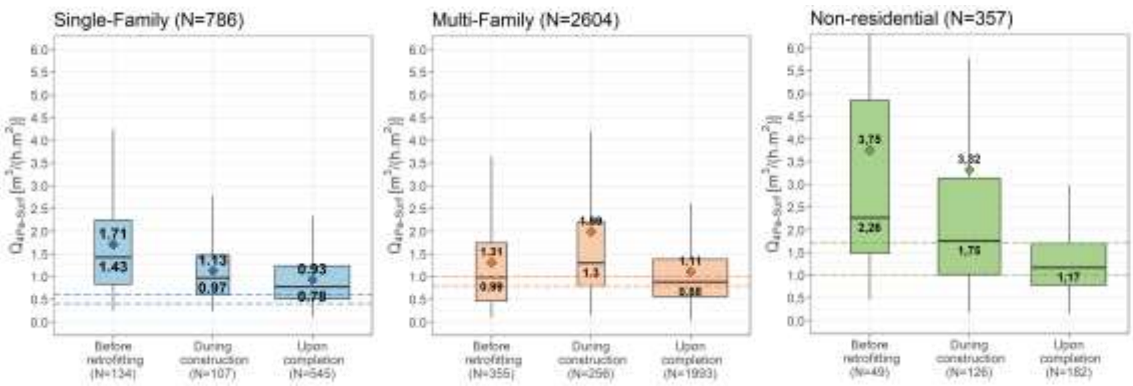

Figure 7: Boxplots of the air permeability in existing buildings depending on the moment of measurement

3.4 Analysis of the detected leakages

During each test, a detailed qualitative leakage detection is performed by testers in accordance with the Standard ISO 9972 and the French standard FD P50-784 (AFNOR, 2016). Leakage locations are usually detected using a smoking device, a thermography, or by feeling the airflow on the envelope with fingers as described in the annex E of ISO 9972. Leakages are classified according to the leakage categories of FD P50-784 (see appendix A) with 8 main categories and 46 sub-categories (see appendix A).

Figure 8 shows the frequency of detected leakages by category in single-family, multi-family and non-residential buildings. Leakages through doors and windows (category C), electrical components (category F) and around penetrations through the envelope (category D) are the most frequent leakages detected in all buildings.

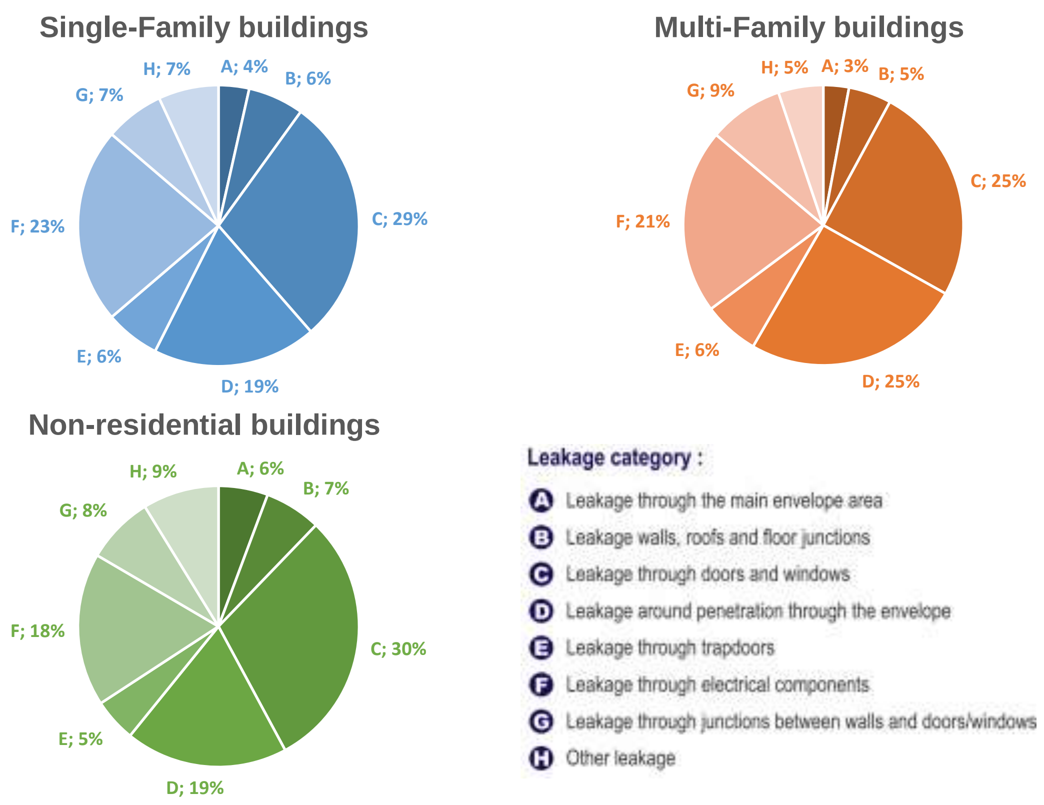

Figure 8: Frequency of detected leakages in single-family, multi-family and non-residential buildings

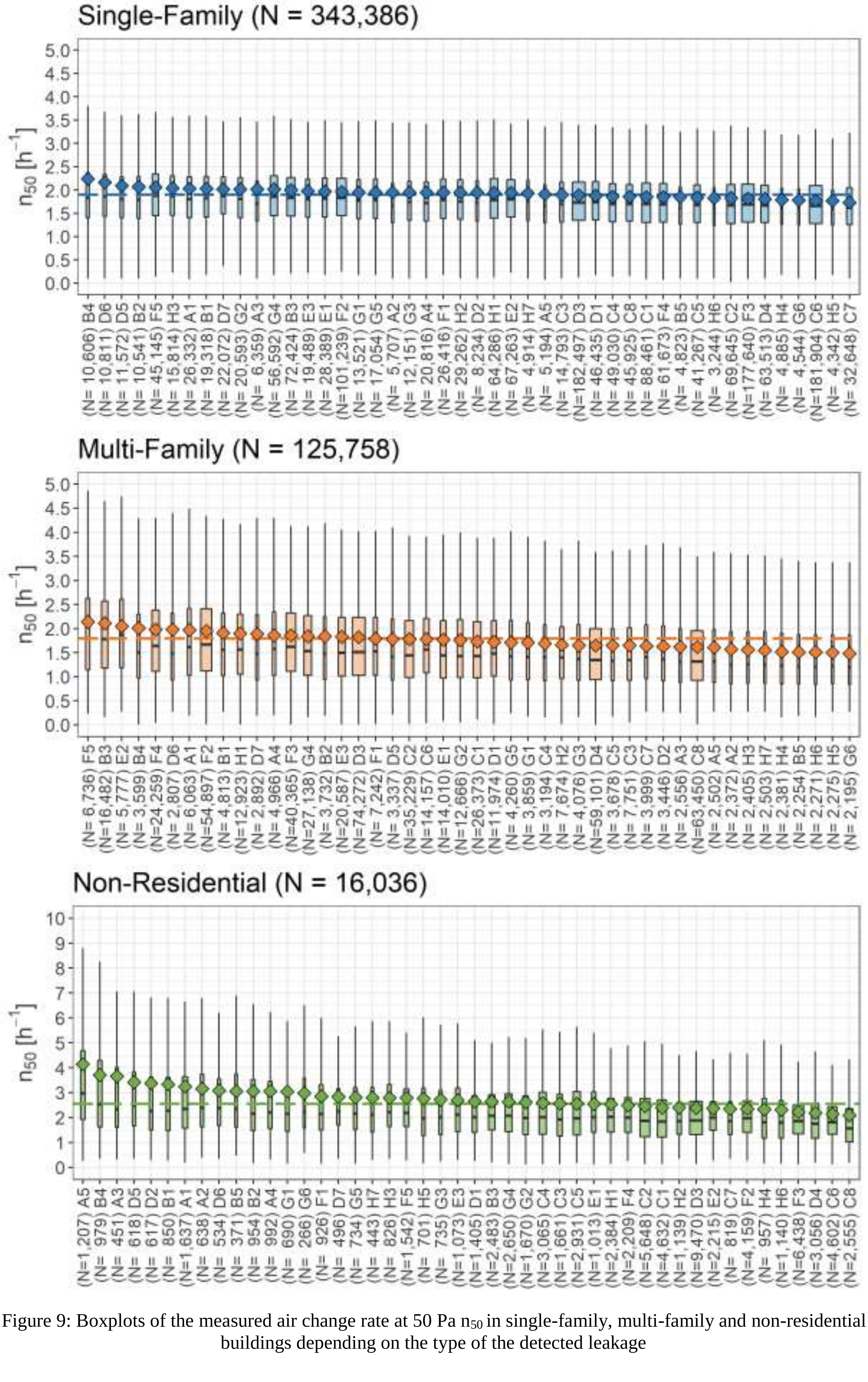

Figure 9: Boxplots of the measured air change rate at 50 Pa n_{50} in single-family, multi-family and non-residential buildings depending on the type of the detected leakage

In order to analyse the impact of leakages on the air permeability, we have constructed 46 subsamples corresponding to the 46 subcategories of leakages. Each subsample contains the data where a particular leakage is observed. We then compared the mean value of air permeability of each subsample to that of the entire sample using Wilcoxon tests. For this analysis, we used the air change rate at 50 Pa ‘‘n_{50}” as indicator to analyse air permeability variations, as it has the lowest error with respect to repeatability, reproducibility, and wind impact (Moujalled *et al.*, 2021).

Figure 9 shows the comparison between the boxplots of n_{50} of all leakage subsamples and the mean value of the entire sample. Leakage subsamples are sorted in decreasing order of the mean value of n_{50}. The figure shows also on the x-axis the occurrence of each leakage. We can identify the leakage subsamples with highest values n_{50}, the corresponding leakage can thus be considered to have greatest impact on the airtightness (p-value << 0.01).

Table 1 shows the top five leakages with the highest values of mean n_{50} in single-family, multi-family and non-residential buildings. It is interesting to note that the B4 leak (junction between wall and ceiling or sloped roof) is among those with a significant impact on airtightness in all three types of buildings, even though it is not very frequent. Overall, leakages through the main envelope area (A) and the junctions between walls and floors (B) are less frequent but have a significant impact on the air tightness of the building.

Table 1: The top five leakages with the greatest impact on air permeability

Type of building	Leakages with highest values of mean n_{50} (Occurrence)
Single-family	**B4-Junction between wall and ceiling or pitched roof (3%)**
	D6-Beam connection with floor or ceiling (3%)
	D5-Beam or joist connection with walls (3%)
	B2-Junction between two vertical walls (3%)
	F5-Lighting components (13%)
Multi-family	F5-Lighting components (5%)
	B3-Junction between wall and floor (13%)
	E2-Attic trap door (absent or ineffective seal) (5%)
	B4-Junction between wall and ceiling or pitched roof (3%)
	F4-Wiring inside internal walls (19%)
Non-residential	A5-False ceiling panels (8%)
	B4-Junction between wall and ceiling or pitched roof (6%)
	A3-mortar/glue junction between masonry blocks, wall panels (3%)
	D5-Beam or joist connection with walls (4%)
	D2-Vapour barrier membrane through which duct, pipe, beams, hatches (4%)

4 CONCLUSIONS

Since its creation in 2007, the French database of building airtightness has been annually fed by measurements performed by qualified testers. The total number of measurements is now about 570,000 with a majority of residential buildings (68% single dwellings, 28% multi-family buildings against 4% non-residential buildings). This is due to the mandatory requirements of the former EP-regulation RT2012 that was implemented in 2013 only for new residential buildings. It has initiated since 2013 a strong increase in the annual number of tests that fluctuates today between 65000 and 80000 approximately. Measurements from 2015 can thus be considered as representative of new French residential buildings. With the new requirement in the current regulation RE2020 for non-residential buildings, we can expect to see a large increase in the number of tests in office buildings and schools in the coming years, similar to residential buildings.

In new single-houses, the mean air permeability is about 0.4 m3/(h.m²) at 4 Pa which is significantly below the mandatory threshold value (0.6 m3/(h.m²)) and 94% of all houses meet the mandatory requirement. In new multi-family buildings, the mean air permeability is about

0.8 m3/(h.m²) at 4 Pa which is significantly below the mandatory threshold value (1.0 m3/(h.m²)) and 94% of all buildings meet the mandatory requirement. In new non-residential buildings, for which there is no mandatory test, the airtightness has improved over the years and is now equivalent to the new multi-family buildings level: 93% of the tested buildings are better than the default value of the RT 2012 (1.7 $m^3.h^{-1}.m^{-2}$). In renovated buildings (no mandatory test), more measurements are needed to improve the knowledge regarding the changes in airtightness before and after renovation. The analyses of detected leakages enable us to identify the most critical leakages that are not always the most frequent ones: leakages through the main envelope area and the junctions between walls and floors are less frequent but have a significant impact on the air tightness of the building.

5 ACKNOWLEDGEMENTS

The database is the property of the French Ministry in charge of the Construction. The analysis was performed by Cerema. The sole responsibility for the content of this publication lies with the authors.

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7 APPENDIX 1 – LEAKAGE DEFINTION

Classification of leakages according to the French standard FD P50-784 (AFNOR, 2016).

Leakage category	Leakage sub-category
A - Main evelope area	A1 - Other leakage on main envelope area
	A2 - Vapour barrier membrane (or similar complex): adhesive junction between strips, puncture or tearing
	A3 - mortar/glue junction between masonry blocks, wall panels
	A4 - puncture (e.g.: wall plug) or unsealed junctions between panels
	A5 - False ceiling panels
B - Wall, roof and floor junctions	B1 - Other leakage through wall and slab junctions
	B2 - Junction between two vertical walls
	B3 - Junction between wall and floor
	B4 - Junction between wall and ceiling or pitched roof
	B5 - Junction between vapour barrier membrane and slab
C Doors and windows	C1 - Other leakage on windows and glazed doors
	C2 - Window/glazed doors: junction between frame and opening panels
	C3 - Window & glazed doors: junction between glass and frame defective seal)
	C4 - Landing door or fire door: poor compression of seals (excluding threshold bar)
	C5 - Landing door or fire door: absent or ineffective threshold bar
	C6 -Sliding door: Excessive space between glass panels, and the frame
	C7 - Sliding door: Evacuation of condensates
	C8 - Rolling shutter casing
D - Penetration through the envelope	D1 - Other element through a wall
	D2 - Vapour barrier membrane through which duct, pipe, beams, hatches
	D3 - Crossing Floor, walls and/or partitions (any type of pipes and electrical wiring…)
	D4 - Ventilation air terminals: leaks at periphery of exhaust/supply air vents
	D5 - Beam or joist connection with walls
	D6 - Beam connection with floor or ceiling
	D7 - Stairs: Junction flooring/stairs or vertical walls/stairs
E - Trapdoor	E1 - Another trapdoor
	E2 – Attic trap door (absent or ineffective seal)
	E3 - Trapdoor to vertical technical duct (absent or ineffective seal)
F - Electrical component	F1 - Other electrical component
	F2 - Electrical board
	F3 - Wiring inside external walls
	F4 - Wiring inside internal walls
	F5 - Lighting components
G - Door/window and wall junctions	G1 - Other leakage through wall and door/window junction
	G2 - Junction between walls and windows or glazed door
	G3 - Junction between walls and landing door or Fire door
	G4 - Junction between internal panels and window and glazed door
	G5 - Junction between internal panels and landing door or Fire door
	G6 - Junction between vapour barrier membrane and door or window
H - Other	H1 - Other leakage
	H2 - Wood-burner, fireplace insert or boiler, or combustion-air air vent
	H3 - Extractor hood with external evacuation
	H4 - Trapdoor for smokes evacuation
	H5 - Zenithal lighting roof lights
	H6 - Elevator door (frame - connecting door …)
	H7 - Arrival air extraction or not described in the thermal calculation