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1 **Mid-term and long-term changes in building airtightness:** 2 **a field study on low-energy houses**

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13 **Abstract**

14 The main objectives of this paper are to quantify and qualify changes in building airtightness on
15 different time scales, and to identify factors that may explain the variations observed. A special
16 measurement protocol, based on ISO 9972 but with some additional requirements, was defined after a
17 detailed literature review. For the mid-term campaign, 30 new detached houses were measured once
18 per year over a 3-year period. It was observed that air permeability increases slightly during the first
19 year (a mean increase of 18%), and then stabilizes during the second and third years. Five of them
20 were measured twice per year but did not show any significant seasonal variation. For the long-term
21 campaign, 31 detached houses built during the last 10 years were remeasured once. Air permeability
22 shows a similar increase to that of the mid-term campaign after 3-10 years (a mean increase of 20%).
23 The results show an overall increase in the number of leakages detected for all houses, but this
24 increase is not always correlated with the change in air permeability. Results pointed to three factors
25 that could explain the deterioration of airtightness: the number of levels, the type of roof and the type
26 of building material and air-barrier.

28 **Keywords:**

29 Airtightness durability, field measurements, building envelope, low-energy house

1 1. Introduction

2 Over the last thirty years, much progress has been made to increase our knowledge about
3 mechanisms governing the airtightness of buildings and the impact of air infiltrations on energy
4 efficiency [1–3], health effects [1,4] and construction quality-related issues[5]. As a matter of fact, air
5 leakage has an increasing rate on the overall energy performance of new low-energy buildings. Since
6 the early 2000s, regulations in many European countries therefore explicitly take airtightness into
7 account, sometimes with mandatory requirements for new buildings (with or without mandatory
8 testing), as a consequence of Europe’s ambition to make nearly zero energy buildings widespread by
9 the end of 2020 [6][7–9]. In France, the current energy performance regulation (RT2012) requires all
10 new residential buildings to comply with limit values for the French air permeability indicator “ $Q_{4Pa-surf}$ ”
11 (the air leakage rate at 4 Pa per the building envelope area excluding the basement floor area):

- 12 • $0.6 \text{ m}^3\text{h}^{-1}\text{m}^{-2}$ for single-family houses (i.e. an air change rate at 50 Pa “ n_{50} ” around 2.3 h^{-1}),
- 13 • $1.0 \text{ m}^3\text{h}^{-1}\text{m}^{-2}$ for multi-family buildings.

14 Compliance is justified either by an airtightness test performed by a qualified tester or by applying a
15 certified quality approach [7]. Moreover, the airtightness test must be performed using the fan
16 pressurisation method (so called blower door test) in accordance with the standard ISO 9972 [10] and
17 the French standard FD P50-784 which specifies additional requirements concerning the application of
18 the ISO standard in the French context [11]. The Blower Door test consists of a false door equipped
19 with a pressurisation fan that is capable of pressurising or depressurising a building and measuring
20 the resultant airflow rates and pressure differences (usually from 10 Pa to 60 Pa with at least five
21 equally spaced pressures differences) across the building envelope for establishing the pressure-
22 leakage relationship of the tested building. The air permeability is then calculated at a reference
23 pressure difference (e.g. 4 Pa, 10 Pa or 50 Pa). The standard ISO 9972 describes in detail the
24 measurement procedure including the measurement conditions, the building preparation, the technical
25 specifications of the measurements devices and the calculation method.

26 Given this context, the number of blower door tests has significantly increased during the last years
27 across the world, especially in the European countries [6]. In France, around 65,000 blower door tests
28 have been performed each year since 2015 [12], and in the UK more than 250,000 tests were
29 recorded between 2015 and 2017 [13].

30 Therefore, the reliability of the test method and result has become a major concern [7,14]. The
31 standard, as well as the competent tester schemes imposed in some countries, provide the minimum

1 framework for making the measurement results reliable. However, it does not tackle all the issues
2 related to the measurement uncertainty. The issue of repeatability and reproducibility of the blower
3 door test was tackled by [14–16]. Recent research has investigated the uncertainty due the wind [17–
4 20], the stack effect [19,21], the zero-flow pressure approximation [22], and the regression method
5 [23,24]. The measurement uncertainty will be discussed in section 2.3.

6 On the other hand, having a requirement about building airtightness is relevant only if the airtightness
7 level is steady over time. As a matter of fact, recent studies have shown that a mandatory level of
8 airtightness leads to last-minute taping and mastic setting that is most probably not durable [7,9]. The
9 durability of airtightness products and assemblies in the mid- and long-term is therefore a pending
10 question.

11 Across a comprehensive literature review, Leprince et al. [25] reported the results of seven field
12 studies measuring averaged changes in the airtightness of various samples of houses from 2 to 25
13 years after construction. Each of them displayed an increase in the average air permeability of the
14 sample of tested houses, ranging from 11% [26] to 162% [27], and the first three years seemed the
15 most critical, which was confirmed by later studies [28,29]. Despite the increase in the average air
16 permeability of the tested houses, the airtightness did not change over time for some houses and has
17 improved for some others. None of these studies has been able to explain the reasons for the different
18 changes in the air permeability between houses. However, several factors that may explain the
19 increase in air permeability in the first three years have been identified, for example:

- 20 • mastic shrinkage can occur the first time the building is heated [30] or when no backer rod is
21 used [31];
- 22 • structure movements and foundation settlement may induce cracking in the junctions between
23 the air barrier and penetrations [32];
- 24 • furnishing a house after construction can imply drilling holes into the envelope [33];
- 25 • occupants' behaviour can be a critical factor in some cases [14].

26 In the longer term, it seems that some products do not deteriorate [31] but the combination of
27 incompatible products or ones implemented in an unsuitable (cold or dusty) environment [34] may lead
28 to increased air permeability. Some products, such as clamped joints of wood frame buildings, may also
29 suffer from transient climatic conditions inducing wetting and drying cycles [35].

30 This paper addresses the issue of the durability of building airtightness in real conditions with regard to
31 low-energy houses. Therefore, we have carried out detailed field measurements on 61 low-energy

1 houses that have been measured using the blower door test from two to four times each at multiple
2 timespans. Contrary to other field studies identified in the literature, this approach allows to study the
3 change in the air permeability of a given house over time, and not only to compare changes between
4 multiple houses. The main objectives of this field study are to quantify and qualify the changes in
5 building airtightness on different time scales, and to identify factors that can explain the variations
6 observed.

7 **2. Method**

8 In order to evaluate the durability of the building airtightness in real conditions in the mid- and long-
9 term, two field measurement campaigns were conducted: a mid-term (MT) campaign and a long-term
10 (LT) campaign. For the MT campaign, we have selected a first sample (MT sample) of 30 new single-
11 detached low-energy houses. For the LT campaign, we have selected a second sample (LT sample)
12 of 31 existing single-detached dwellings.

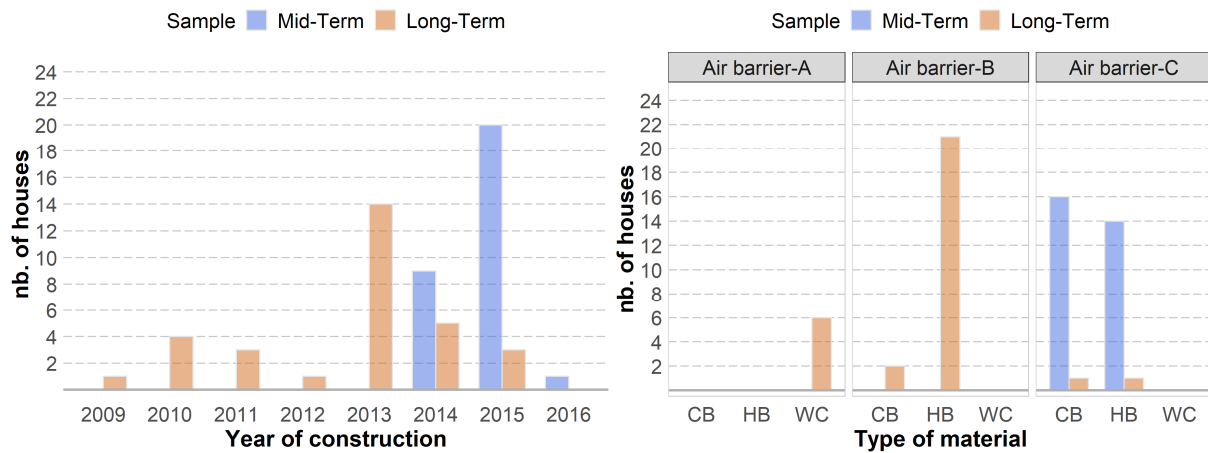
13 All dwellings were selected according to well-defined criteria to reduce uncertainties about the main
14 factors impacting building airtightness. In particular, dwellings from both samples were all tested upon
15 completion, and the test reports were available and in accordance with standard ISO 9972 [10] and its
16 French appendix FD P50-784 [11]. The description of their air barrier was also available. The
17 availability and the quality of the test reports were of particular importance because the airtightness
18 levels measured upon completion (called measurement n_0) were to be used as reference to examine
19 how it changes over time.

20 2.1. Description of the houses studied

21 **Table 1** summarizes the main characteristics of the houses studied in both MT and LT samples. **Fig. 1**
22 shows the distribution of houses according to the year of construction, the main material of the
23 buildings and the type of air barrier.

24 The MT sample is composed of 30 new single-detached low-energy houses built mainly in 2014 and
25 2015, with 20 one-storey houses and 10 two-storey houses. The average floor area is 124.1 m² with a
26 minimum of 87 m² and a maximum of 172.2 m², and the average volume is 217.1 m³ with a minimum
27 of 156.1 m³ and a maximum of 363.9 m³. All houses are built of masonry with interior insulation (16
28 houses with concrete blocks and 14 with hollow bricks). The majority of roofs are made of light-frame
29 wood truss (20 houses), against 8 houses with traditional wood frame and 2 houses with an exposed
30 traditional wood frame. A single exhaust ventilation system with humidity control is installed in all

1 houses. Airtightness is obtained through plasterboard and mastic on the inside facing of the walls in all
 2 houses (air barrier C) as shown in **Fig. 1**.



4
 5 **Fig. 1.** Distribution of houses depending on the year of construction (left), the main material of the
 6 buildings and type of air barrier (right) (CB= Concrete block, HB= Hollow brick, WC= Wood
 7 construction, Air barrier-A= air barrier provided by vapour barrier, Air barrier-B= air barrier provided by
 8 coating on the masonry, Air barrier C= air barrier provided by plasterboard and mastic on the inside
 9 facing of the walls).

10
 11 The LT sample is composed of 31 single-detached low-energy houses built during the last ten years
 12 from 2009 to 2015, with 7 one-storey houses and 24 two-storey houses. The average floor area is
 13 147.9 m² with a minimum of 83.1 m² and a maximum of 269 m², and the average volume is 256.6 m³
 14 with a minimum of 138.9 m³ and a maximum of 478.2 m³. The majority of houses are built of masonry
 15 with interior insulation (22 houses with hollow bricks and 3 with concrete blocks), against 6 wooden
 16 houses. The majority of roofs are made of light-frame wood truss (27 houses), against 4 houses with a
 17 flat roof. A balance ventilation system is installed in 1 house while all the others have an extract-only
 18 ventilation system with humidity control. The airtightness of the masonry houses in the LT sample is
 19 mainly obtained by a coating on the masonry (air barrier B), while the airtightness of the wooden
 20 houses is obtained by the vapour barrier (air barrier A) as shown on **Fig. 1**.

21
 22
 23
 24

1 **Table 1.** Main characteristics of the dwellings studied.

	MT sample	LT sample
Sample size	30 dwellings	31 dwellings
Year of construction	2014: 9 2015: 20 2016: 1	< 2013: 9 2013: 14 2014: 5 2015: 3
Floor Area	Min: 87 m ² Max: 172 m ² Mean: 124 m ²	Min: 80 m ² Max: 269 m ² Mean: 139 m ²
Volume	Min: 175 m ³ Max: 364 m ³ Mean: 258 m ³	Min: 124 m ³ Max: 478 m ³ Mean: 236 m ³
Envelope area	Min: 156 m ² Max: 309 m ² Mean: 217 m ²	Min: 169 m ² Max: 594 m ² Mean: 304 m ²
Nb. of levels	1-story: 20 2-story: 10	1-story: 7 2-story: 24
Type of air-barrier	A: 0 B: 0 C: 30	A: 6 B: 22 C: 3
Construction type	frame structure: 0 bearing walls: 30	frame structure: 6 bearing walls: 25
Type of material	Concrete block: 16 Hollow Brick: 14 Wood construction: 0	Concrete block: 3 Hollow Brick: 22 Wood construction: 6
Type of floor	Floor on crawl space: 18 Slab on grade: 12	Floor on crawl space: 24 Slab on grade: 7
Type of roof	Light-frame wood truss: 20 Traditional wood frame: 8 Exposed wood frame: 2 Flat roof: 0	Light-frame wood truss: 27 Traditional wood frame: 0 Exposed wood frame: 0 Flat roof: 4
Ventilation system	Single-exhaust: 30 Balanced: 0	Single-exhaust: 30 Balanced: 1
Heating system	Heat pump: 14 Gas boiler: 8 Wood stove: 7 Electric heating: 1	Heat pump: 6 Gas boiler: 3 Wood stove: 1 Electric heating: 21
Specific equipment	Thermodynamic water heater: 18 Electric heat water: 2 Solar thermal: 1 Solar PV: 1 DHW by gas boiler: 0	Thermodynamic water heater: 25 Electric heat water: 1 Solar thermal: 2 Solar PV: 1 DHW by gas boiler: 2
Measured air permeability "Q _{4Pa-surf} " upon completion	Min : 0.13 m ³ h ⁻¹ m ⁻² Max : 0.52 m ³ h ⁻¹ m ⁻² Mean : 0.31 m ³ h ⁻¹ m ⁻² Std-Dev : 0.08 m ³ h ⁻¹ m ⁻²	Min : 0.07 m ³ h ⁻¹ m ⁻² Max : 0.58 m ³ h ⁻¹ m ⁻² Mean : 0.33 m ³ h ⁻¹ m ⁻² Std-Dev : 0.13 m ³ h ⁻¹ m ⁻²
Measured air permeability "n ₅₀ " upon completion	Min : 0.68 h ⁻¹ Max : 2.16 h ⁻¹ Mean : 1.39 h ⁻¹ Std-Dev : 0.34 h ⁻¹	Min : 0.44 h ⁻¹ Max : 2.50 h ⁻¹ Mean : 1.37 h ⁻¹ Std-Dev : 0.54 h ⁻¹

2

3 The measurements upon completion (measurement n₀) of both samples showed the same mean
4 value of air permeability Q_{4Pa-surf} around 0.3 m³h⁻¹m⁻² (mean air change rate at 50 Pa n₅₀ around 1.4 h⁻¹),
5 significantly below their required target of 0.6 m³h⁻¹m⁻² (i.e. air change rate at 50 Pa n₅₀ around 2.3
6 h⁻¹ [7]), with larger variations among the LT sample (Q_{4Pa-surf} standard-deviation of 0.13 m³h⁻¹m⁻² for
7 the LT sample against 0.08 m³h⁻¹m⁻² for the MT sample).

1 2.2. Measurement method

2 The MT campaign aims at characterising the yearly changes in building airtightness of new dwellings
3 over a 3-year period. The following measurements were therefore made:

- 4 • The airtightness of each building was measured once per year over the 3-year period (called
5 measurements n_1 , n_2 and n_3 respectively).
- 6 • Five buildings of this sample were measured twice per year in order to investigate the impact
7 of seasonal variations.

8 The LT campaign aims at characterising the changes in building airtightness of existing dwellings over
9 a longer period from 3 to 10 years. The airtightness of each dwelling was therefore measured once
10 (called measurement n_x).

11 The main challenge of this project is to understand the variation of the airtightness and to identify
12 whether it is related to the materials/assembly ageing, the maintenance conditions or other factors
13 such as the occupants' behaviour. A specific measurement protocol was therefore defined after a
14 detailed literature review [25]. The protocol is mainly based on standard ISO 9972 [10] and its French
15 national appendix [11] for the pressurisation measurement method with additional requirements to
16 reduce uncertainty due to the measurement procedure:

- 17 • Each dwelling was measured under the same conditions as the first measurement upon
18 completion as far as possible: same qualified tester, same calibrated measurement devices
19 (complying with the required accuracy of ISO 9972 and FD P50-784), same building
20 preparation, same pressure difference sequences, same season, and wind force no higher
21 than 3 on Beaufort scale (i.e. wind speed less than $6 \text{ m}\cdot\text{s}^{-1}$). Measurements were performed in
22 both pressurisation and depressurisation conditions. Besides, the indoor and outdoor air
23 temperatures and relative humidities were measured during each test, as well as the wind
24 force on Beaufort scale. Deviations from the conditions of the first test were reported.
- 25 • Detailed qualitative leakage detection was performed at each test in accordance with the
26 Standard ISO 9972 [10] and the French standard FD P50-784 [11]. Leakage locations were
27 detected using a smoking device and by feeling the airflow on the envelope with fingers as
28 described in the annex E of ISO 9972. Each detected leakage is described, photographed,
29 classified according to the leakage categories of FD P50-784 (see appendix A), and ranked
30 according to a qualitative scale (weak, medium and strong). **Fig. 2** illustrates examples of
31 leakage detection through the frame of a sliding door, an attic trap door and ceiling downlight.

1 Therefore, the detection of leakage location has been done thoroughly enough to track
2 changes in leakage distribution over the duration of the measurement campaigns.

- 3 • Questionnaires were filled in by occupants at each measurement in order to identify the
4 modifications of the building envelope due to the action of the occupants (i.e. drillings made in
5 the air barrier after the first test, replacement of products, etc.).

6 In total, 84 and 31 measurements of building airtightness were performed for the MT and LT samples
7 respectively, plus another 10 measurements for the seasonal impact.



8 **Fig. 2.** Examples of leakage detection by a smoking device, from left to right: leakage through the
9 frame of a sliding door (leakage C6, strong), leakage through attic trap door (leakage E2, medium)
10 and leakage through ceiling downlight (leakage F5, strong).

11 2.3. Uncertainty in airtightness measurements and analysis methodology

12 Part of the changes in airtightness measurements is due to the measurement uncertainty. Therefore, it
13 is essential to consider the uncertainty in the analysis of changes in airtightness measurements.

14 In addition to the uncertainty of the measuring devices, global uncertainty in airtightness measurement
15 may have several other sources:

- 16 • Tester behaviour (including building preparation);
- 17 • Repeatability and reproducibility;
- 18 • Wind and thermal draft impact;
- 19 • Regression technique;
- 20 • Seasonal variation of airtightness.

21 To limit the impact of tester behaviour, many countries (including France) have developed competent
22 tester schemes and specific standards that among other things describe the building preparation [36].

23 Regarding the repeatability and the reproducibility of the blower door test, this issue has been tackled
24 by [14–16] with the following main conclusions:

- 1 • The average air leakage rate had a repeatability standard deviation ranging from 3.5% at 4 Pa
2 to 1.4% at 50 Pa [14–16]. The average air leakage rate had a reproducibility standard
3 deviation ranging from 5.9% at 4 Pa to 2.4% at 50 Pa under favourable conditions (i.e. no
4 wind and low-temperature difference) [15].
- 5 • There can be a significant difference between the results in depressurisation and in
6 pressurisation, and the repeatability and reproducibility get improved when tests are
7 performed both in pressurisation and depressurisation [15].

8 Various studies have been focusing on wind impact in the last years [17,18,23,37]. It was found that
9 the model error due to the steady wind on the estimated airflow rate is relatively small at the high-
10 pressure point (about 3% with wind speeds below 6 m.s⁻¹ at 50 Pa), but it can become very significant
11 with a low-pressure point (up to 60% at 10 Pa) [17]. As stated in §2.2, all measurements were carried
12 out with wind speed no higher than 3 on the Beaufort scale (i.e. wind speed less than 6 m.s⁻¹), in order
13 to reduce the error due to wind on the air leakage rate at 50 Pa.

14 The seasonal variation of building airtightness was investigated in various studies [7,38]. The
15 conclusions of these studies are contrasted. This is why it has been decided in this study to perform
16 measurements always at the same season.

17 Based on these conclusions, the air leakage rate at 50 Pa “q₅₀” was chosen as indicator to analyse the
18 changes in airtightness in this study. It presents the lowest error regarding repeatability,
19 reproducibility, and wind impact. It is also less sensible to the regression technique [23]. Given the
20 strict conditions imposed in our measurement method, the overall uncertainty can be considered lower
21 than 10% as stated by ISO 9972.

22 The changes in air leakage rate were statistically analysed as follow:

- 23 • A one-sided paired t-test (95% confidence level) was performed to analyse the statistical
24 significance of the increase in the mean q₅₀ between the reference measurement n₀ and the
25 other measurements of each sample. A Shapiro test was also performed to check the
26 normality of the samples of measurements.
- 27 • Multiple linear regression (MLR) was performed to analyse the correlation between changes in
28 the measured air leakage rates q₅₀ and the changes in the numbers of leakages detected.

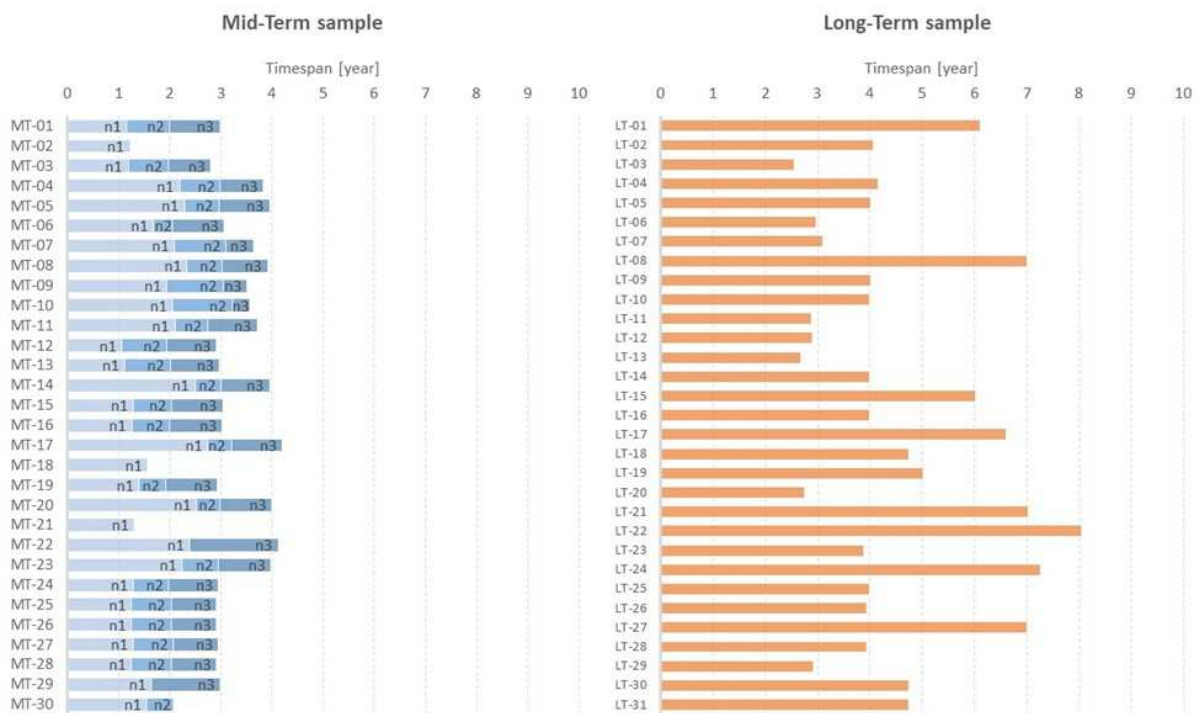
29 Regarding the measurements of seasonal variations, no statistical analysis was performed as the
30 sample size was too small (5 buildings). Only changes in the measured air leakage rates for each
31 building were examined.

1 **3. Results and discussion**

2 *3.1. Changes in envelope air permeability*

3 **Fig. 3** shows the timespans between the different measurements in both samples. For the MT sample,
 4 1st-year measurements (measurements n_1) started in November 2016 and finished in October 2018, or
 5 from 1 to 3 years after the measurements n_0 upon completion. The measurements were delayed due
 6 to the difficulty in finding owners willing to be involved in a 3 year-long measurement campaign. The
 7 average timespan between measurements n_0 and n_1 is therefore 1.7 years, and the average
 8 timespans between the following measurements are less than one year to compensate for the delay
 9 (0.7 year between n_1 and n_2 , and 0.9 year between n_2 and n_3). For three houses, measurements n_2
 10 and n_3 were not made because owners were not willing to be part of the study till the end. In addition,
 11 one house was excluded from the MT sample in the analysis because of problems during
 12 measurement n_1 .

13 For the LT sample, all measurements (measurements n_x) were conducted in 2017, from 3 to 8 years
 14 after n_0 (average timespan of 4.6 years between n_0 and n_x). Only 9 houses older than 5 years were
 15 measured. As for the MT sample, it was difficult to find houses fulfilling selection criteria with volunteer
 16 owners. One house was excluded from the LT sample in the analysis because of problems during
 17 measurement n_x .



18

19 **Fig. 3.** The timespan between the different measurements of the MT and LT samples.

1 Before presenting the results, it is important to note that all tests upon completion (measurements n_0
2 of both samples) were made in either depressurisation (27 and 31 houses of the MT and LT samples
3 respectively) or pressurisation (3 houses of the MT sample). Indeed, the standard ISO 9972 does not
4 impose to make the test in both pressurisation and depressurisation. Therefore, only one of the two
5 tests is made most of the time (most commonly the depressurisation test).

6 As the changes in the air leakage rates are calculated in comparison with the measurements upon
7 completion n_0 , we used the results of either pressurisation or depressurisation tests of the
8 measurements n_1 , n_2 , n_3 and n_x according to the tests of measurements n_0 . As discussed in section
9 2.3, there can be a significant difference between the results in depressurisation and pressurisation.
10 Therefore, we compared the changes in q_{50} in pressurisation and depressurisation between the
11 measurements n_1 , n_2 and n_3 for all houses of the MT sample. Results showed similar changes in both
12 depressurisation and pressurisation between different measurements for around 90% of the houses.
13 This confirms the importance of making the test in both pressurisation and depressurisation as
14 proposed by [15,17].

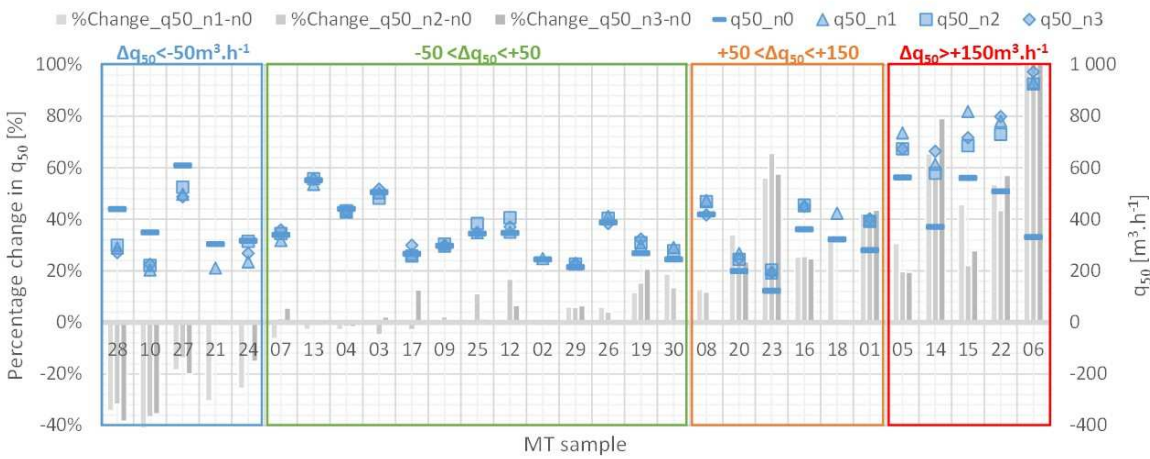
15 The houses MT-11 and LT-24 were excluded from the samples because the calculated uncertainties
16 on the air leakage rate q_{50} (according to ISO 9972) were higher than 10% during the measurements n_1
17 and n_x respectively.

18 3.1.1. Changes in air permeability per house

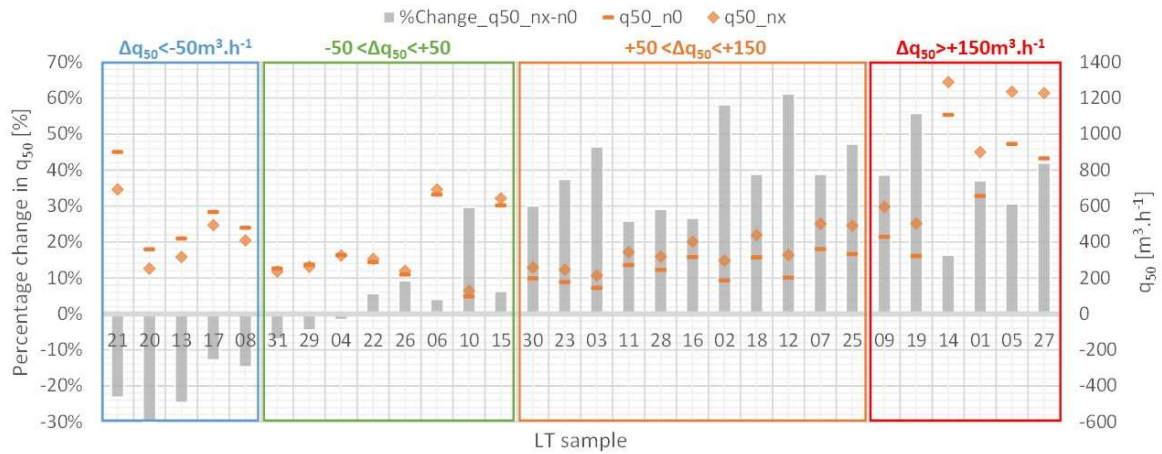
19 **Fig. 4** shows changes in the air leakage rate at 50 Pa “ q_{50} ” between the different measurements for
20 each house in the MT sample. The houses are sorted in ascending order of the changes in q_{50}
21 between n_0 and n_1 . They are classified into four categories depending on the changes in q_{50} :

- 22 • significant decrease in q_{50} ($< -50 \text{ m}^3\cdot\text{h}^{-1}$): 5 houses of the MT sample showed a significant
23 decrease in the air leakage rate between measurements n_0 and n_1 in particular (-38% to -
24 20%). Neither the detailed leakage detection nor the questionnaires to occupants made it
25 possible to explain the improvement of the airtightness of these houses, except for houses
26 MT-21 (adjustment of the service door overlooking the garage) and MT-28 (adjustment of the
27 window hinges).
- 28 • little or no variation in q_{50} (-50 to $+50 \text{ m}^3\cdot\text{h}^{-1}$): airtightness remained stable between the
29 different measurements for almost half of the MT sample (13 houses).

- moderate increase in q_{50} (+50 to +150 $\text{m}^3\cdot\text{h}^{-1}$): 6 houses in the MT sample showed a moderate increase in the air leakage rate between measurements n_0 and n_1 (+15% to +60%). In particular, fitting a kitchen hood in the house MT-01 seems to have deteriorated the envelope airtightness. We note that for house MT-23 the roof and the interior ceiling has been retrofitted due to significant deterioration caused by a storm.
- strong increase in q_{50} ($> +150 \text{ m}^3\cdot\text{h}^{-1}$): only five houses in the MT sample showed a strong increase in the air leakage rate between measurements n_0 and n_1 (+30% to +180%). As for MT-01, fitting a kitchen hood in the house MT-14 seems to have deteriorated the envelope airtightness. The replacement of windows in house MT-22 seems also to have deteriorated the envelope airtightness. We note the specific case of house MT-06 with a strong increase of +180% in q_{50} between measurements n_0 and n_1 . This house with an exposed wood-frame ceiling has become much leakier mainly because of leakages appearing at the junctions between the wood frame and the plasterboard (caused by shrinkage of the sealant and settlement of the structure).



15
16 **Fig. 4.** Changes in q_{50} between the different measurements of each house in the MT sample.



1

2 **Fig. 5.** Changes in q_{50} between the different measurements of each house of the LT sample.

3

4 **Fig. 5** shows changes in the air leakage rate at 50 Pa “ q_{50} ” between measurements n_0 and n_x for each
 5 house in the LT sample. The houses are sorted in ascending order of changes in q_{50} between n_0 and
 6 n_x . As for the MT sample, houses are classified into four categories depending on changes in q_{50} :

7

- significant decrease in q_{50} ($< -50 \text{ m}^3.\text{h}^{-1}$): five houses in the LT sample showed a significant
 8 decrease in the air leakage rate between measurements n_0 and n_x (-30% to -10%). Neither the
 9 detailed leakage detection nor the questionnaires to occupants made it possible to explain the
 10 improvement in the airtightness of these houses, except for house LT-21 where gaps between
 11 the plasterboard and the exposed wood-frame ceiling have been sealed after measurement n_0
 12 (thereby improving the envelope airtightness).

13

- little or no variations in q_{50} (-50 to $+50 \text{ m}^3.\text{h}^{-1}$): airtightness remained stable between
 14 measurements n_0 and n_x for only eight houses in the LT sample.

15

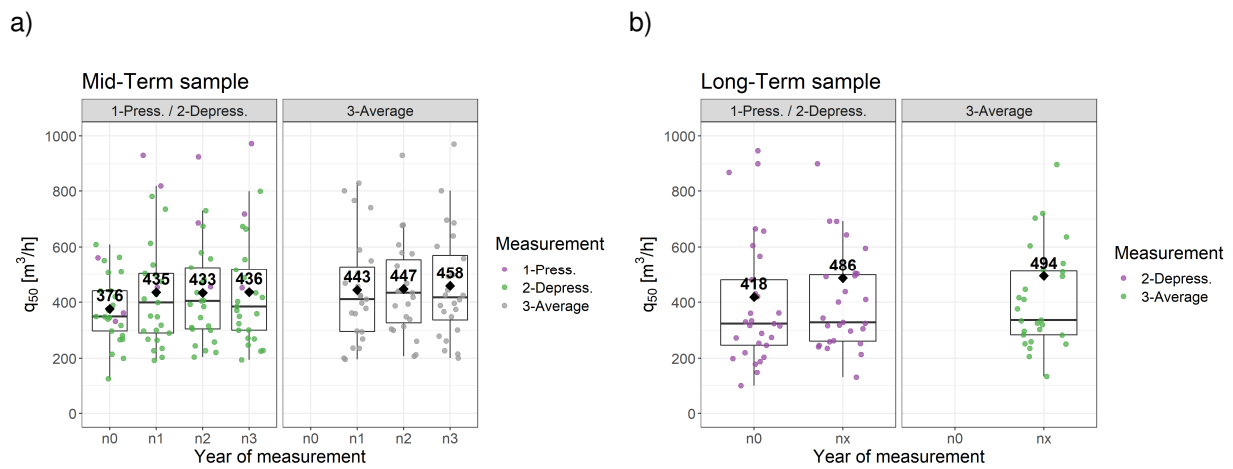
- moderate increase in q_{50} ($+50$ to $+150 \text{ m}^3.\text{h}^{-1}$): ten houses in the LT sample showed a
 16 moderate increase in air leakage rate between measurements n_0 and n_x ($+25\%$ to $+60\%$). In
 17 particular, fitting a kitchen hood in houses LT-02 and LT-07 seems to have deteriorated the
 18 envelope airtightness. The replacement of windows in house LT-16 seems also to have
 19 deteriorated the envelope airtightness.

20

- strong increase in q_{50} ($> +150 \text{ m}^3.\text{h}^{-1}$): seven houses in the LT sample showed a strong
 21 increase in the air leakage rate between measurements n_0 and n_x ($+20\%$ to $+60\%$). Fitting a
 22 kitchen hood in the house LT-01 seems to have deteriorated the envelope airtightness.

1 3.1.2. Overall changes in air permeability

2 **Fig. 6** shows the boxplots of the measured air leakage rates at 50 Pa q_{50} for the different
 3 measurements in the MT and LT samples respectively. For the measurements n_0 of both samples,
 4 tests were performed by either pressurisation or depressurisation, unlike the other measurements
 5 where tests were performed by both pressurisation and depressurisation as described in section 3.1.
 6 As the first test (n_0) was done in only one direction, the left panel in **Fig. 6-a** and **Fig. 5-b** represents
 7 the result of either the pressurisation or the depressurisation test (according to the direction of the first
 8 test). The right panel represent the results of the average between both tests for measurements n_1 , n_2
 9 and n_3 in the MT sample, and measurement n_x in the LT sample.



10 **Fig. 6.** Boxplots of the measured air leakage rates at 50 Pa “ q_{50} ” for measurements n_0 , n_1 , n_2 and n_3 in
 11 the MT sample (a) and for measurements n_0 and n_x in the LT sample (b) for the pressurisation/
 12 depressurisation tests (left panel), and the average between both tests (right panel).

13 For the MT sample, when considering both pressurisation and depressurisation measurements at n_0 ,
 14 an increase in q_{50} between measurements n_0 and n_1 can be observed, along with a stabilization of q_{50}
 15 at n_2 and n_3 :

- 16 • Changes between measurements n_0 and n_1 : a statistically significant increase in the mean
 17 value of q_{50} by $+58.9 \text{ m}^3 \cdot \text{h}^{-1}$, i.e. +18% (p-value = $0.034 < 0.05$) over an average timespan of
 18 1.7 years.
- 19 • Changes between measurements n_0 and n_2 : a statistically significant increase in the mean
 20 value of q_{50} by $+57.2 \text{ m}^3 \cdot \text{h}^{-1}$, i.e. +18% (p-value = $0.024 < 0.05$) over an average timespan of
 21 2.7 years.

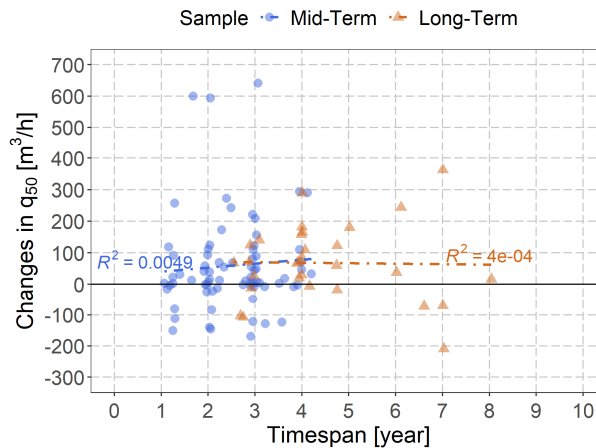
1 • Changes between measurements n_0 and n_3 : a statistically significant increase in the mean
2 value of q_{50} by $+60.4 \text{ m}^3\cdot\text{h}^{-1}$, i.e. $+19\%$ ($p\text{-value} = 0.037 < 0.05$) over an average timespan of
3 3.4 years.

4 • Changes between measurements n_1 and n_2 ($p\text{-value} = 0.396 \gg 0.05$), n_2 and n_3 ($p\text{-value} =$
5 $0.325 \gg 0.05$) and n_1 and n_3 ($p\text{-value} = 0.414 \gg 0.05$) are not statistically significant.

6 For the LT sample, similar results as for the MT sample are to be observed, with a statistically
7 significant increase in the mean value of q_{50} between n_0 and n_x by $67.7 \text{ m}^3/\text{h}$, i.e. $+20\%$ ($p\text{-value} =$
8 $0.002 < 0.05$) over an average timespan of 4.6 years. We note that the increase in the air leakage rate
9 is clearly higher than the estimated measurement uncertainty of 10% for both samples.

10 3.1.3. Correlation between changes in q_{50} and the age of houses

11 **Fig. 7** shows the variation in changes in q_{50} for the MT and LT samples according to the age of the
12 houses. A lack of correlation between the changes in q_{50} and the age of the houses is to be observed
13 for both samples. Air permeability does not therefore seem to change with the age of the building; it
14 varies mainly during the first two years, and then stabilizes, as observed in previous studies [25].
15 Variations during the first two years may have several causes, including actions by the occupants
16 when they move within the building (e.g. installing furniture, picture frames, downlights, etc.), initial
17 heating of the building or the first seasonal cycles.



18
19 **Fig. 7.** Measured changes in q_{50} for MT and LT samples according to the age of the houses (timespan
20 between the measurement at completion n_0 and the other measurements).

1 3.2. Analysis of explanatory factors

2 Regarding the MT sample, as there is almost no change between the results of n_1 , n_2 and n_3 , we will
3 focus in this analysis on the change between n_0 and n_1 .

4 In order to identify factors that could explain the change in houses airtightness, we analysed the
5 impact of the main characteristics of houses (builder, number of levels, type of air-barrier, type of
6 material, type of floor, type of roof, type of heating, specific HVAC equipment) and the modifications
7 made by occupants (modifications to windows and walls).

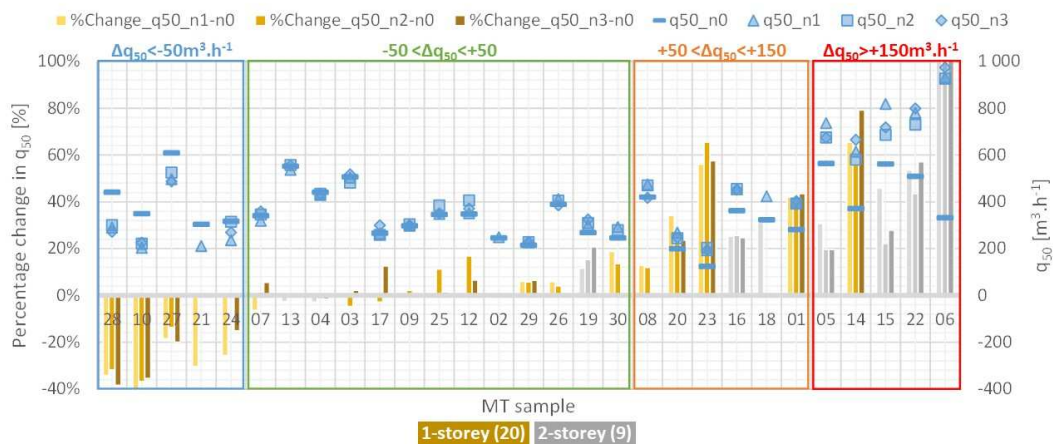
8 It is important to note that the size of the houses in our samples is variable, with volumes ranging from
9 124 to 478 m³ and envelope areas from 156 to 594 m² as described in section 2.1. Theoretically, the
10 larger the envelope area, the greater could be the change in the air leakage rate q_{50} . Nevertheless, we
11 have checked the relationship between the change in q_{50} and the envelope area. Results showed a
12 lack of correlation between both variables for both samples (correlation coefficient of 0.15 and 0.11 for
13 MT and LT samples respectively). In addition, 2-storey houses are not necessarily those with the
14 largest envelop area. Thus, the analysis according to q_{50} are not biased by the size of houses.

15 Among all the factors considered, only three factors seem to influence changes in the air permeability
16 of houses:

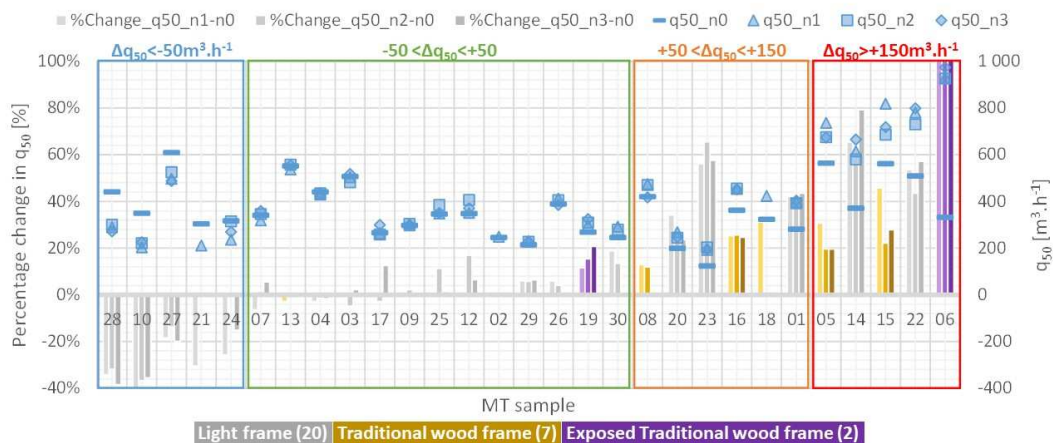
17 1. Number of floors: the increase in the air leakage rate seems to be greater for the 2-storey
18 detached houses in the MT sample (**Fig. 8**), with an average increase in q_{50} of 41% for the 2-
19 storey houses against 4% for the 1-storey houses. 2-storey houses seem therefore to
20 deteriorate more than 1-storey houses. This is perhaps due to greater foundation settlement in
21 the case of 2-storey houses, but also to the first floor support beams penetrating the inner skin
22 of the building envelope thereby providing additional leakage pathways.

23 2. Type of roof: the increase in the air leakage rate seems also to be greater for the houses
24 with traditional wood frame roofs in the MT sample (**Fig. 9**). It is interesting to note the case
25 of the two houses with exposed wood frames in this sample (MT-06 & MT-19). MT-06 has
26 become much leakier (q_{50} at n_1 almost 4 times higher than n_0), mainly because of leakage
27 appearing at the junctions between the wood and the plasterboard, while the airtightness
28 level of MT-19 has remained almost stable between n_0 and n_1 . Given that the airtightness of
29 both houses is obtained with the same method, the conditions of creating of the air-barrier
30 may have an impact on the durability of the airtightness: this needs to be further
31 investigated.

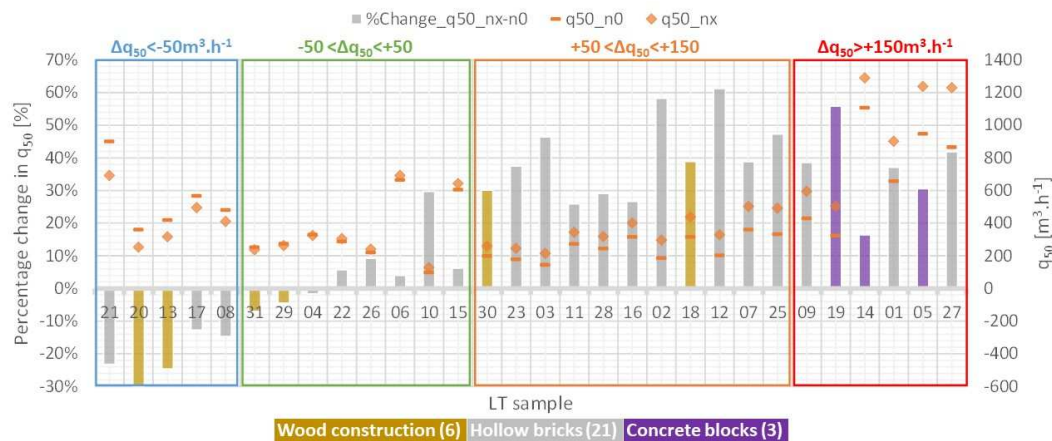
1 3. Type of material and air-barrier: we observe that the airtightness of four of the wood-frame
 2 houses in the LT sample (6 houses) has generally remained stable and has even improved
 3 (**Fig. 10**). For these wood-frame houses, airtightness is obtained by a vapour barrier (air
 4 barrier A), while the airtightness of all the other houses in the LT sample is mainly obtained by
 5 means of a coating on the masonry (air barrier B), as mentioned in §2.1. Wood-frame houses
 6 with airtightness obtained by means of an air-vapour barrier seem therefore to deteriorate less
 7 than other houses. However, it is difficult to conclude from this observation based on only six
 8 wood-frame houses. This needs further investigation.



9
 10 **Fig. 8.** Changes in q_{50} between the different measurements of each house in the MT sample
 11 depending on the number of floors.



12
 13 **Fig. 9.** Changes in q_{50} between the different measurements of each house in the MT sample
 14 depending on the type of roof.



1
2 **Fig. 10.** Changes in q_{50} between the different measurements of each house in the LT sample
3 depending on the type of construction material.

4 Owing to the small size of the samples, it was not possible to provide quantitative, statistically
5 representative changes associated with these factors.

6 Regarding modifications to the envelope made by occupants, the information was collected through
7 questionnaires. We have identified mainly two categories of modifications:

- 8
- modifications to windows: maintenance or replacement of some elements;
 - modifications to walls: replacement of some elements or drilling the walls.
- 9

10 As mentioned in §3.1.1, the replacement of windows has probably caused the envelope airtightness to
11 deteriorate in two houses in the MT sample (MT-22 and MT-23) and one house in the LT sample (LT-
12 16), while window maintenance has probably improved the envelope airtightness in two houses in the
13 MT sample (MT-21 and MT-28).

14 Regarding modifications to walls, all houses were generally modified by the occupants whatever the
15 change in the airtightness (drilling the walls to install furniture, decoration, hoods, downlight leds, etc).
16 In some cases (LT-25 & LT-27), the deteriorating airtightness may be due to the installation of a heat
17 pump which required drilling the walls to fit cables and ducts. In other cases (LT-08 & LT-21), the
18 improvement in the airtightness may be due to sealing by the occupants of leaks detected during the
19 test upon completion at the junctions between the ducts and the ceiling. However, it is difficult to draw
20 general conclusions as to the impact of occupants' modifications on airtightness changes.

21 3.3. Changes in leakage

22 **Fig. 11** and **Fig. 12** show the changes in the number of leakages for the MT and LT samples
23 respectively for each category of leakage as described in section 2.2. The houses are sorted in

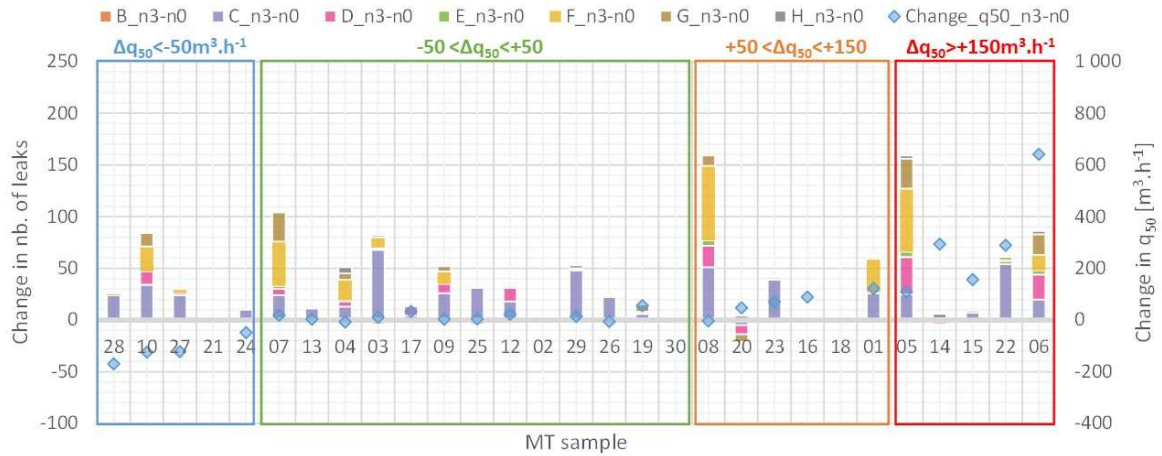
1 ascending order of changes in q_{50} . The description of the leakage categories is given in Appendix A.

2 The main categories are as follows:

- 3 • A: leakage through the main envelope area;
- 4 • B: leakage through walls, roofs and floor junctions;
- 5 • C: leakage through doors and windows;
- 6 • D: leakage around penetration through the envelope;
- 7 • E: leakage through trapdoors;
- 8 • F: leakage through electrical components;
- 9 • G: leakage through junctions between walls and doors/windows;
- 10 • H: other leakage.

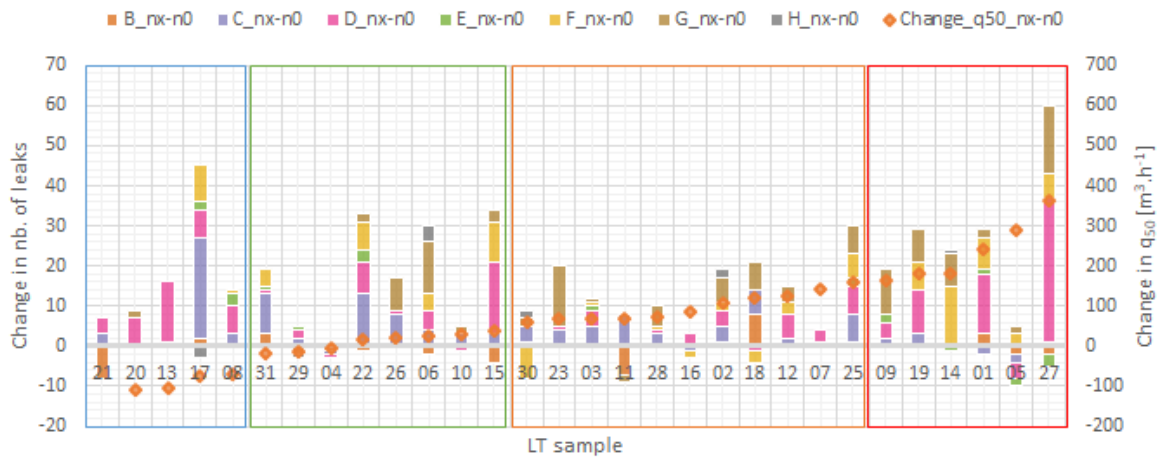
11 The figures show an increase in the number of leakages for doors and windows (C), electrical
12 components (F), penetrations through the envelope (D) and junctions between walls and
13 doors/windows (G).

14 In order to analyse the relationship between the change in the air leakage rate and the changes in
15 detected leakages, we conducted a multiple linear regression (MLR) for the MT and LT samples,
16 where the change in q_{50} is the dependent variable and the changes in detected leakages for each
17 category are the explanatory variables. **Table 2** shows the results of the regressions. For the LT
18 sample, all variables are statistically non-significant (p -value > 0.01). For the MT sample, the p -value
19 is lower than 0.01, but the adjusted R^2 is weak with only 58% of the variance found in the change in
20 q_{50} explained by the changes in the detected leakages. Among all the categories of leakages, only
21 those through trap doors and electrical components (e.g. ceiling downlight) are statistically significant.
22 However, the results are inconsistent with a negative value for the regression coefficient of leakages
23 through electrical components (i.e. air leakage rate would decrease with the increase in the number of
24 leaks through electrical components). Indeed, as we can see in **Fig. 11** and **Fig. 12**, for some houses
25 with a decrease in q_{50} , there is an increase of leakages equivalent to houses with a strong increase in
26 q_{50} . Therefore, thorough leakage location detection (by a smoking device and feeling the airflow on
27 fingers) is of no use if does not quantify leakages for the analysis of onsite durability. New methods
28 are therefore needed to detect and to quantify leakage. Cardoso [39] has recently investigated the
29 reductive sealing technique that showed promising results for quantitative and qualitative assessment
30 of air leakage paths.



1
2

Fig. 11. Changes in detected leaks numbers for the MT sample



3
4

Fig. 12. Changes in detected leaks numbers for the LT sample

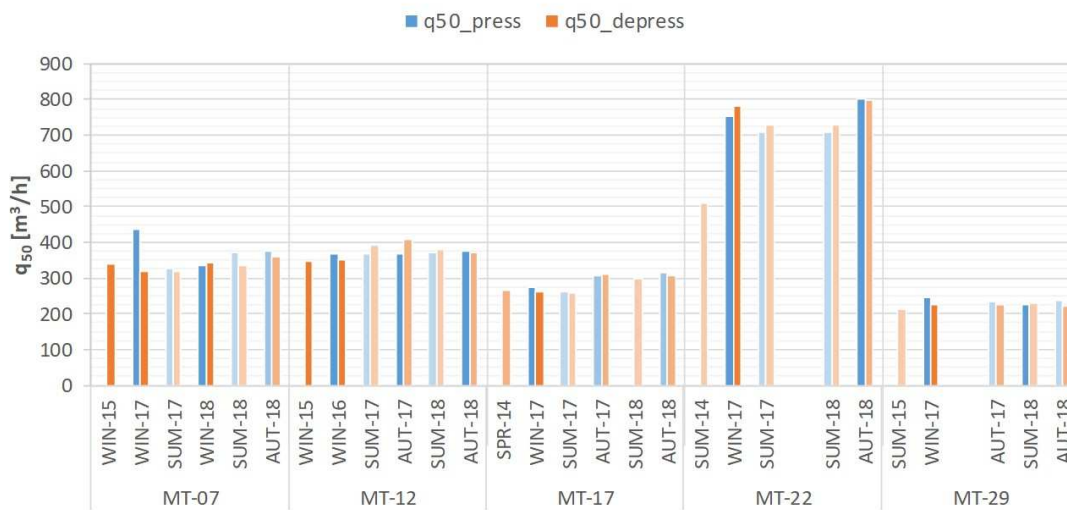
5 **Table 2.** MLR results for the change in q_{50} in relation to the changes in detected leaks (NS: non-
6 significant, p -value > 0.01)

Explanatory variables	MT sample: n_3-n_0			LT sample: n_x-n_0		
	Estimate	St. error	p-value	Estimate	St. error	p-value
<i>Changes in detected Leaks</i>						
A - main envelope area	NS	NS	NS	NS	NS	NS
B - wall & roof/floor junction	NS	NS	NS	NS	NS	NS
C - doors and windows	NS	NS	NS	NS	NS	NS
D - penetrations through envelope	NS	NS	NS	NS	NS	NS
E - trap doors	117.613	25.419	0.000	NS	NS	NS
F - electrical components	-7.321	1.953	0.002	NS	NS	NS
G - walls & door/window junction	NS	NS	NS	NS	NS	NS
H - other	NS	NS	NS	NS	NS	NS
Adjusted R²		0.582			0.337	
F-statistic		5.778			3.102	
p-value		0.001			0.020	

1 3.4. Impact of seasonal variations

2 **Fig. 13** shows the changes in the measured air leakage rates at 50 Pa q_{50} depending on the time of
3 measurement for the five houses in the MT sample.

4 Overall, no seasonal variation in q_{50} is to be observed except for MT-22. In the case of MT-22, q_{50} has
5 greatly increased after the measurement at completion (SUM-14). But since the second measurement
6 in winter 2017 (WIN-17), the house seems to be slightly more airtight in summer than in winter.
7 Unfortunately, measurement n_2 is missing between SUM-17 and SUM-18 to confirm this observation.
8 It is interesting to note that this is the only 2-storey house while the other four are 1-storey houses.



9

10 **Fig. 13.** Changes in q_{50} for the measurements with seasonal variations in the MT sample (WIN:
11 Winter; SUM: Summer; AUT: Autumn; SPR: Spring)

12 **4. Conclusions**

13 The durability of building airtightness of low energy single-detached houses was assessed through
14 two mid-term (MT) and long-term (LT) field measurement campaigns. The results showed that the
15 airtightness of houses can deteriorate mainly during the first two years and then seems to stabilise, as:

- 16 • For the MT sample, the mean and median values of the air leakage rates q_{50} in measurements
17 n_1 , n_2 and n_3 are equivalent.
- 18 • The MT and LT samples show the same mean change in the air leakage rate q_{50} (respectively
19 +18% and +20%, clearly higher than the estimated measurement uncertainty of 10%).

20 However, we have observed that building airtightness deteriorated significantly in some houses while
21 in others it stabilised or even improved. This study has led us to the following useful conclusions:

- 1 • One of the two houses with an exposed wood-frame became much leakier, mainly because of
2 leakages appearing at the junctions between the wood and the plasterboard (shrinkage of
3 mastic), while the airtightness of the other house remained almost stable. The conditions of
4 creating the air-barrier seem therefore to have an impact on airtightness durability.
- 5 • The increase in the number of leakages detected by a smoking device is not correlated with
6 changes in the airtightness of the houses. New methods are therefore needed to both locate
7 and quantify leakage more accurately. Thorough leakage detection is of no use if it does not
8 quantify leakage for analysis of onsite durability.
- 9 • Changes in airtightness do not appear to be correlated in this study with any of the following
10 parameters: builder, type of floor, type of heating, specific HVAC equipment.

11 The factors that seem to impact changes in airtightness are:

- 12 • The type of building material and air-barrier: it seems that the airtightness of wood-frame
13 houses with airtightness obtained by an air-vapour barrier tends to stabilise or even improve
14 over the years, maybe due to the expansion of wood with humidity.
- 15 • The number of floors: 2-storey houses seem to deteriorate more than 1-storey ones, which is
16 maybe due to more substantial foundation settlement, and to the first floor support beams
17 penetrating the inner skin of the building envelope thereby providing additional leakage
18 pathways.
- 19 • The type of roof: the airtightness of houses with exposed wood frame roofs seems to
20 deteriorate more than other roofs. The joints between the wooden beams and the
21 plasterboards may be the source of significant leaks, particularly in the case of wood
22 shrinkage.

23 Regarding the houses where the airtightness has improved (10 houses for both samples), this
24 improvement is perhaps due to the building material (2 wooden houses), the maintenance of windows
25 (2 houses), or the sealing of leaks by occupants (2 houses). However, for the other four houses, we
26 have not been able to explain this.

27 Information collected about modifications to the envelope has explained part of the change in q_{50} .
28 However, neither leakage detection nor building characteristics were correlated with the observed
29 changes in q_{50} . There are therefore probably other parameters not considered in this study, which
30 have an impact on airtightness durability.

1 The results of this study do not stress the need to perform long-term studies on the durability of
2 airtightness, but on the contrary to better understand where and why leakages appear during the early
3 years, which causes the deterioration of building airtightness. Other parameters need to be
4 considered, such as the environmental conditions (hygrothermal, dustiness) when setting up the air
5 barrier or changes in temperature and humidity inside the building during the first year. In addition,
6 modifications made by occupants need to be known in more detail. More frequent airtightness
7 measurements (e.g. monthly measurements) could be performed on a small sample of houses over
8 the period from creation of the air barrier until one year after building completion, recording the
9 aforementioned parameters at each measurement and using reliable method to qualify and quantify
10 detected leakages such as the reductive sealing technique.

11 **Acknowledgements**

12 This work was supported by ADEME and French ministry for construction. The authors would like to
13 thank all the testers who performed measurement for this project, and in particular Gilles Francès
14 leader of the LT measurement campaign. We also thank the homeowners who made this study
15 possible by giving us access to their houses many times during the 3 years of the project. The full
16 reports of the project and the measurements' summary sheets can be found on the following website:
17 <https://www.durabilitair.com/ressources-etancheite-air>.

18

1 **Appendix A. Leak definitions and categories.**

2 The following table shows the leakage definitions and categories as given by the French Standard FD

3 P50-784 relative to the application of the standard ISO 9972.

Leakage category	Leakage subcategory
A - leakage through the main envelope 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 - leakage through walls, roofs 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 - leakage through 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/or top and bottom of the frame C7 - Sliding door: Evacuation of condensates C8 - Rolling shutter casing
D - leakage around penetration through the envelope	D1 - Other element through a wall D2 - Vapour barrier membrane through which duct, pipe, beams, hatches D3 - Crossing Floor and walls and/or partitions (any type of pipes and electrical wiring ...) D4 - Ventilation air terminals: leaks at periphery of exhaust or 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 - leakage through trapdoors	E1 - Other trapdoor E2 - Attic trap door (absent or ineffective seal) E3 - Trapdoor to vertical technical duct (absent or ineffective seal)
F - leakage through electrical components	F1 - Other electrical component F2 - Electrical board F3 - Wiring inside external walls F4 - Wiring inside internal walls F5 - Lighting components
G - leakage through junctions between walls and doors/windows	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 leakage	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

4

5

6

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