



HeriTACE

# Improving energy efficiency of historical windows

Deliverable D2.5

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## Project information

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## Deliverable information

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## Glossary

| Acronym/abbreviation/term | Description                                                                                                                                  |
|---------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|
| archetype                 | Here: a pattern or a type of building with common traits/configurations that represents a subset of buildings in the targeted neighbourhoods |
| EU                        | European Union                                                                                                                               |
| EPBD                      | Energy Performance of Buildings Directive (of the European Commission)                                                                       |
| HeriTACE                  | Future-proofing HERItage Buildings by Optimising Comfort and Energy in Time and spACE                                                        |
| HVAC                      | Heating, ventilation, air conditioning                                                                                                       |
| R <sup>2</sup> ES         | Renewable and Residual Energy Sources                                                                                                        |
| WP                        | Work package                                                                                                                                 |

# Executive Summary

## Project context

The deliverable “D2.5: Improving Energy Efficiency of Historical Windows” is a report that documents the properties, mainly in terms of airtightness, of existing and improved historical windows in Task 2.5 of the HeriTACE project.

The aim of this deliverable is threefold. First of all, the typical airtightness of historical window frames is documented and discussed. This input is relevant at component level to evaluate optimization approaches, but also at building scale as input for building airtightness levels. Secondly, technical solutions are investigated to improve the thermal performance of historical windows by changing gaskets and hardware. Testing according to EN 1026 and classification according to EN 12207 allows to compare the performance with modern windows. For Estonian windows different renovation strategies are evaluated focusing on double window systems. Thirdly, in line with task 2.1, the potential of pulse test measurement is assessed to evaluate window performance on site.

This deliverable should be considered in combination with description of the building envelope analysis for historical townhouse typologies (D2.1), insulation and airtightness concepts (D2.2), as well as heritage aspects (D5.2) and users/owners’ perspectives (D5.3) to achieve a holistic overview of the existing conditions related to airtightness and window renovation targeted in HeriTACE. The information concerning airtightness is further adopted when performing energy simulations (D3.6 and D3.7), defining baseline scenarios (D5.4), and developing technical guidelines for building envelope solutions (D6.6).

## Outcomes

Overall, the research demonstrates that historic windows can be upgraded to significantly improve airtightness and energy performance without necessarily requiring replacement. However, successful interventions depend primarily on addressing geometric tolerances, deformations and frame-to-wall interfaces rather than merely adding gaskets. Across the investigated case studies, airtightness was found to vary substantially between buildings and window types, highlighting the importance of case-specific assessment and quality control during refurbishment.

The main country-specific findings and conclusions are:

### Belgium

- On-site airtightness measurements in 13 historic townhouses revealed substantial variability in building airtightness, with  $qE50$  values ranging from approximately 4.8 to 13.3  $\text{m}^3/(\text{h}\cdot\text{m}^2)$ . Windows and front doors were identified as important contributors to overall air leakage. Window airtightness generally corresponded to EN 12207 classes 1-2, while most front doors exceeded the leakage limits for class 1.
- Laboratory and field investigations showed that original heritage windows typically exhibit air leakage rates corresponding to EN 12207 classes 1-2. Significant variations were observed between apparently similar windows, indicating that

airtightness is strongly influenced by geometric tolerances, deformations and maintenance condition rather than age alone.

- Conventional refurbishment strategies based primarily on the installation of a gasket resulted in limited airtightness improvements. The research demonstrated that successful airtightness upgrading requires both the correction of geometric deformations and sufficient gasket compression. Without these measures, the benefits of sealing systems remain limited.
- The most effective heritage-compatible solution consisted of continuous interior sealing systems combined with geometric corrections of the sash and frame. These interventions enabled airtightness levels corresponding to class 3, while double-window configurations equipped with modern multi-point locking systems achieved class 4 performance.
- Pulse testing showed promising agreement with conventional blower-door measurements at building scale, with most measurements differing by less than 10%. However, practical limitations and lower robustness compared to standard pressurisation testing currently restrict its application. No reliable component-level application for windows could be established.

## **Estonia**

- Airtightness measurements were performed on historic windows in four buildings and showed generally poor performance, with approximately half of the investigated windows failing to meet even the requirements of EN 12207 class 1. Technical inspections identified missing hardware, visible cracks and poor frame-to-jamb connections as common defects.
- Sealing measures demonstrated that leakage through the frame-to-jamb interface is often more significant than leakage through the window frame itself. After sealing and taping these interfaces (as is often done for heating seasons), nearly half of the tested windows achieved class 4 airtightness, highlighting that it could be a viable strategy, although requiring periodic installation and removal by the inhabitants.
- Laboratory studies confirmed that historic double-window systems can be significantly upgraded while retaining their original appearance. Prototype solutions incorporating modern triple-glazed insulated glass units into traditional double-frame configurations showed strong potential for improving thermal performance ( $U_w \approx 0.7-0.8 \text{ W/(m}^2\cdot\text{K)}$ ) compared to the historic window type with  $U_w \approx 2 \text{ W/(m}^2\cdot\text{K)}$ ) while preserving heritage character on the exterior side.
- Visual inspections indicated that the condition of historic windows varies considerably. Approximately 60% of the investigated windows were considered suitable for preservation and refurbishment, whereas replacement was considered unavoidable in cases where severe deterioration of both windows and surrounding structures had occurred.
- Exploratory calculations relating gap dimensions to measured air permeability showed encouraging results, suggesting that simple geometric measurements may eventually support rapid airtightness assessments. However, additional laboratory validation is required before practical application.

## Italy

- The Italian case studies highlight the need for heritage-compatible window improvement strategies that can deliver substantial energy-performance gains while reducing the pressure for wholesale replacement of original historic joinery
- The investigations on 7 windows in 2 buildings, both double and single windows, retrofitted/not retrofitted windows complement and confirm the findings in Belgium and Estonia:
  - Retrofitted windows with sealing can reach good air-tightness class – class 3 for the double windows, class 2 for the single window in this case.
  - The retrofitted window at Palazzo Vescovile just reaching class 1 with closed shutters shows however also, that the sealing has to be well done and maintained.
  - The not retrofitted window in bad state shows as expected the highest leakage – clearly beyond that at Palazzo Vescovile
- The testing method with MLM has proven to be well implementable with some limits: logistics and implementation in used buildings are possible, limits lie rather on the low maximum power of the equipment for big and leaky windows and in the observed detachment of the tape especially with measurement under pressure.

## Conclusions

The results show that heritage-compatible window refurbishment can achieve substantial airtightness improvements while preserving original historic fabric. The effectiveness of refurbishment depends not only on the selection of sealing systems, but also on the correction of geometric deformations and the quality of frame-to-wall connections. Double-window concepts offer the highest airtightness levels and low thermal transmittance while respecting heritage values. Pulse testing shows potential as a rapid building-scale diagnostic tool, although further development is required before reliable component-level applications become feasible. The findings provide important input for subsequent HeriTACE tasks related to building simulation, joinery atlas, renovation scenarios and technical guidance development.

## 1. Introduction

The ambitions of the European Union (EU) are substantial: to achieve climate neutrality by 2050. The European Green Deal and the New European Bauhaus aim to achieve a sustainable and inclusive society through transdisciplinary collaboration and innovation. Historic cities in Europe present an additional challenge. It is evident that the historically valuable buildings in these cities must be preserved while respecting and considering the inherent heritage and societal values. However, it is unclear how we can balance the aspirations on heritage conservation on individual units with the overarching ambition for climate neutrality at the building stock level. More specifically, there is a need for a framework to assess these different aspects at building or neighborhood level and offer insights and solutions to address this challenge.

The HeriTACE project investigates how we can future proof our heritage buildings in a manner that bridges the gap between heritage restrictions and environmental ambitions. The project focuses specifically on small to medium-sized heritage townhouses pre-dating 1945. Achieving the ambitious goal of climate-neutrality requires a transdisciplinary team to consider all aspects of renovation: heritage value, energy use, user comfort, functionality, cost-effectiveness, and waste management. Heritage restrictions often preclude generic solutions, necessitating innovative approaches to insulation, heating, ventilation, and heat/cold generation.

The aim of this deliverable is threefold. First of all, the typical airtightness of historical window frames is documented and discussed. This input is relevant at component level to evaluate optimization approaches, but also at building scale as input for building airtightness levels. Secondly, technical solutions are investigated to improve the thermal performance of historical windows by changing gaskets and hardware. Testing according to EN 1026 and classification according to EN 12207 allows to compare the performance with modern windows. For Estonian windows different renovation strategies are evaluated focusing on double window systems. Thirdly, in line with task 2.1, the potential of pulse test measurement is assessed to evaluate window performance on site.

This deliverable should be considered in combination with description of the building envelope analysis for historical townhouse typologies (D2.1), insulation and airtightness concepts (D2.2), as well as heritage aspects (D5.2) and users/owners' perspectives (D5.3) to achieve a holistic overview of the existing conditions related to airtightness and window renovation targeted in HeriTACE. The information concerning airtightness is further adopted when performing energy simulations (D3.6 and D3.7), defining baseline scenarios (D5.4), and developing technical guidelines for building envelope solutions (D6.6).

This deliverable is structured as follows:

- Section 2 provides context on the airtightness of window frames
- Section 3 comprises an overview of the adopted test methods to evaluate the airtightness of window frames
- In section 4 the results are documented and discussed.
- Section 5 summarizes the main conclusions

## 2. Airtightness of window frames

### 2.1 Literature

Literature on airtightness of windows can be subdivided into on-site testing, air leakage databases and laboratory testing. Weidt and Weidt (1980) tested 192 windows on-site in Minnesota (US; United States) and found that window type was the dominant factor controlling air leakage (material type did not affect results significantly). A selection of the results is reported in table 1. Most common defects that gave rise to excessive air leakage were weather strip discontinuity, poor sash fit and squareness, and malfunctioning hardware. Mind that for 60% of the windows tested the air leakage exceeded the specifications stated by their manufacturer. Daoud et al. (1991) found an average leakage of 10,32m<sup>3</sup>/h.m<sup>2</sup> for 154 aluminum windows tested on site in Kuwait. Turn-and-tilt windows and fixed windows performed best, horizontally hinged windows the worst. Most of the defects found were basically independent of size, e.g. gaps between the vertical sections of double sliders, missing hardware, missing hole caps.

Table 1. Airtightness of window frames in literature

| [m <sup>3</sup> /h.m] at 50Pa | Weidt & Weidt <sup>a</sup> | ASHRAE <sup>b</sup> |      |       | AIVC <sup>b</sup> |        |      | Carruthers and Newman <sup>c</sup> |      |      | Lawson et al. <sup>c</sup> |       |       |
|-------------------------------|----------------------------|---------------------|------|-------|-------------------|--------|------|------------------------------------|------|------|----------------------------|-------|-------|
|                               |                            | Min                 | Mean | Max   | Low               | Median | High | Low                                | Mean | High | Min                        | Mean  | Max   |
| single sliding                | 3,37                       | 0,97                | 3,26 | 10,03 | 3,24              | 4,89   | 15,4 | 1,6                                | 2,28 | 2,96 | –                          | –     | –     |
| double sliding                | 2,61                       | 1,31                | 3,02 | 10,03 |                   |        |      |                                    |      |      |                            |       |       |
| single window                 | 4,10                       | 3,02                | 4,24 | 6,04  | 2,97              | 5,65   | 7,91 | 0,84                               | 1,39 | 1,95 | 5,22                       | 13,05 | 20,88 |
| double window                 | 3,08                       | 0,97                | 3,17 | 9,25  |                   |        |      |                                    |      |      |                            |       |       |

<sup>a</sup> On site testing.

<sup>b</sup> Database (source not specified).

<sup>c</sup> Lab testing.

Provan and Younger (1986) reported laboratory test results of 795 windows tested between 1971 and 1986 in the United Kingdom (UK). Turn-and-tilt, top hung and side hung windows were found to be very tight, followed by pivot windows. Sliders on the other hand showed the poorest performance. Only the distribution of the windows in 4 performance levels was reported, as indicated in table 2.

Table 2 Laboratory test on airtightness of window frames by Provan and Younger. The distribution of windows according to four performance levels is shown, and the maximum air leakage per level at 50Pa pressure difference is indicated

| Window type       | Class 1 1.26 m <sup>3</sup> /h.m | Class 2 4.85 m <sup>3</sup> /h.m | Class 3 6.35 m <sup>3</sup> /h.m | Class 4 7.69 m <sup>3</sup> /h.m |
|-------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Horizontal pivot  | 73%                              | 20%                              | 3%                               | 1%                               |
| Vertical pivot    | 64%                              | 28%                              | 6%                               | 0%                               |
| Side hung         | 83%                              | 12%                              | 0%                               | 5%                               |
| Top hung          | 86%                              | 14%                              | 0%                               | 0%                               |
| Bottom hung       | 100%                             | 0%                               | 0%                               | 0%                               |
| Tilt-and-turn     | 85%                              | 15%                              | 0%                               | 0%                               |
| Horizontal slider | 0%                               | 88%                              | 13%                              | 0%                               |
| Vertical slider   | 26%                              | 48%                              | 15%                              | 4%                               |

Carruthers and Newman (1977) tested the airtightness of aluminum window frames with neoprene seals in the UK. Mean values and standard deviations are reported, but these results implicitly comprise the effect of different operators and test rigs. Assuming a normal distribution was applied, the first quartile, mean value and third quartile results are calculated and reported in table 1. Lawson et al. (1982) analyzed the performance of 8 wooden window frames tested in the lab, see table 1. The Air Infiltration and Ventilation Center (AIVC) (2002) provides a database on airtightness of building components with data

on the median value, second and third quartiles. ASHRAE (American Society of Heating Refrigeration and Air-conditioning Engineers) fundamentals (1993) on the other hand, reports the minimum, mean and maximum values for leakage rates. Mind that neither ASHRAE nor AIVC specify whether the reported values are characteristic for the initial performance of windows, or relate to on site performance. A selection of results is reported in table 1; all data for windows without weather-stripping are omitted because these are obsolete; weather stripping became mainstream in the 60's (1986). The single and double windows are side hung.

First of all, the median AIVC and mean ASHRAE values correspond reasonably well to the mean values of the on-site measurements by Weidt and Weidt. Remarkably, according to ASHRAE data and Weidt and Weidt, double sliders perform better than single sliders, and double windows likewise perform better than single windows. The AIVC data report significantly higher value for sliding windows compared to all other references. Lab tests on single and double side-hung windows by Carruthers and Newman clearly show lower leakage rates compared to the databases and on-site testing. Based on reported drawings and pictures, it can be presumed that the high air flow rates reported by Lawson et al. were caused by incomplete weather stripping. When looking at the lab results by Provan and Younger, the results for the sliders confirm the earlier findings, albeit slightly higher than Carruthers and Newman. Side hung and tilt-and-turn windows show much better performance compared to all other values.

Concluding, based on tables 1 and 2, the initial performance of sliding windows lies in the range of 1.5 up to 6m<sup>3</sup>/h.m, with a median value around 3m<sup>3</sup>/h.m. Side-hung windows perform significantly better, and will typically yield leakage rates between 0 and 3m<sup>3</sup>/h.m, with a mean of 1m<sup>3</sup>/h.m. Exposure to outdoor conditions will probably increase the air flow rates, but the only two references render diverging trends. Note that within the three types of sources (on-site testing, databases, lab testing), the oldest references always report the lowest air flow rates; there is no indication of technological evolution in between different reports.

A more recent study of Van Den Bossche and Janssens (2016) reported on the airtightness of 437 windows (230 in aluminum, 100 vinyl, 107 in wood). The authors concluded that there were little differences in between the different window profile materials. Single, turn-and-tilt windows, were found to be clearly more airtight than double windows and composed windows, whereas sliding windows are almost 2.5 times more leaky than single windows. 75% of all windows have an air leakage rate below 1.05 m<sup>3</sup>/h.m<sup>2</sup> at 50Pa, which is significantly better than the limit of airtightness class 4 according to EN 12207 (see figure 1).

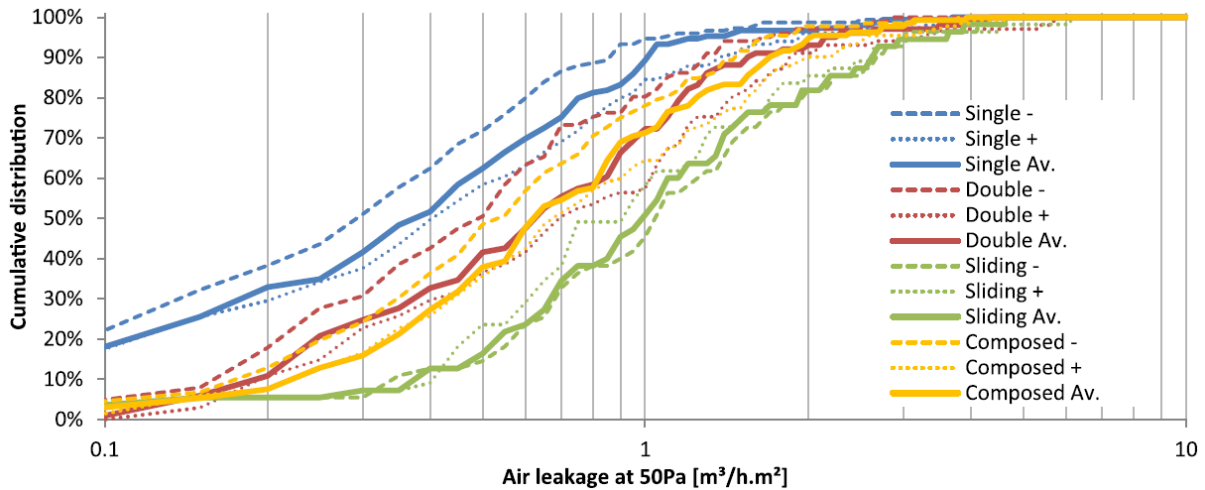


Figure 1 Cumulative distribution of air leakage rate at 50 Pa positive and negative pressure for all window types

## 2.2 Performance requirements

The European Standard EN 12207 provides the classification framework for expressing the air permeability of windows and external pedestrian door sets that have been tested according to EN 1026. While EN 1026 establishes the experimental methodology and measurement procedures, EN 12207 defines how the results are normalized, interpreted, and assigned to a performance class.

In EN 12207, air permeability is defined as the rate of air flow through a completely closed and locked specimen under a specified differential air pressure, divided by the total area of the specimen. The measurement data from EN 1026—obtained as volumetric flow rates at each pressure level—are used to determine the air flow rate per unit area in cubic meters per hour per square meter ( $\text{m}^3/\text{h}\cdot\text{m}^2$ ). These results are then compared to the threshold values specified in EN 12207 for the corresponding test pressures. Tests are conducted in both overpressure as underpressure.

The air flow rate through an opening for an applied pressure difference is commonly expressed by the empirical power law equation (1):

$$\dot{V} = C \cdot \Delta P^n \quad (1)$$

With  $\dot{V}$ : air flow rate ( $\text{m}^3/\text{h}$ ),  $\Delta P$ : pressure difference (Pa), and C: flow coefficient ( $\text{m}^3/\text{h}\cdot\text{Pa}^n$ ) and n: flow exponent (-). All results from literature were converted into these quantities and normalized to 50 Pa; the discharge coefficient  $C_d$  for converting Equivalent Leakage Areas was assumed to be 1, and the flow exponent is set to 0.66 (if not specified). It should be noted that the power law equation is valid of openings with a fixed geometry. When conducting air leakage tests on window frames it is possible that the position of the sash with respect to the frame changes due to the pressure that is exerted. By consequence, the measure air flow rate does not necessarily align with the power law. A typical phenomenon that occurs is that the sash shifts towards the opening direction during the test. For an inward opening window the airtightness typically increases as a function of pressure when underpressure is applied on the exterior side (the gasket is compressed due to the

movement), and the airflows increase at higher pressures when subjected to positive pressures on the exterior side (decompression of the gasket).

Airtightness of windows is typically expressed per meter opening joint or per square meter. The first one better correlates with the geometrical aspects that determine the air leakage through the window. However, the latter is better suited to calculate the effect on the overall airtightness of buildings because typically only information on window area is available.

Here the surface-averaged values will be adopted. For each configuration, the relationship between flow rate and applied pressure difference ( $\Delta P$ ) is typically plotted on a logarithmic scale and can be approximated by the power law (equation 1).

EN 12207 divides performance into five main airtightness classes, numbered 0 to 4, where Class 0 indicates that the specimen could not meet the minimum requirements of Class 1. Class 1 represents basic airtightness, while Class 4 denotes the highest performance level recognized under the standard.

For windows and external doors, the test pressures are typically 50-100-150-200-250-300-450-600Pa. At each pressure level, the maximum allowable air leakage per unit area decreases progressively across the classes. For example, a Class 1 element may exhibit up to 50 m<sup>3</sup>/h·m<sup>2</sup> at 100 Pa, whereas Class 4 requires the leakage to remain below 3 m<sup>3</sup>/h·m<sup>2</sup> at 600 Pa. The lowest of the two directional results (pressurization vs. depressurization) determines the final class assigned to the product.

### 3. Test methods

#### 3.1 Lab test according to EN 1026

The EN 1026 standard sets a method for determining the air permeability of windows and door sets when subjected to both positive and negative pressures. It applies to specimens installed according to the manufacturer's instructions, and ensures reproducibility and comparability between different laboratories.

Before applying the specimen, the air permeability of the test chamber itself is measured (with the specimen sealed or blanked off). This "background leakage" is important for later correction. The chamber leakage must not exceed 30 % of the total measured leakage (specimen + chamber) at the same pressures; otherwise the test is invalid.

The standardized procedure uses a series of pressure steps (both positive—pressurization—and negative—depressurization): 50-100-150-200-250-300-450-600Pa. The same sequence is applied in both directions. Before measurement at each step, pulses are applied (three pressure pulses at 10 % above the maximum test pressure or a threshold, whichever is higher) to help stabilize seals and minimize hysteresis.

At each pressure step, once the airflow stabilizes, the air flow rate  $Q_x$  through the specimen is recorded. These measurements are then corrected to reference conditions (commonly 293 K and 101.3 kPa) using temperature and pressure correction formulas provided in the standard. After correction, the chamber leakage is subtracted to yield the net airflow through the specimen.

Across the test sequence, the air permeability is computed in terms of volumetric flow per unit area ( $\text{m}^3/\text{h}\cdot\text{m}^2$ ). The resulting "air permeability curve" is then used to classify the window or door set according to EN 12207, based on maximum permissible leakage at certain pressures.

#### 3.2 On site testing according to EN ISO 9972

The airtightness of building envelopes is typically measured according to EN ISO 9972. Also see D2.1 for a more detailed description.

Air leakage is typically measured under both depressurisation and pressurisation conditions, in increments of  $\sim 10$  Pa, within the range of  $\pm 10$  to  $\pm 80$  Pa. Note that this is significantly lower than the test pressures required according to EN 1026 (up to 600Pa).

From the trend line of airflow versus pressure for both depressurisation and pressurisation measurements, the leakage airflow at 50 Pa is determined and averaged. As the airtightness of the building envelope is characterized by the air leakage rate at 50 Pa,  $q_{50}$  (in  $\text{m}^3/(\text{h}\cdot\text{m}^2)$ ), it is common to express the air leakage of building components also at a pressure difference of 50Pa.

In Estonia BlowerDoor Window and Door Measurement System was used for on-site airtightness testing. During the test the window was covered with tarpaulin and airflow through the window joint was measured by thin plate with a known size round orifice and pressure difference between both sides of it. Tarpaulin was attached to the window jamb or

jamb extension. Windows were tested before and after tightening and taping joints to improve window airtightness (Figure 2). Measurement data was collected using BlowerDoor TECTITE Express 5.1 program. Windows were classified according to collected data and standard EN 12207:2016.

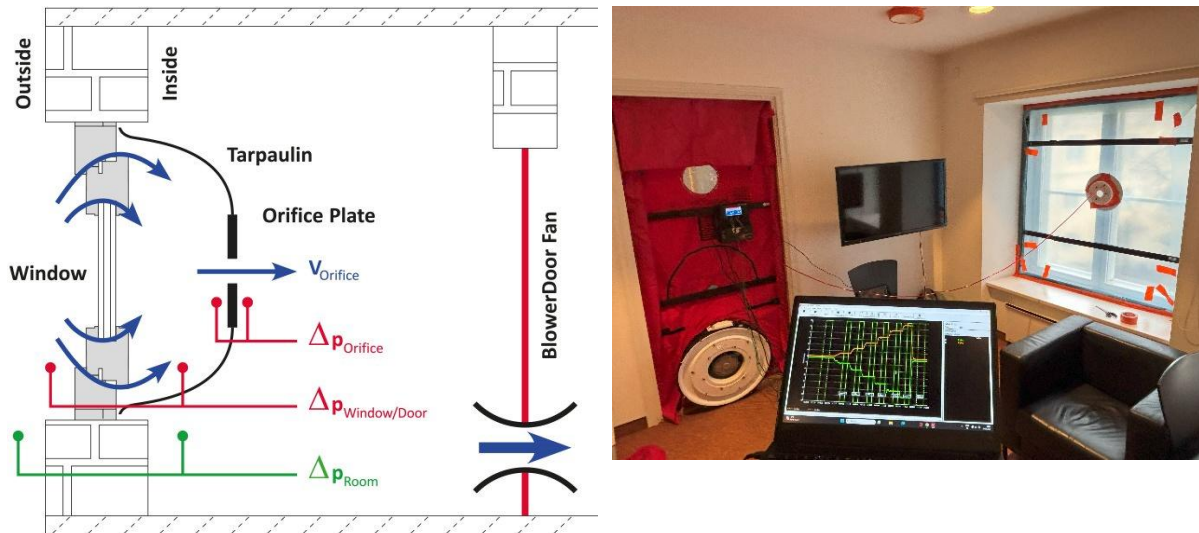


Figure 2. Principle of on-site testing using BlowerDoor Window and Door Measurement System (left) and how test was carried out in field (right).

### 3.3 Pulse testing

The Pulse test is a low-pressure airtightness measurement method developed as a rapid and non-invasive alternative to conventional fan pressurization testing. Unlike blower door testing, which requires the installation of a fan in an external opening and applies pressure differences up to 50 Pa, the Pulse method operates directly at pressure levels representative of natural conditions (typically 4-10 Pa). The test equipment is positioned within the building and does not require a door or window opening to be blocked.

Prior to the measurement, the building is prepared in a similar manner to EN ISO 9972 testing. External windows and doors are closed, intentional ventilation openings are sealed as required by the selected test protocol, and internal doors are opened to ensure that the tested volume behaves as a single pressure zone. The protected volume of the building is entered into the measurement software and baseline pressure conditions are recorded for approximately 30 to 60 seconds to account for natural pressure fluctuations caused by wind and stack effect.

The test is performed by releasing a short pulse of compressed air (typically lasting 1.5 to 2 seconds) from a calibrated pressure vessel into the building. This creates a transient pressure increase of approximately 4 to 10 Pa. During the pulse, high-frequency sensors continuously measure the pressure response of the building as well as the pressure and temperature inside the compressed-air vessel. From the known air mass released and the resulting pressure evolution, a mass balance is established for the building volume. Using

this mass balance, the leakage airflow and pressure data are analysed through an iterative least-squares fitting procedure based on the Power Law relationship between airflow and pressure difference. The resulting leakage coefficient and flow exponent are used to determine the leakage airflow directly at low pressure, typically  $Q_4$ . If required for comparison with conventional airtightness metrics, the results can subsequently be extrapolated to the equivalent airflow at 50 Pa ( $Q_{50}$ ).

## 4. Test results

### 4.1 Belgium

This study aims to develop a detailed understanding of the contribution of external joinery, specifically windows and doors, to the airtightness performance of historic townhouses in Ghent. Although airtightness is commonly evaluated through whole-building indicators such as the air change rate at 50 Pa ( $n_{50}$ ) or air permeability ( $q_{50}$ ), these metrics provide limited insight into the role of individual building components. Therefore, this research adopts a component-based approach, focusing on the extent to which external joinery contributes to overall air leakage and how this contribution varies according to the characteristics and condition of the joinery.

Particular attention is given to original nineteenth-century windows, which are often considered a significant source of uncontrolled air infiltration in historic buildings. The research investigates the baseline airtightness performance of existing joinery and identifies the dominant leakage mechanisms responsible for airflow through these elements. Furthermore, the study evaluates the effectiveness of commonly applied heritage-compatible restoration measures, ranging from minimal interventions to more comprehensive refurbishment strategies. The influence of individual sealing measures, including the type, position, and number of sealing profiles, is examined to determine their relative contribution to reducing air leakage.

In addition to the performance of the joinery itself, the research considers the role of interfaces between windows, doors, and the surrounding building envelope. Leakage paths at frame-to-wall connections and the influence of finishing layers such as plaster are analysed to assess their significance within the overall airtightness performance of the building. The study also examines how different testing conditions and measurement configurations may affect recorded airtightness values and the interpretation of results.

To provide a broader perspective, case studies with varying typologies, renovation levels, and construction characteristics are compared to identify recurring patterns and determine whether external joinery consistently represents a dominant source of air leakage. The performance of restored historic windows is further evaluated against that of newly manufactured heritage-compatible reproduction windows, allowing an assessment of the airtightness levels that can realistically be achieved while respecting heritage values.

Ultimately, the research seeks to identify restoration strategies that offer the most effective balance between heritage preservation, practical feasibility, and airtightness improvement. By quantifying the contribution of windows and doors to the total air leakage rate of historic townhouses and assessing the potential benefits of upgrading these elements, the study aims to provide evidence-based guidance for energy-efficient and heritage-sensitive renovation practices.

#### 4.1.1 Whole building airtightness

This study first adopts an experimental, in-situ measurement approach to assess the airtightness performance of historic townhouses, with a specific focus on external joinery. The methodology is based on standardized airtightness testing (EN ISO 9972, see section 3.1), combined with a component-based analysis, allowing the contribution of individual building elements—such as windows and doors—to be quantified (section 3.2).

A series of controlled measurements is carried out in a set of case study buildings. First, the global airtightness of each building is determined using blower door testing. Subsequently, targeted interventions—specifically the temporary sealing of external joinery elements—are applied to isolate the impact of windows and doors on the overall air leakage.

The study is based on a sample of historic townhouses representative of the urban building stock constructed between 1800 and 1915 in Ghent. These buildings are characterised by masonry walls, wooden floor structures, and traditional external joinery.

The selected case studies vary in terms of:

- construction period and architectural characteristics,
- level of renovation,
- type and condition of external joinery (original versus replaced systems),
- presence of additional leakage paths (e.g. chimneys or ventilation systems).

This variation enables a comparative analysis of how different joinery configurations and conditions influence the airtightness performance of historic buildings.

##### 4.1.1.1 Test protocol

The airtightness of the selected buildings is assessed using blower door testing in accordance with EN ISO 9972. Both pressurisation and depressurisation tests are performed to ensure reliable and reproducible results.

The blower door test determines the air leakage rate of a building by creating a controlled pressure difference between the indoor and outdoor environment. Based on the measured airflow at different pressure levels, key airtightness indicators are derived, including the air change rate at 50 Pa ( $n_{50}$ ) and the air permeability ( $q_{50}$ ).

All measurements are conducted following a consistent and standardized protocol to ensure comparability between buildings. Two test configurations, as defined in EN ISO 9972, are applied:

- **Method A**, representing the building in normal operating conditions, is used for baseline measurements;
- **Method B**, focusing on the performance of the building envelope, is applied for component-level analysis.

For the baseline tests (Method A), buildings are prepared according to the standard, with intentional openings treated as prescribed to reflect typical usage conditions. For the component-level investigation (Method B), specific building elements—such as windows and doors—are systematically and temporarily sealed in order to isolate their contribution to air leakage.

Environmental conditions, including wind speed and indoor-outdoor temperature differences, are monitored throughout the measurements to minimise uncertainty. Tests are only conducted under conditions that comply with the limits specified in the standard.

To quantify the contribution of external joinery, a stepwise testing approach is implemented. Each building undergoes multiple measurement configurations:

1. **Baseline test:** determination of the global airtightness of the building under standard conditions;
2. **Selective sealing tests:** temporary sealing of windows and/or doors to eliminate air leakage through these elements;
3. **Comparative analysis:** evaluation of the differences between test conditions to quantify the contribution of external joinery.

This approach enables the identification of:

- the relative share of air leakage attributable to windows and doors,
- the effect of sealing or improving these components,
- the interaction between external joinery and surrounding construction elements, particularly at junctions with the building envelope.

#### 4.1.1.2 Test cases

This study is based on a series of in-situ measurements conducted in a selection of historic townhouses. In order to ensure transparency and reproducibility of the results, a clear overview of the investigated buildings and measurement cases is provided.

The selected sample consists of 13 buildings located in Ghent, representative of pre-1945 masonry townhouses. Each building was analysed through multiple measurement configurations, allowing both global and component-level airtightness to be assessed.

In each building, one or multiple windows and/or doors were included in the analysis, depending on accessibility and representativeness. The number of measured elements varies between buildings, ranging from single-window cases to multiple façade elements within the same dwelling.

Table 3 provides an overview of the investigated buildings, the number of measurement cases, and the extent to which external joinery was included in the analysis.



Figure 3 Overview of historic town houses in Ghent for airtightness measurements

The case study **MEERS** represents a historic townhouse with a moderate renovation level. The building shows typical characteristics of 19th-century masonry construction, including traditional wooden joinery and plastered interior walls. Even though the last recorded renovation dates back to the year 2000 where a part of the windows were renovated, the condition of the façade and joinery elements suggests ageing and partial degradation, which may contribute to increased air leakage at interfaces and material transitions. The case is particularly relevant for evaluating the impact of weathering and façade exposure on airtightness performance.

The case **MARTENS1** is a semi-detached townhouse with specific geometric characteristics, including an exposed side wall. This configuration increases the potential for air leakage compared to typical terraced houses. The case highlights the influence of building typology and façade exposure on airtightness performance.

**MARTENS2** is a highly restored townhouse (2015), representing a case where modern interventions have been implemented with attention to airtightness. The building features upgraded joinery, likely including thin double glazing and improved sealing systems. This case provides insight into the effectiveness of high-quality renovation measures on airtightness performance and serves as a benchmark for well-executed interventions.

The case **CITADEL** is an original or minimally renovated townhouse (renovation dates back to 1945) with largely preserved historic elements. The building includes traditional wooden windows and doors, which, despite their age, may still perform relatively well if properly

maintained. This case highlights that original buildings can exhibit competitive airtightness performance, depending on the condition and usage of joinery elements.

**MUINK** represents a fully renovated townhouse with a high level of execution quality. Renovations started in 2007, and the building includes modern building techniques and improved joinery systems, combined with carefully finished interfaces. This case is relevant for assessing the upper limit of achievable airtightness within heritage constraints and illustrates the importance of craftsmanship in renovation.

The townhouse **KONING** is a moderately renovated building with a mix of original and replaced elements. External joinery may consist of both traditional and newer systems, resulting in heterogeneous airtightness performance. This case allows for the assessment of partial renovations and their impact on air leakage distribution.

**KEIZER** is a renovated townhouse where the overall airtightness performance is influenced by both improved elements and remaining weak points. Particular attention is drawn to interior finishes and junction details, which may act as leakage paths despite improvements in joinery. The existing windows have been refurbished and new glass was installed (around the year 2000). This case illustrates the importance of holistic renovation approaches.

The case **KUIPER** represents a building under renovation or construction. Due to significant uncontrolled leakage paths, reliable blower door measurements could not be fully performed. Nevertheless, this case highlights the extreme impact of open construction stages and unfinished envelope components on airtightness.

**BREDERODE** is a recently (2015) renovated townhouse with modern joinery systems with double glazing. The quality of interior finishing, particularly plastering around window frames, plays a significant role in the airtightness performance. This case demonstrates the importance of detailing at the interface between joinery and masonry.

The townhouse **SLUIS** shows characteristics of limited renovation, with visible deficiencies in interior finishes such as missing plaster layers. These deficiencies result in increased air leakage through the building envelope. The case is particularly relevant for analysing the role of finishing layers in combination with joinery performance. No refurbishment of the windows.

**DENDER** is a well-renovated townhouse with attention to airtightness detailing. The renovation was done around 2015. The building includes improved sealing systems in both windows and doors, such as brushes and sealing strips. This case provides insight into the effectiveness of relatively simple airtightness measures applied to existing joinery systems.

The case **HERT** represents an additional townhouse included to broaden the dataset. The building is moderately renovated in the nineties of last century, and provides supplementary data for comparative analysis. Its characteristics contribute to understanding variability across similar building typologies. Some windows are still original, some have been replaced.

**EYCK** is a historically representative townhouse with limited renovation interventions in 1996. The building includes traditional materials and construction techniques, which makes it useful for benchmarking original airtightness performance against renovated cases. The windows have been replaced.

#### 4.1.1.3 Results

Only in a limited number of cases the air leakage rate of the front door or the windows was evaluated. By means of tape and foil these components were closed off to quantify the air leakage rate.

Table 3 Test results on whole building airtightness, doors and windows.

| Case      | Building envelope (m <sup>2</sup> .h) | Windows         | Renovation year | front door (m <sup>3</sup> /h) | front door (%) | Windows (m <sup>3</sup> /h) | Windows (%) | Windows (m <sup>3</sup> /h.m <sup>2</sup> ) |
|-----------|---------------------------------------|-----------------|-----------------|--------------------------------|----------------|-----------------------------|-------------|---------------------------------------------|
| Meers     | 4395,00 ± 92,04                       | partly replaced | 2000            | 140,00 ± 124,55                | 3,19%          | 813,00 ± 333,38             | 18,50%      | 12,36                                       |
| Martens2  | 4367,00 ± 90,99                       | refurbished     | 2015            | /                              | /              | /                           | /           | /                                           |
| Citadel   | 4501,00 ± 126,03                      | original        | 1945            | 295,00 ± 149,40                | 6,55%          | /                           | /           | /                                           |
| Muink     | 4424,50 ± 65,09                       | replaced        | 2007            | 169,00 ± 107,82                | 3,82%          | /                           | /           | /                                           |
| Koning    | 3929,00 ± 43,55                       | refurbished     | 2002            | 178,00 ± 80,66                 | 4,53%          | /                           | /           | /                                           |
| Keizer    | 7408,00 ± 107,05                      | partly replaced | 2000            | /                              | /              | /                           | /           | /                                           |
| Kuiper    | excessive                             | /               | /               | /                              | /              | /                           | /           | /                                           |
| Brederode | 3857,00 ± 90,61                       | replaced        | 2015            | /                              | /              | /                           | /           | /                                           |
| Sluis     | 6308,00 ± 196,12                      | original        | 2000            | 315,00 ± 254,23                | 4,99%          | 846,00 ± 192,49             | 13,41%      | 27,29                                       |
| Dender    | 6737,00 ± 186,90                      | refurbished     | 2015            | /                              | /              | /                           | /           | /                                           |
| Hert      | 8013,00 ± 480,78                      | partly replaced | 1990            | /                              | /              | /                           | /           | /                                           |
| Eyck      | 5471,00 ± 169,60                      | replaced        | 1996            | /                              | /              | /                           | /           | /                                           |
| Martens1  | 6803,00 ± 268,11                      | partly replaced | 2015            | /                              | /              | /                           | /           | /                                           |

For five houses the air leakage rate of the front door was quantified. On average the air flow rate at 50Pa was 219m<sup>3</sup>/h per door. In these buildings the door often does not comprise gasket at the sill, entailing significant air leakage. Looking at the classification standard for windows, the threshold value for the worst leakage class (i.e. class 1) amounts to 31.5m<sup>3</sup>/h.m<sup>2</sup>. From the results it can be derived that even this level is typically not obtained for the front door. In relative terms for these buildings, the leakage through the front door accounts for 4.6% of the total air leakage. The surface area of the front door ranges between 0.2% and 0.8% of the building envelope surface, which implies that the front door is one of the most leaky building components.

For two buildings also the air leakage of the windows was evaluated. For these windows the derived airtightness classification was class 1 and class 2, which confirms the extreme airflow rates and the high relative importance of air leakage through the existing window frames.

#### 4.1.2 Exploratory study – 3 windows

In section 4.1.1 the airtightness of heritage windows was evaluated using whole building airtightness tests. The results showed that considerably high air leakage rates were recorded, but the sample group was limited. In practice it showed difficult to seal all window openings while maintaining adequate pressure difference levels for testing. Hence, in a next step heritage windows from selected case were tested in lab conditions for a first lab assessment of airtightness performance.

##### 4.1.2.1 Museum Smidt van Gelder

This is a refurbished window of the museum Smidt van Gelder, located in a belle-epoque dwelling in beaux-arts style from 1905 designed by architect Joseph Hertogs. In the refurbishment a gasket type Deventer S0032 was installed at the sash-frame interface and central stile. The original hardware was replaced by a reproduction model, that allowed to gently compress the gasket without excessive stress on the hardware. Given the quality of the wood only limited deformations were recorded.

For this window 2 tests were executed: one with gasket and one without. With a gasket an air leakage rate of  $3.92 \text{ m}^3/\text{h.m}^2$  was measured (class 3), where in absence of the gasket this increased to  $16.01 \text{ m}^3/\text{h.m}^2$  (class 2). This demonstrates that reasonable airtightness can be achieved by combining a gasket with adjusted hardware when the deformations are limited. During the watertightness test water infiltrated at 50Pa pressure difference (class A1).

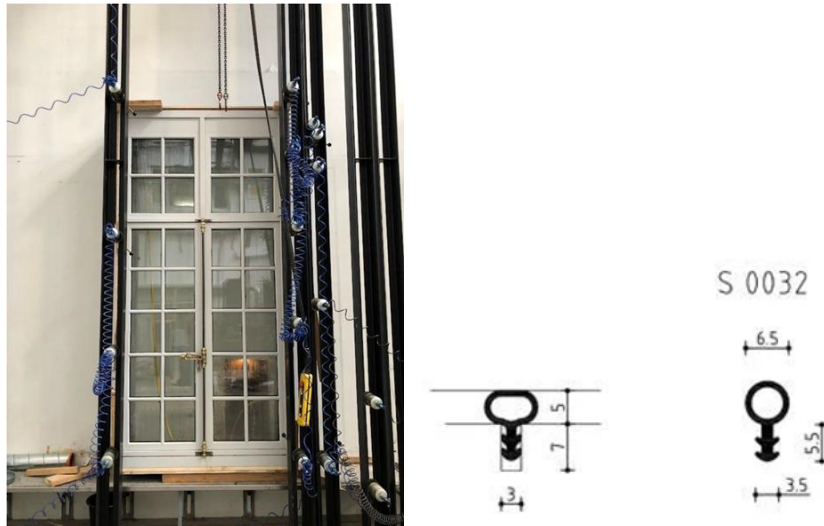


Figure 4 Historic window Museum Smidt van Gelder (left), gasket system (right)

Table 4 Airtightness of 3 historical window frames

| Configuration                  | Air flow rate<br>( $\text{m}^3/\text{h.m}^2@50\text{Pa}$ ) | Performance<br>class |
|--------------------------------|------------------------------------------------------------|----------------------|
| <b>Museum Smidt van Gelder</b> |                                                            |                      |
| with gaskets                   | 3,92                                                       | 3                    |
| without gaskets                | 16,01                                                      | 2                    |
| <b>Rozier</b>                  |                                                            |                      |
| Original                       | 23,03                                                      | 1                    |
| Refurbished                    | 17,22                                                      | 1                    |
| <b>City Hall Ghent</b>         |                                                            |                      |
| TL1                            | 119,96                                                     | 0                    |
| TL2                            | 10,98                                                      | 1                    |
| TL3                            | 3,14                                                       | 3                    |
| TL4                            | 1,93                                                       | 3                    |
| TL5                            | 1,57                                                       | 4                    |
| TL6                            | 3,14                                                       | 3                    |
| TL7                            | 1,92                                                       | 3                    |
| TL8                            | 1,57                                                       | 4                    |

#### 4.1.2.2 Rozier

The window was extracted from the Plateau-Rozier complex in the Blandijnberg neighbourhood of Ghent. This neo-classicistic building from 1890. Again, this window has a fixed upper part comprising two panes, and a double-awning part below with 6 panes. This is the original window that has not undergone any refurbishments over time. It should

be noted that due to malfunctioning and degradation the hardware was removed and both sashes were mechanically blocked by means of screws for the testing.

The same window was refurbished and tested again for comparison. In the refurbishment the wood was sanded, corrections were made to render it level, and a gasket was installed. Again, the proper hardware was not installed before the test, and as the glass was not yet installed, plywood panels were used during the test (it is presumed this does affect the test results).



Figure 5 Original and refurbished window Rozier

The air leakage rate of the original window amounted to  $23.03\text{m}^3/\text{h.m}^2$ , whereas the refurbished window resulted in an air flow rate of  $17.22\text{m}^3/\text{h.m}^2$  @50Pa pressure difference. Even though there is a slight improvement of the performance, the leakage class remains 1 in both cases. Watertightness tests pointed out that both configurations failed when subjected to a rain load without pressure difference, resulting in classification A0.

#### 4.1.2.3 Ghent City Hall

For the third window a replica window for the Ghent City Hall was studied. This is a building dating back to 1482. To optimise the performance different configurations were evaluated, in which the type, number, and location of gaskets was varied. The graph below provides an overview of the different configurations.

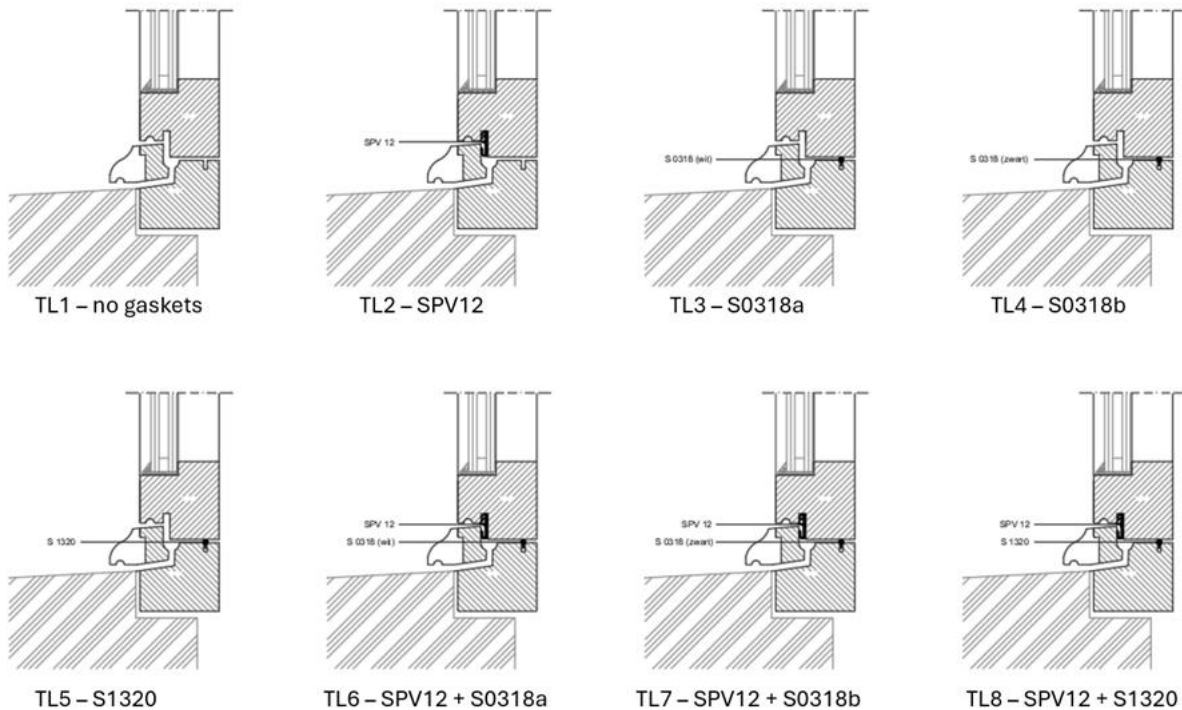


Figure 6 Window city hall: gasket configurations

The air leakage rates of the different configurations are reported below. Note that the Y-axis is logarithmic, which implies that the leakage rate of window TL1 is several orders of magnitude higher than the other configurations. The installation of a gasket does have a significant impact (TL2), but due to the location of this gasket it is bypassed by the drainage holes. As a result, it is still considerably worse compared to the solutions with an interior gasket (TL3-TL8). Also for the remaining windows a division appears in the results: those windows with gasket S0318a clearly underperform compared to the other solutions (S0318a and S0318b are identical in geometry, but the latter is made from a more rigid elastomer).

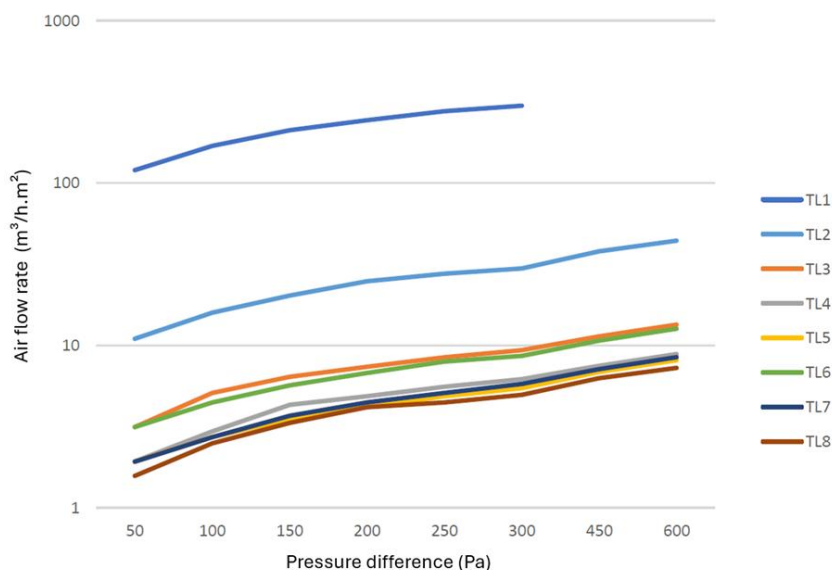


Figure 7 Windows city hall: airtightness of different window configurations

Subsequently, for this window also the watertightness was evaluated. Four different parameters were considered in this study: the central gasket, the interior gasket, the type of drainage, and the presence of a drip nose on the sash. In total 10 different configurations were tested according to EN 1027, and the watertightness class was recorded in table 5.

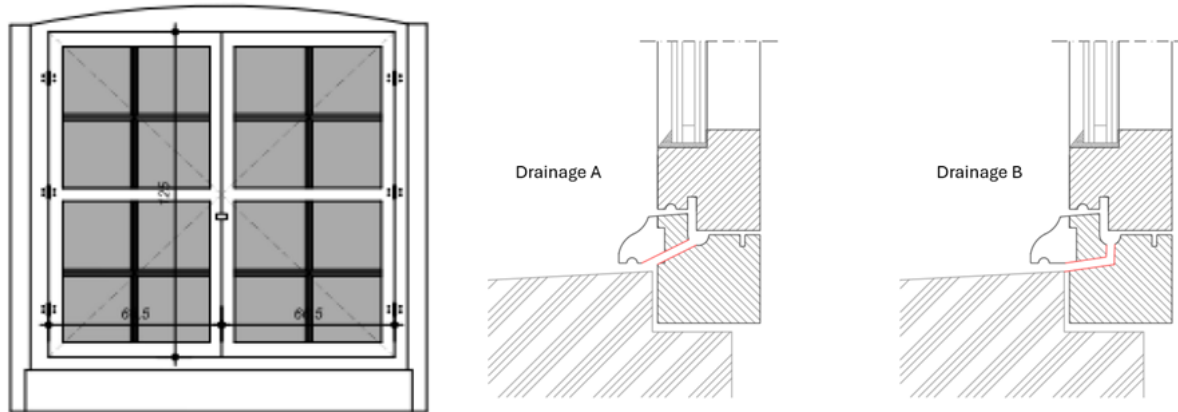


Figure 8 Windows city hall: front view and cross-section with drainage

In absence of any gasket and drainage, rainwater infiltrated to the interior without pressure difference. Adding drainage allowed to improve the performance one class, which implies that water did enter as soon as a pressure difference was applied. Only when 2 gaskets were installed with adequate drainage, performance class 4 could be achieved (watertight up to 150Pa). It should be noted that these performance levels are still far from code compliant for most buildings in Belgium.

Table 5 Windows city hall: different configurations and watertightness performance

| Configuration | Central gasket | Interior gasket | Drainage A | Drainage B | Drip nose | Watertightness class |
|---------------|----------------|-----------------|------------|------------|-----------|----------------------|
| TW01          | /              | /               | sealed     | sealed     | no        | 0 (fail at 0Pa)      |
| TW02          | /              | /               | sealed     | open       | no        | 1A (0APa)            |
| TW03          | /              | /               | open       | sealed     | no        | 1A (0APa)            |
| TW04          | /              | /               | sealed     | open       | no        | 1A (0APa)            |
| TW05          | /              | /               | open       | open       | yes       | 1A (0APa)            |
| TW06          | SPV12          | /               | open       | sealed     | yes       | 1A (0APa)            |
| TW07          | SPV12          | /               | open       | open       | yes       | 2A (50Pa)            |
| TW08          | SPV12          | S0318b          | open       | open       | no        | 2A (50Pa)            |
| TW09          | SPV12          | S0318b          | sealed     | open       | yes       | 3A (100Pa)           |
| TW10          | SPV12          | S0318b          | open       | open       | yes       | 4A (150Pa)           |

#### 4.1.3 Optimization study

The experimental approach was primarily based on the principles of EN 1026, which defines laboratory testing procedures for the air permeability of windows and doors. Rather than aiming for formal product certification, the standard was used as a methodological framework to ensure a controlled and reproducible testing procedure.

Data processing followed the regression procedures described in EN 12114, allowing the determination of airflow coefficients and flow exponents from multiple pressure levels. Subsequently, measured leakage rates were normalised according to EN 12207, enabling comparison with established airtightness performance classes.

The standards were therefore employed as analytical reference frameworks rather than as strict compliance criteria, allowing meaningful comparison between historic and restored window configurations. It is important to note that pressure differences up to 600Pa are not always feasible using on site conditions.

Measurements were conducted in two complementary environments:

- **In situ measurements**, performed on windows in their original building context;
- **Laboratory measurements**, performed on the same window specimens after removal from the building and installation in a controlled test rig.

This dual approach enabled evaluation of both real-life performance and behaviour under controlled boundary conditions.

In the in-situ setup, the investigated window was isolated from the surrounding façade using an airtight temporary enclosure. Particular care was taken to ensure that only airflow through the window component itself contributed to the measured leakage rate.

For laboratory testing, the window was mounted in a dedicated timber test frame and sealed along its perimeter. This configuration eliminated leakage through the surrounding construction and allowed repeated measurements during successive restoration stages.

Measurements were performed under both positive and negative pressure differences. In addition to representing conventional pressure loading, the selected pressure directions were interpreted in terms of their mechanical effect on the window assembly.

Two functional loading conditions were therefore distinguished:

- **Closing-direction loading (DI)**, in which pressure forces increase the contact pressure between frame and sash;
- **Opening-direction loading (OP)**, in which pressure forces reduce contact pressure and tend to open existing leakage paths.

This distinction was considered particularly relevant for historic windows, where airtightness strongly depends on geometric tolerances, deformation of the sash and local contact conditions between adjoining components. However, as the results showed to be very similar, in this report only the results for underpressure (opening-direction loading) will be reported.

#### *4.1.3.1 Test samples*

The experimental program was organised around nineteenth-century timber windows originating from the former Maternity Building at the Bijloke site in Ghent. The investigation combined in-situ measurements with laboratory testing and evaluated a sequence of progressively more intensive restoration interventions. The windows formed part of a larger ensemble of architecturally valuable historic joinery and was selected within the framework of the HeriTACE project because multiple identical windows were available for restoration and experimental evaluation.

The original windows consisted of slender timber frame and sash profiles fitted with single glazing. The window retained its historic construction principles, including traditional joinery details, original opening mechanisms and characteristic profile geometry. As is common for historic joinery, prolonged exposure to environmental loading and ageing

resulted in local deformation, wear of the hardware, irregular contact between frame and sash, and variable joint widths along the perimeter. These characteristics make the specimens representative of the challenges encountered when improving the airtightness performance of historic windows while preserving heritage significance. Table 6 below provides an overview of the different test configurations.

Table 6 Window optimisation: configurations and gasket types

| Type             | Name   | Conditions | Window | Modifications                                           | Exterior gasket | Central Gasket<br>(central stile) | Central Gasket<br>(perimeter) | Interior gasket |
|------------------|--------|------------|--------|---------------------------------------------------------|-----------------|-----------------------------------|-------------------------------|-----------------|
| Original window  | sOG1   | Site       | 1      | None                                                    | /               | /                                 | /                             | /               |
|                  | aOG1   | Atelier    | 1      | None                                                    | /               | /                                 | /                             | /               |
|                  | sOG2   | Site       | 2      | None                                                    | /               | /                                 | /                             | /               |
|                  | aOG2   | Atelier    | 2      | None                                                    | /               | /                                 | /                             | /               |
|                  | sOG3   | Site       | 3      | None                                                    | /               | /                                 | /                             | /               |
|                  | aOG3   | Atelier    | 3      | None                                                    | /               | /                                 | /                             | /               |
| State-of-the-art | sRE3a  | Site       | 3      | Central stile gasket                                    | /               | SPV12                             | /                             | /               |
|                  | sRE3b  | Site       | 3      | Addition of interior window                             | /               | SPV12                             | /                             | /               |
|                  | aRE1a  | Atelier    | 1      | Single gasket (perimeter + central stile)               | /               | SPV12                             | S0032                         | /               |
|                  | aRE1b  | Atelier    | 1      | Refurbishment of glazing putty                          | /               | SPV12                             | S0032                         | /               |
|                  | aRE1c  | Atelier    | 1      | Correction of torsion in sashes                         | /               | SPV12                             | S0032                         | /               |
|                  | aRE1d  | Atelier    | 1      | Check of tolerances at gasket (addition of cover strip) | /               | SPV12                             | S0032                         | /               |
|                  | aRE1e  | Atelier    | 1      | Alternative gaskets                                     | /               | S5510                             | S1320                         | /               |
|                  | aRE2a  | Atelier    | 2      | Central gasket                                          | /               | SPV12                             | S0032                         | /               |
| Improvement      | aRE2b  | Atelier    | 2      | Interior gasket                                         | /               | /                                 | /                             | S5510           |
|                  | aRE2c  | Atelier    | 2      | Exterior gasket                                         | S5510           | /                                 | /                             | /               |
|                  | aRE2d1 | Atelier    | 2      | Exterior + Central gasket                               | SPV12           | SPV12                             | S0032                         | /               |
|                  | aRE2d2 | Atelier    | 2      | Exterior + Central gasket                               | S5510           | SPV12                             | S0032                         | /               |
|                  | aRE2e1 | Atelier    | 2      | Interior + central gasket                               | /               | SPV12                             | S0032                         | custom          |
|                  | aRE2e2 | Atelier    | 2      | Interior + central gasket                               | /               | SPV12                             | S0032                         | SPV12           |
|                  | aRE2e3 | Atelier    | 2      | Interior + central gasket                               | /               | SPV12                             | S0032                         | S5510           |
|                  | aRE2f1 | Atelier    | 2      | Exterior + central + interior gasket                    | SPV12           | SPV12                             | S0032                         | custom          |
|                  | aRE2f2 | Atelier    | 2      | Exterior + central + interior gasket                    | S5510           | S5510                             | S0032                         | S5510           |
|                  | sREP   | Site       | 4      | New window                                              | /               | S5510                             | S5510                         | /               |

#### 4.1.3.1.1 Original windows

There were 3 original windows, either tested in the existing condition located on site (Site), or tested after dismantling and transportation in lab conditions (atelier). These are indicated by OG, with a prefix referring to the test location (s/a), and a suffix (1,2,3) indicated the specific specimen.

Although the windows belong to the same architectural typology, variations were observed in the original closing mechanisms. Some windows were equipped with conventional espagnolette hardware, whereas others incorporated similar locking systems concealed behind timber cover profiles. In addition, several windows had undergone local modifications during their service life, including supplementary screw fixings intended either to reduce draughts or to maintain distorted sashes in the closed position. These interventions were implemented inconsistently and resulted in substantial variation in local contact conditions between frame and sash.

The combination of slender profile geometry, variable closure conditions, long-term wear and accumulated construction tolerances results in a discontinuous contact interface between sash and frame. Consequently, the airtightness performance of the original windows is primarily governed by geometric and mechanical irregularities rather than by the presence of dedicated airflow paths. These discontinuities constitute the dominant leakage mechanism of the historic joinery and form the basis for comparison with the restored and reproduction window configurations investigated in this study.

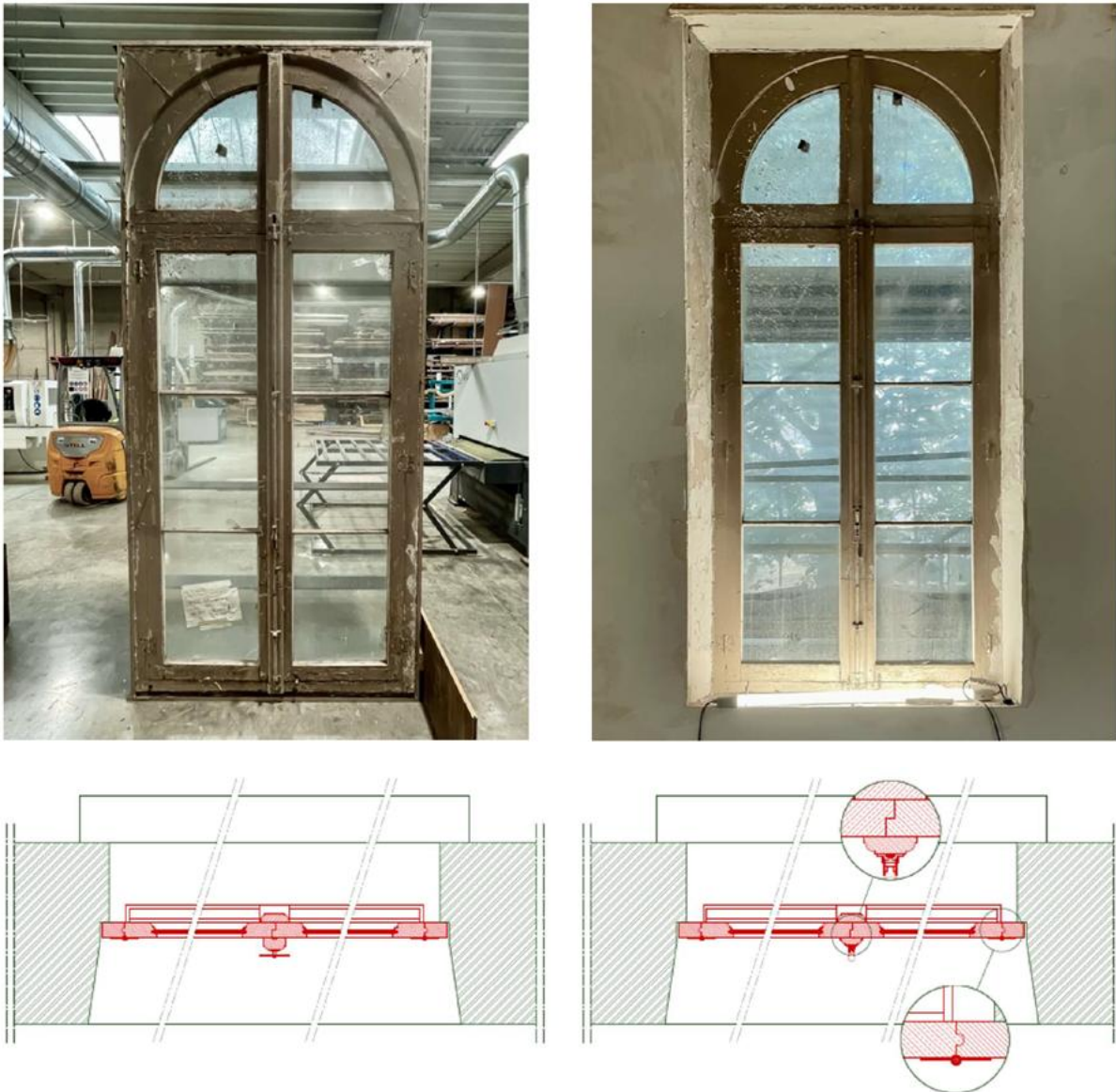


Figure 9 lab assessment (top left); on site assessment (top right), horizontal section original window (bottom)

## Results

In the configurations with a foil, the Lindab LT600 was connected to a foil that was taped against the wall. Evidently this foil may be more vulnerable to punctures compared to a plywood frame. Next to that, also at the interface with the wall it relies on a tape to ensure continuity. Finally, an additional concern with the foil might be that in underpressure it is in direct contact with the window, possibly impeding an equal distribution of the pressure over the window surface. In contrast the plywood frame provides a more rigid configuration, but inherently comprises a number of corner joints that require caulking, and also needs an airtight connection to the wall by means of tape, caulking, or closed-cell foam tape. A plywood frame requires more preparation in advance to allow testing. Hence, this comparative analysis allows to verify whether tests with a foil provide a reliable test condition.

The figure below reports the air leakage rates for the different original windows. The lines are almost perfectly linear ( $R^2 > 0.99$ ) which indicates that the power law assumption is valid. In certain cases displacement or deformation of window components may render the power law inadequate for curve fitting, but the results indicate this is not the case.

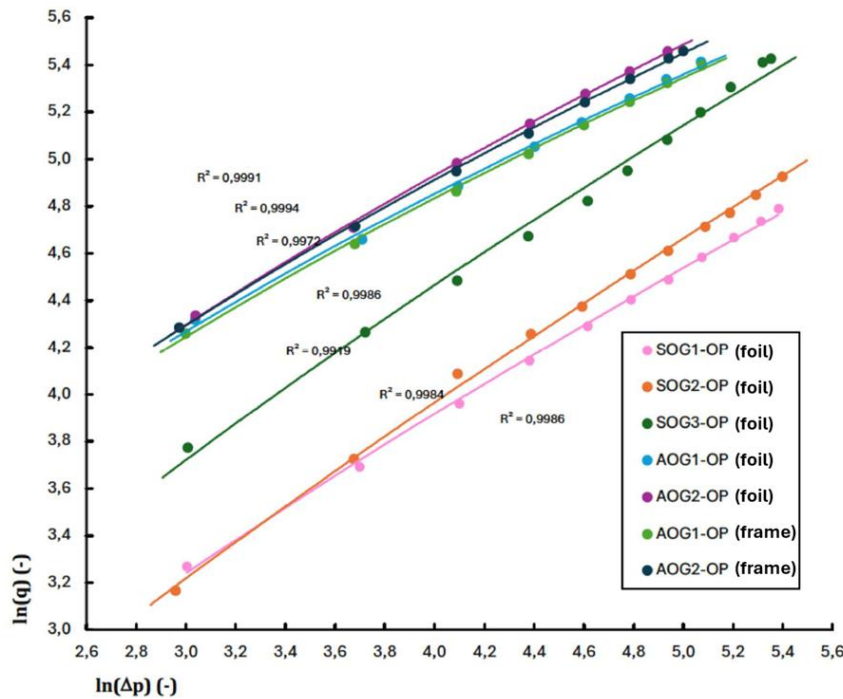


Figure 10 Reliability of on site testing with foils and frames

Table 7 Air leakage rate at 100Pa pressure difference and associated performance class for on site and atelier testing with foils and frame.

| Name | Location | Test setup | Leakage ( $\text{m}^3/\text{h} \cdot \text{m}^2 @ 100\text{Pa}$ ) | Performance class |
|------|----------|------------|-------------------------------------------------------------------|-------------------|
| aOG1 | Atelier  | foil       | 37,21                                                             | 1                 |
| aOG2 | Atelier  | foil       | 41,61                                                             | 1                 |
| aOG1 | Atelier  | frame      | 36,61                                                             | 1                 |
| aOG2 | Atelier  | frame      | 40,24                                                             | 1                 |
| sOG1 | Site     | foil       | 15,49                                                             | 2                 |
| sOG2 | Site     | foil       | 17,03                                                             | 2                 |
| sOG3 | Site     | foil       | 27,73                                                             | 1                 |

There are a number of striking conclusions:

- The variation in window performance is larger than the variation introduced by selecting either foil or plywood frame. The differences are very small (2-3%) which entails that the test procedure with a foil provides reliable results.
- There is a significant variation in performance in between the 3 original windows. The airtightness, or lack thereof, is mainly determined by the geometry and

tolerances of the windows. Differences in decay and deformation may hence give rise to significant differences in performance.

- The air leakage recorded on site, in the original configuration, is significantly lower than that measured in lab conditions. It was anticipated that on site test would entail higher leakage rates because additional leakage at the window-wall interface may occur. However, the analysis indicated that the dismantling of windows and transport to the lab had a detrimental effect on the airtightness.

#### 4.1.3.1.2 State-of-the-art-refurbishments

##### **Single gasket (sRE3a)**

The state-of-the-art restoration strategy of the contractor consisted of the installation of a single rubber sealing gasket at the central stile interface (sRE3a). The original locking hardware, hinges and glazing system were otherwise preserved and continued to operate according to the original nineteenth-century design principle. The existing glazing was replaced with new single drawn glass to ensure a consistent and well-defined glazing condition throughout the experimental campaign.

Contact surfaces between sash and frame were cleaned and locally levelled to improve geometric continuity. Where required, the frame geometry was corrected, damaged mortise-and-tenon joints were repaired or replaced, and defects such as cracks, splits and gaps were filled. These interventions aimed to restore the dimensional stability and contact quality of the original joinery before introducing additional airtightness measures.

For the in-situ restoration configuration (sRE3a), no rubber gasket was installed at the perimeter joints. These locations were deliberately left untreated in order to minimise the risk of damage to the historic joinery and to preserve the minimally invasive character of the intervention. During the subsequent workshop restoration sequence, sealing elements were introduced at these joints, allowing the influence of this additional intervention on airtightness performance to be evaluated separately.



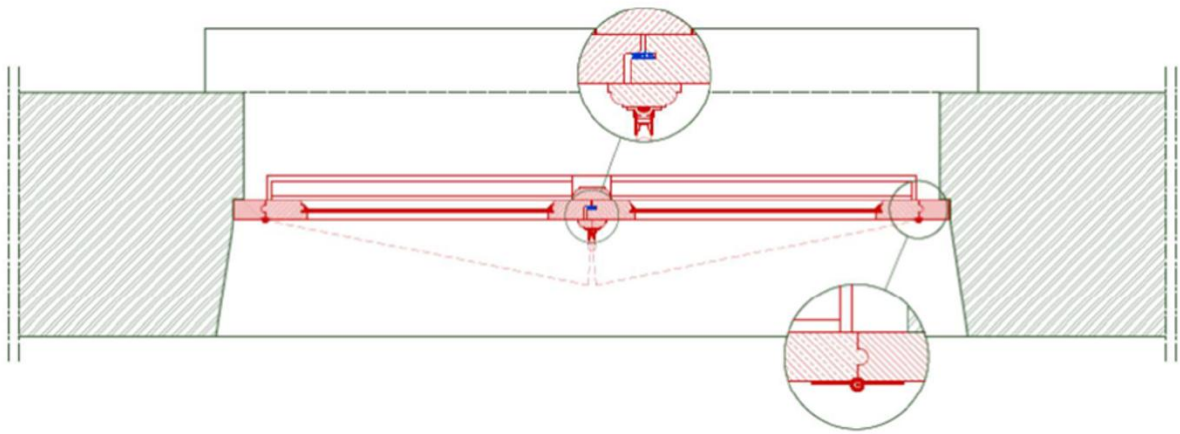
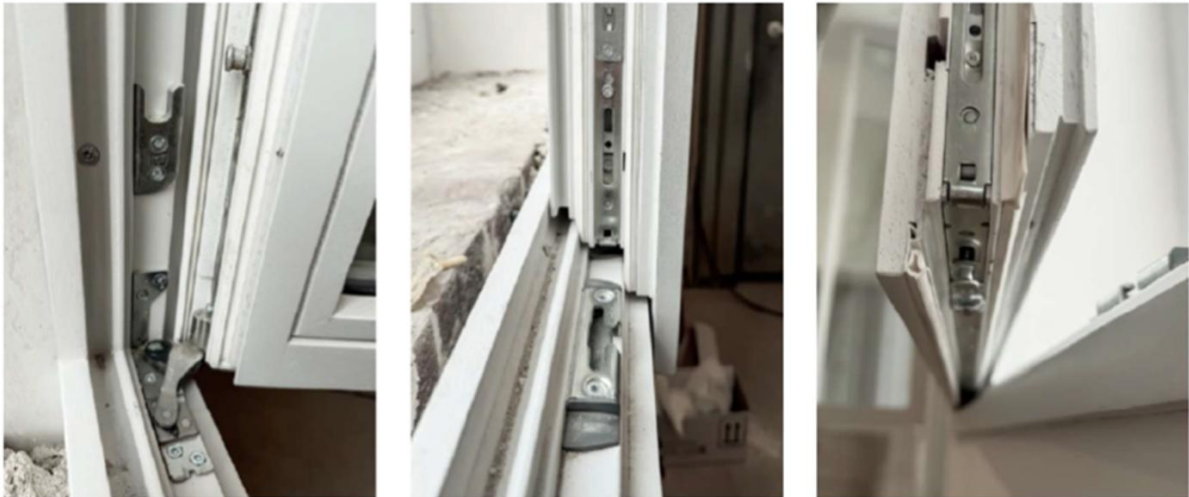


Figure 11 Refurbished window with single gasket. Pictures and horizontal section.

### **Double window (sRE3b)**

This configuration is identical to the previous one, but an additional new wooden window is installed on the interior side. The original window, including gaskets, remained as previously described.



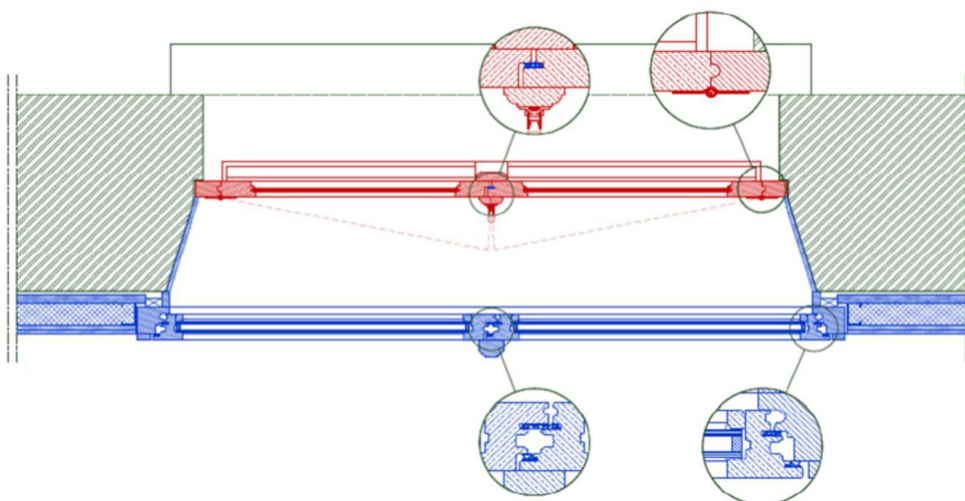


Figure 12 Original window with additional new window on the inside. Pictures and horizontal section.

### Step-wise refurbishment (aRE1a-e)

For the aRE1 window, the effect of the different steps of the refurbishment process were evaluated. Please refer to the overview table for a detailed description of the modifications.

### Results

Test sample sRE3a is the standard state-of-the-art solution of the specialized contractor. Compared to the original window an additional gasket was installed at the central stile. sRE3a1 refers to this configuration, whereas in sRE3a2 that gasket was removed to compare with the original windows.

Alternatively, sample sRE3b refers to the same sample as sRE3a, but now an additional new wooden window was installed at the inside to create a double window. Again, sRE3b1 refers to the final configuration, whereas in sRE3b2 the central stile gasket was removed.

Furthermore, on window aRE1 a sequence of tests was conducted in lab to check the impact of the separate measures.

Table 8 Air leakage rate at 100Pa pressure difference and associated performance class for performance optimised heritage window.

| Name   | Location | Test setup | Leakage (m <sup>3</sup> /h.m <sup>2</sup> @100Pa) | Performance class |
|--------|----------|------------|---------------------------------------------------|-------------------|
| sRE3a1 | Site     | foil       | 29,14                                             | 1                 |
| sRE3b1 | Site     | foil       | 1,82                                              | 4                 |
| sRE3a2 | Site     | foil       | 44,25                                             | 1                 |
| sRE3b2 | Site     | foil       | 2,42                                              | 4                 |
| aRE1a  | Atelier  | frame      | 35,35                                             | 1                 |
| aRE1b  | Atelier  | frame      | 36,3                                              | 1                 |
| aRE1c  | Atelier  | frame      | 21,84                                             | 2                 |
| aRE1d  | Atelier  | frame      | 18,11                                             | 2                 |
| aRE1e  | Atelier  | frame      | 18,06                                             | 2                 |

## Main conclusions:

- The refurbished window (sRE3a1) is rated in performance class 1, but more importantly, is only slightly better than the original windows tested in lab conditions, but worse than the original windows tested on site. As explained above, the dismantling and transport of the original windows increases the air leakage rate.
- The refurbishment itself has a negligible impact on the airtightness. However, when the gasket is removed the air flow rate increases to  $44.25\text{m}^3/\text{h.m}^2$  at 100Pa pressure difference. In the refurbishment of the windows the mullions, jambs and sash are cleaned: one possible explanation might be that in the cleaning only material is removed, increasing the tolerances between the different components.
- When an additional window is installed (sRE3b1), the overall airtightness evidently shifts to that of a new window (class 4). Removing the central gasket of the outer window (sRE3b2) has a small impact.
- The sequential testing points out that the installation of the gasket did not have a significant impact. Only when the deformation of the sashes was addressed the leakage decreased by 40%. Additionally, in a subsequent step the compression of the gaskets was checked and where it was insufficient additional cover strips were installed. These covers strips reduced the width of the joint, allowing the gasket to indeed get compressed. The combined effect of entailed a reduction of 50%. This indicates that typical deformations recorded here exceed the tolerance margin of the gaskets.
- The effect of replacing the glass putty and changing gasket was very limited for this specific window.

#### 4.1.3.1.3 Optimization

The extensive restoration configurations (aRE2) were developed as an experimental extension of the heritage-compatible restoration strategies investigated in the minimal restoration pathway. Whereas the state-of-the-art interventions were intended to quantify the performance and limitations of commonly applied restoration measures, the improvement configurations were specifically designed to investigate the governing leakage mechanisms identified during the earlier test phases.

The objective of this experimental series was to determine to what extent the dominant leakage paths could be eliminated and to assess the maximum airtightness that could be achieved within the constraints of the existing window geometry. Consequently, the investigated interventions were not necessarily derived from established restoration guidelines, but were developed as analytical design interventions targeted at specific leakage mechanisms observed during the experimental campaign.

To facilitate this investigation, multiple sealing levels and alternative gasket positions were introduced, allowing the influence of sealing location and sealing continuity on air leakage behaviour to be evaluated independently. This approach enabled a systematic assessment of the relationship between frame-sash contact conditions and overall airtightness performance.

**Central gasket (aRE2a)**

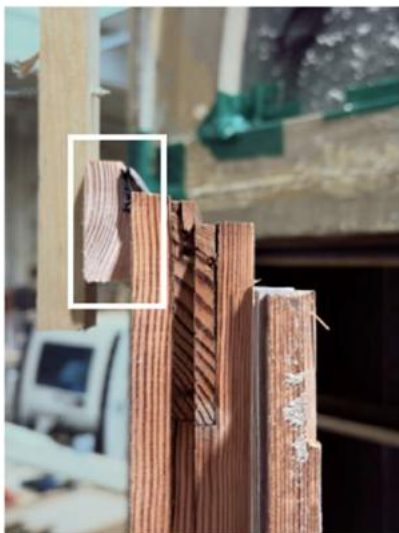
The centre gasket configuration (aRE2a) consisted of the installation of a single rubber sealing gasket at the original frame-sash contact interface. This configuration corresponds to the final stage of the minimal restoration sequence tested in the workshop environment and served as the reference configuration for the extensive restoration pathway.

**Interior gasket (aRE2b)**

The interior gasket configuration was created by installing a continuous sealing line on the interior side of the frame-sash interface using timber cover strips. The cover strips were mounted over the existing joint and provided with a dedicated groove in which the rubber gasket was installed. In the closed position, the gasket was compressed against the window frame, thereby creating an alternative sealing plane independent of the original contact interface.

The use of cover strips offered several advantages from an experimental perspective. The intervention was largely reversible, reduced the risk of damage to the historic joinery, and allowed visual inspection of the contact zone between gasket and timber. Furthermore, the configuration enabled the effect of introducing a new sealing plane to be investigated without extensive modification of the original frame-sash geometry.

To accommodate the cover strips, the original hinges were replaced and repositioned. This modification was necessary to ensure the technical feasibility of the proposed sealing arrangement within the constraints of the existing window geometry.



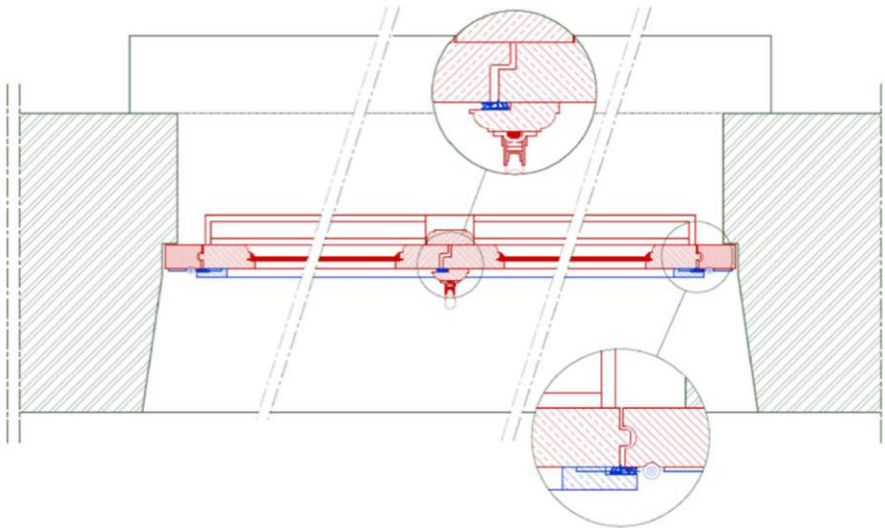


Figure 13 Original window with interior gasket configurations. Pictures and horizontal section.

### Exterior gasket (aRE2c)

The exterior gasket configuration was created by introducing a single sealing line on the exterior side of the frame-sash interface using timber cover strips. Similar to the interior gasket configuration, the cover strips were designed to accommodate a continuous rubber gasket and thereby establish an alternative sealing plane independent of the original contact interface.

Due to the presence of the original drip molding at the bottom rail of the sash, the cover-strip system could not be installed along the lower edge of the window. Consequently, the exterior sealing line was limited to the jambes and head mullion, resulting in a discontinuous perimeter seal. In contrast to the interior gasket configuration, no modifications to the original hinges were required. The intervention could therefore be implemented while preserving the original interior appearance and hardware arrangement of the window although it does affect the original appearance of the window. This alteration does affect the original appearance of the window and, for this reason, would not normally be accepted in the case of listed heritage. Even in the case of valuable joinery on non-listed buildings, such alterations that affect the architectural details are typically not desirable. Hence, these results must be read as a conceptual approach, relevant for cases where an exterior gasket can be integrated in existing windows.

This configuration was specifically included to evaluate the influence of gasket location and sealing continuity on airtightness performance. The inability to extend the sealing line over the entire perimeter provided an opportunity to assess the impact of local interruptions within an otherwise continuous sealing plane.

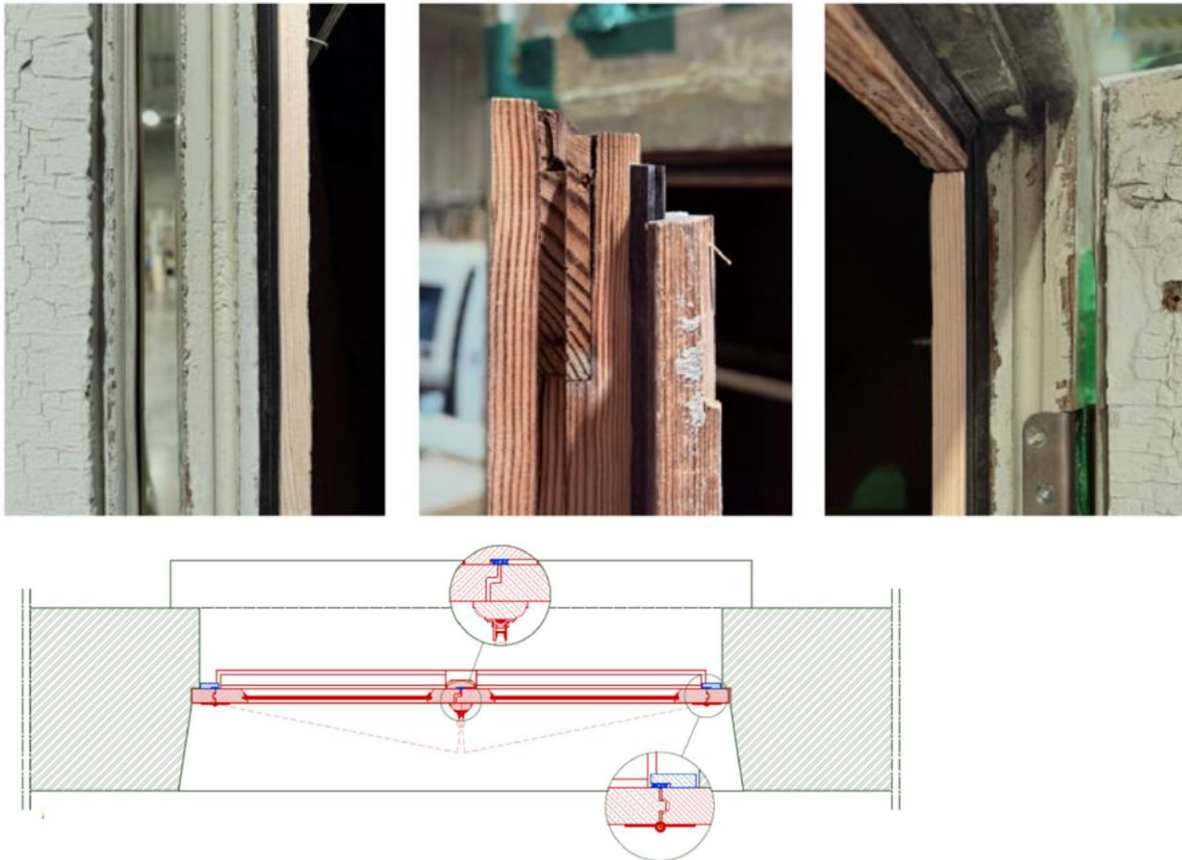


Figure 14 Original window with exterior gasket configurations. Pictures and horizontal section.

### Exterior + central gasket (aRE2d)

The combined exterior and central gasket configuration consisted of a dual sealing arrangement combining the centre gasket configuration (aRE2a) with the exterior gasket configuration (aRE2c). The original frame-sash sealing interface was therefore supplemented by a second sealing plane positioned on the exterior side of the window.

Within this configuration, different gasket profiles were investigated while maintaining an identical sealing layout. This enabled the influence of gasket geometry and mechanical properties to be evaluated independently from the position of the sealing interfaces.

The configuration was specifically designed to assess the combined effect of a centre sealing plane and an additional exterior sealing plane on overall airtightness performance. By introducing two sequential barriers to airflow, the configuration provides insight into the extent to which multiple sealing interfaces can reduce leakage through historic timber windows.

### Interior + central gasket (aRE2e)

The combined central and interior gasket configuration consisted of a dual sealing arrangement combining the centre gasket configuration (aRE2a) with the interior gasket configuration (aRE2b). The original frame-sash sealing interface was therefore supplemented by an additional sealing plane positioned on the interior side of the window.

As in the previous configurations, different gasket profiles were evaluated while maintaining an identical geometric arrangement. This enabled the influence of gasket properties to be investigated independently from the sealing layout.

The configuration was introduced to assess the combined effect of a primary sealing interface at the original frame-sash contact plane and a secondary sealing interface located on the interior side of the window. Compared with the center-exterior configuration, this arrangement allowed the influence of sealing-plane location to be investigated while maintaining the same number of sealing interfaces.

Due to geometric constraints near the upper corner of the sash, the interior sealing line could not be installed as a fully continuous perimeter gasket. Consequently, local interruptions remained within the sealing plane. Additional measures were implemented in the laboratory setup to approximate the behaviour of a continuous gasket and to evaluate the influence of these discontinuities on the measured airtightness performance.



Figure 15 Original window with interior and central gasket configurations.

### **Exterior + central + interior gasket (aRE2f)**

The triple-sealing configuration represented the most extensive intervention investigated within the experimental restoration pathway. The configuration combined sealing planes at the interior side of the window, the original frame-sash interface, and the exterior side of the frame-sash joint, thereby creating three successive barriers to airflow.

Within this configuration, only the gasket profile was varied, while the position of the sealing planes remained unchanged. This approach enabled the influence of gasket properties to be assessed independently from the geometric arrangement of the sealing system.

Unlike the heritage-compatible in-situ restoration configurations, the experimental workshop configurations included additional sealing elements at the perimeter joints. These locations were deliberately incorporated into the experimental restoration program because the controlled workshop environment allowed interventions to be implemented without the practical and conservation constraints associated with reuse in historic buildings.

The triple-sealing configuration therefore represents the highest intervention level investigated in this study and serves as an experimental approximation of the maximum airtightness that can be achieved while retaining the original window geometry although it does affect the original appearance of the window. Similar to the situation with the exterior gasket, the test samples provide insights on a conceptual level, and the practical implementation needs to be evaluated on a case-by-case basis to check if and how a gasket can be integrated without modifying the original appearance.

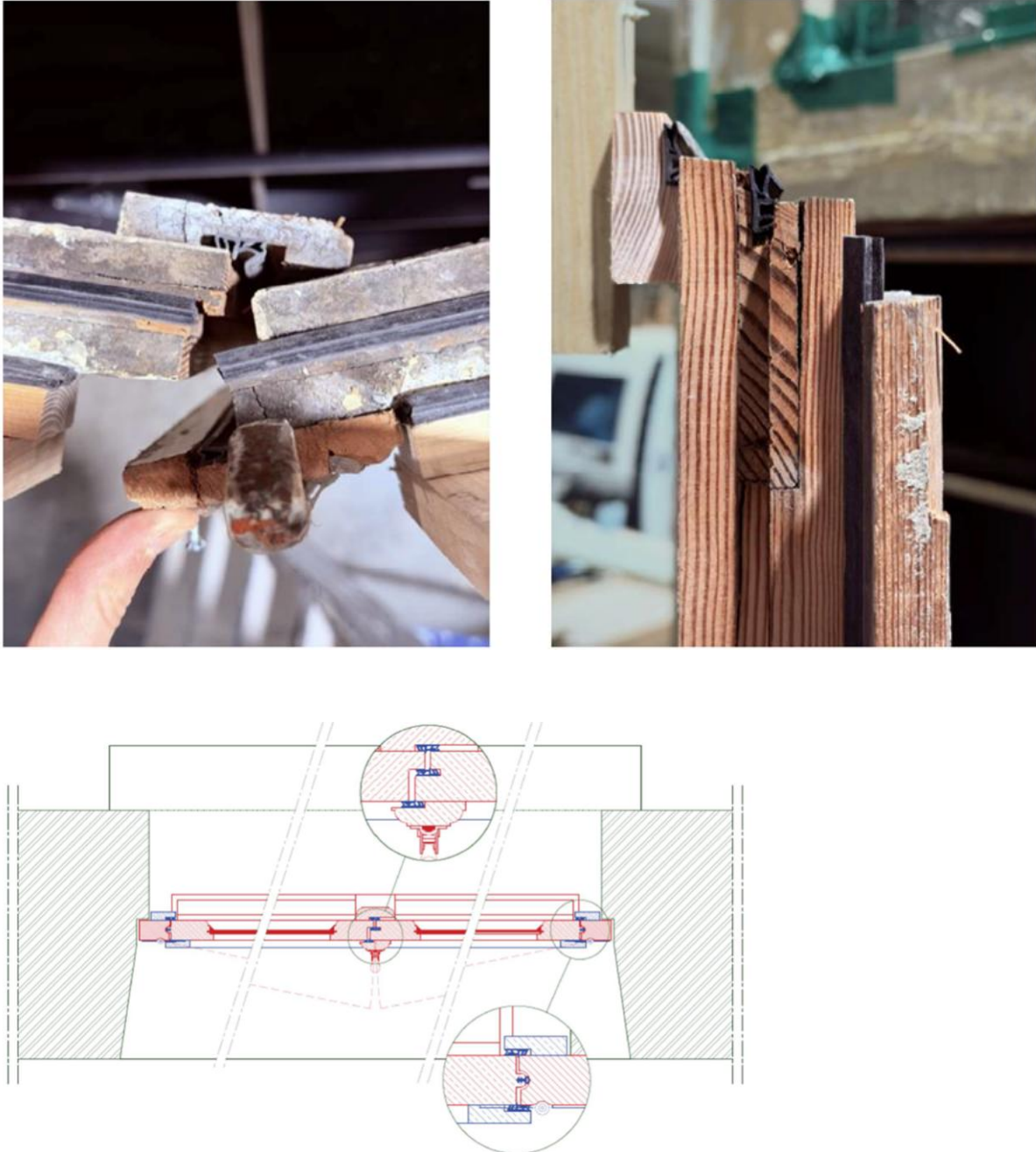


Figure 16 Original window with interior, central, and exterior gasket configurations. Pictures and horizontal section.

## Results

In this sequence a range of different gasket configurations were evaluated. The tests with suffix a, b and c refer to a single gasket on a central, interior and exterior location respectively. Tests with suffix d and e comprise 2 gaskets, and aRE2f2 has all 3 gaskets.

Table 9 Air leakage rate at 100Pa pressure difference and associated performance class for different gasket configurations.

| Name   | Location | Test setup | Leakage (m <sup>3</sup> /h.m <sup>2</sup> @100Pa) | Performance class |
|--------|----------|------------|---------------------------------------------------|-------------------|
| aRE2a  | Atelier  | frame      | 15,2                                              | 2                 |
| aRE2b  | Atelier  | frame      | 9,42                                              | 2                 |
| aRE2c  | Atelier  | frame      | 28,96                                             | 1                 |
| aRE2d1 | Atelier  | frame      | 11,7                                              | 2                 |
| aRE2d2 | Atelier  | frame      | 9,73                                              | 2                 |
| aRE2e1 | Atelier  | frame      | 6,52                                              | 3                 |
| aRE2e2 | Atelier  | frame      | 6,82                                              | 3                 |
| aRE2e3 | Atelier  | frame      | 4,67                                              | 3                 |
| aRE2f1 | Atelier  | frame      | 5,69                                              | 3                 |
| aRE2f2 | Atelier  | frame      | 4,49                                              | 3                 |

Main conclusions:

- If only a single gasket is installed, it is best located at the interior side (aRE2b). There it is easier to ensure contact between the sash and the frame. Remarkably, an exterior gasket (aRE2c) shows better performance than a central gasket, even though drainage holes and vents by default short-circuit the airtightness plane. Again, this highlights that the central gasket is most susceptible to tolerance issues when the deformation is extensive.
- In line with previous results, windows aRE2e with central + interior gasket perform better than aRE2d with central and exterior gasket.
- The addition of a 3rd gasket makes little sense. The continuity of a single gasket trumps the succession of multiple gaskets. Moreover, other tests have shown that windows with 3 gaskets sometimes even perform worse: it is more difficult to ensure adequate compression of 3 different gaskets simultaneously.

### 4.1.3.1.4 Reproduction (sREP)

The final test specimen consisted of a newly manufactured timber reproduction window designed as a faithful representation of the original nineteenth-century window typology. The reproduction preserved the overall geometry, ornamentation, profile composition and visual proportions of the historic joinery while incorporating contemporary manufacturing standards and performance-oriented detailing.

In contrast to the historic windows, the reproduction specimen was manufactured from new timber using controlled production techniques and dimensional tolerances. As a result, the frame and sash exhibited uniform clearances and stable geometric relationships,

eliminating many of the deformation- and wear-related irregularities observed in the original specimens.

The reproduction window incorporated a continuous rubber gasket along the entire perimeter of the operable sash. In addition, a secondary sealing line was provided at the meeting stile between the two casements, creating a double-barrier sealing strategy. Both sealing interfaces were designed to be compressed uniformly under closing pressure, ensuring consistent contact conditions around the complete window perimeter.

A further distinction from the restored historic windows was the position of the sealing system relative to the drainage detailing. Whereas the heritage-compatible restoration configurations retained a direct connection between the drainage cavity and the exterior environment, the reproduction window located the sealing line on the interior side of the drainage path. Consequently, no direct airflow connection remained between the outdoor environment and the indoor space.

Several construction details were moderately modernised to improve durability and moisture management while preserving the architectural character of the historic window. The frame depth was increased to accommodate double glazing, resulting in improved thermal performance. New hinges and a traditional espagnolette locking system were used to maintain visual and functional compatibility with the original design.

The reproduction window therefore represents a benchmark configuration in which the historic architectural appearance is retained, while modern manufacturing accuracy, continuous sealing interfaces and optimised detailing are employed to maximise airtightness performance.

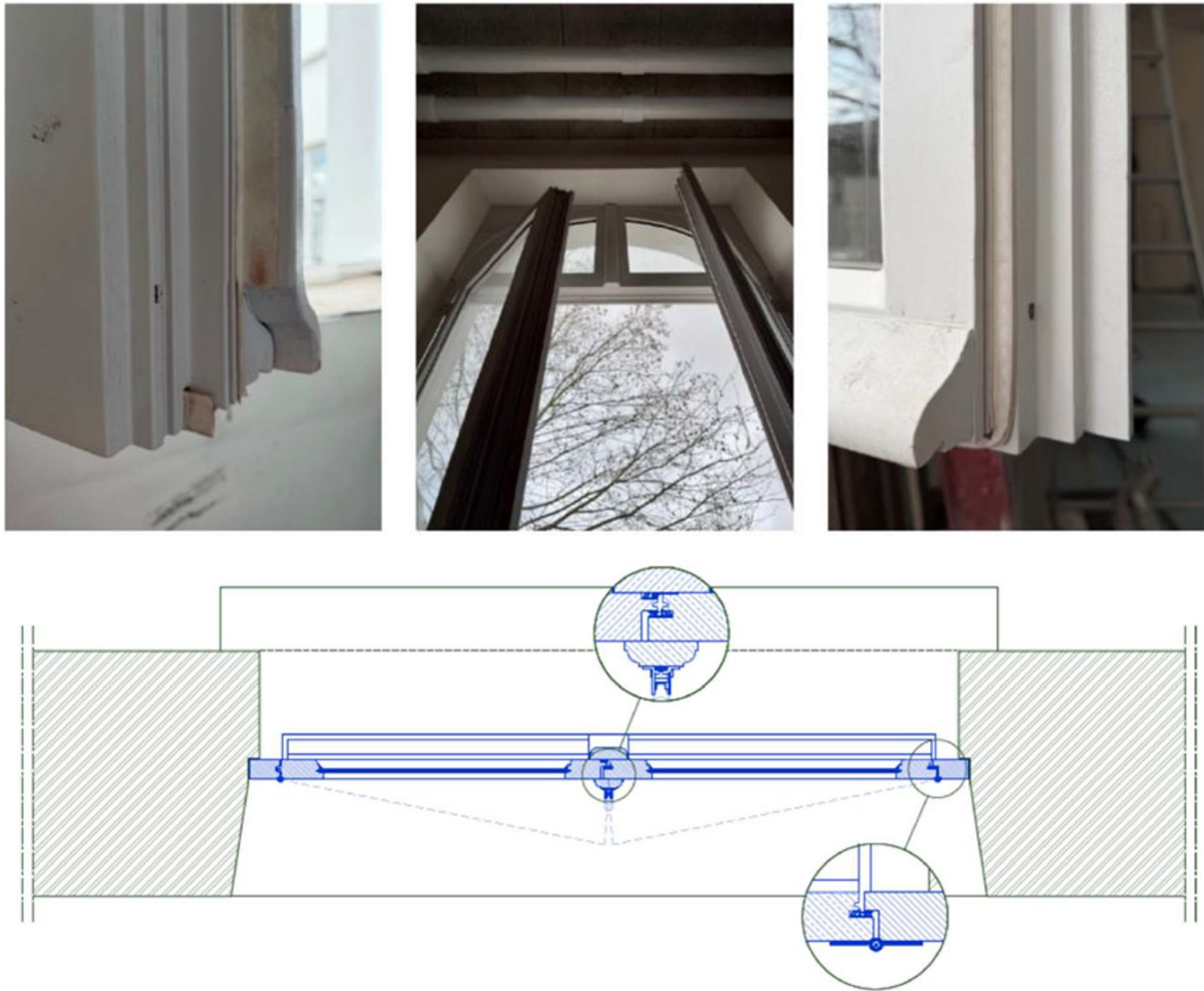


Figure 17 Reproduction window. Pictures and horizontal section.

## Results

Finally, a fac-simile window was made as one of the original windows was impossible to refurbish. This window has a continuous central gasket (sash-frame and central stile).

Table 10 Air leakage rate at 100Pa pressure difference and associated performance class for a reproduction window.

| Name | Location | Test setup | Leakage ( $\text{m}^3/\text{h.m}^2@100\text{Pa}$ ) | Performance class |
|------|----------|------------|----------------------------------------------------|-------------------|
| sREP | Site     | foil       | 14,22                                              | 2                 |

Main conclusions:

- This 'new' window only achieved performance class 2. The leakage rate was similar to the refurbished window with central gasket (aRE2b) and worse than the refurbished window with interior gasket (aRE2b).
- Even though the overall size and composition of this window is similar to the double window (sRE3b), it does differ significantly in terms of section. The

reproduction window only has a single gasket, whereas the new window of aRE2b comprises a central gasket and interior gasket. More importantly, the reproduction window has simple hardware. The new window is fitted with modern hardware, including locking cams, locking pins, corner drives, and therefore features a multi-point locking system.

#### 4.1.4 Pulse test

The conventional blower door test, standardized in EN ISO 9972, remains the reference method for quantifying building airtightness. However, the method requires the installation of a fan in an external opening and measures airflow characteristics under an imposed pressure difference of 50 Pa, which is substantially higher than pressure differences typically experienced under normal operating conditions. The recently developed Pulse test has been proposed as a faster and less invasive alternative. By generating a short pulse of compressed air and analysing the resulting pressure response, the method directly characterises airtightness at low pressure levels that are closer to natural conditions.

This study investigates the applicability of the Pulse method for in-situ airtightness measurements in heritage buildings, with a particular focus on 19th-century townhouses representative of the building stock studied within HeriTACE. Measurements were carried out on both historic and contemporary dwellings to evaluate the robustness of the method across a range of building typologies and airtightness levels. The Pulse method was compared against blower door testing at building scale and, for selected experiments, against component-level measurements using a Lindab Ltest system.

The study addressed the following research questions:

1. To what extent is the Pulse test a practical and reliable method for characterising airtightness at whole-building level?
2. How well do Pulse-test leakage measurements correspond with results obtained using the reference blower door method?
3. Can the Pulse method be used to characterise the airtightness of individual building components, such as windows?

##### 4.1.4.1 Test protocol

The Pulse test was evaluated through an extensive measurement campaign on both historic townhouses and contemporary dwellings. The objective was to assess the practical applicability, repeatability and reproducibility of the method under real field conditions and to compare its performance with established airtightness testing techniques. The measurement protocol was developed to ensure a direct comparison between the Pulse method and reference tests while keeping building conditions identical for both techniques.

To ensure consistency between measurement methods, all buildings were prepared according to the same protocol. Ventilation openings and intentional air transfer devices were sealed, external windows and doors were closed, and all internal doors within the tested volume were opened so that the building acted as a single pressure zone. Mail slots and ventilation grilles were temporarily sealed, while large open fireplaces or chimneys were closed where necessary. The protected volume and envelope area were determined

from building plans or on-site measurements prior to testing. Several buildings were tested under multiple volume configurations, for example by including or excluding basements or attic spaces from the protected volume. This allowed the evaluation of the Pulse method across a range of building sizes and leakage levels while maintaining identical testing conditions for both Pulse and blower door measurements.

The Pulse system was installed inside, the compressed-air vessels were positioned as centrally as possible within the ground-floor space to promote a uniform propagation of the pressure wave throughout the building. To minimise reflections and measurement disturbances, a clearance of at least 1 m was maintained around the vessels. The controller and pressure sensors were positioned outside the direct path of the pressure wave, typically at the maximum cable distance from the air-release vessels. Before each measurement sequence, the system recorded ambient pressure conditions for approximately 30 to 60 seconds in order to characterise background pressure fluctuations caused by wind and stack effect. A short compressed-air pulse of approximately 1.5 to 2 seconds was then released into the building, generating a pressure increase typically between 4 and 10 Pa. Pressure and temperature data were recorded at high frequency throughout the measurement process. The measurement software used the recorded pressure response together with the known volume of compressed air released from the calibrated pressure vessels to determine the leakage coefficient and flow exponent through iterative fitting of the Power Law relationship. The primary output of the method was the leakage flow rate at 4 Pa ( $Q_4$ ), which was subsequently extrapolated to 50 Pa ( $Q_{50}$ ) to enable direct comparison with blower door measurements. For each test configuration, a minimum of three valid Pulse measurements was targeted. Measurements were considered valid only when the resulting flow exponent remained within physically meaningful limits and when the goodness-of-fit of the model exceeded the acceptance threshold implemented by the manufacturer. When a valid result could not be obtained, the equipment position was adjusted and the measurement repeated.

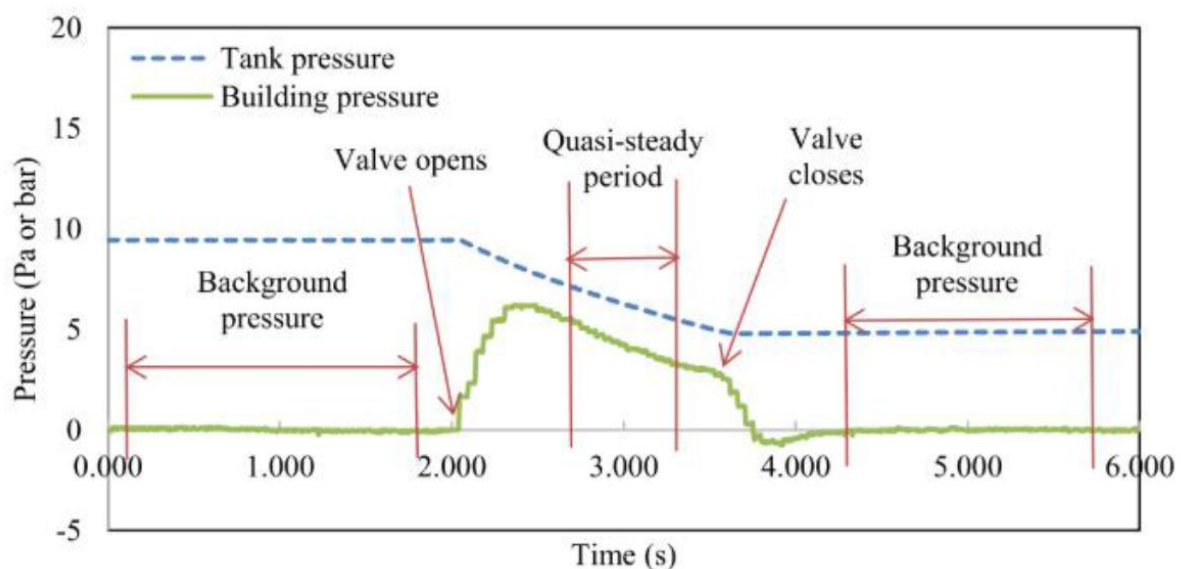


Figure 18 Graphical analysis test method (Zheng et al. 2018)

The performance of the Pulse method was assessed using both quantitative and practical indicators. Quantitative evaluation focused on the repeatability of consecutive Pulse

measurements and on the reproducibility of Pulse-derived leakage rates relative to blower door results. Practical evaluation considered the number of successful measurements obtained, the time required to achieve three valid tests, and the influence of equipment positioning on measurement success. Special attention was given to identifying situations in which the Pulse method experienced difficulties, such as buildings with complex internal layouts, elongated circulation paths or compartmentalised floor plans. The pressure-time response recorded during each test was therefore analysed alongside the calculated leakage rates to better understand the limitations of the method.

#### *4.1.4.2 Tested buildings*

The measurement campaign was carried out on a set of six residential buildings located in Belgium. The sample consisted of three historic townhouses dating from the late nineteenth and early twentieth century and three recently constructed dwellings built after 2010. The inclusion of both building categories enabled the evaluation of the Pulse method across a broad range of airtightness levels, building volumes and geometrical configurations. The historic buildings were representative of the townhouse typology that is common throughout the urban fabric of Ghent and forms an important focus of the HeriTACE project. These buildings are characterised by large protected volumes, multiple floors, central stairwells and a building envelope containing typical leakage paths such as original joinery, chimneys and ageing building fabric. The contemporary dwellings were included to investigate the applicability of the Pulse method in buildings with generally lower leakage rates and different internal layouts. To increase the number of test cases, several buildings were measured under different volume configurations by including or excluding basement and attic spaces from the protected volume. This resulted in a total of ten building-scale test scenarios.

Each building was assigned a unique code. HERT, KONING and VIS refer to historic 19th-century townhouses representative of the heritage building stock investigated within the HeriTACE project, while SCHOOT, GEEL and BAAL refer to contemporary dwellings constructed after 2010. In some buildings, multiple test configurations were evaluated by modifying the protected volume. The designation BASIS refers to the reference configuration, while labels such as KITCHEN and KA indicate alternative configurations in which additional spaces were included in the protected volume. KITCHEN refers to the configuration in which the kitchen was included in the measurement volume, whereas KA refers to the configuration in which both the kitchen and attic space were included. These alternative configurations allowed the Pulse method to be evaluated over a wider range of building volumes and leakage levels.

Protected volumes ranged from approximately 580 m<sup>3</sup> to 950 m<sup>3</sup>, while envelope areas ranged from approximately 470 m<sup>2</sup> to 680 m<sup>2</sup>. All measurements were performed under comparable preparation conditions and in accordance with the measurement protocol described in the previous section. For each test scenario, Pulse measurements were compared directly with reference blower door measurements performed on the same building and under the same boundary conditions.



Figure 19 Setup of pressure vessel and controller to avoid direct interaction

In addition to whole-building testing, a limited number of component-level measurements were performed to investigate whether the Pulse method could isolate the airtightness of individual windows. Two measurements were carried out on a historic timber window and one on a steel-framed window. Results were compared with reference measurements obtained using a Lindab Ltest system at 4 Pa.

#### 4.1.4.3 Results

##### Airtightness characteristics of the tested buildings

Figure 19 provides an overview of the airtightness performance of the tested buildings based on the reference blower door measurements. The results are expressed both as the air permeability at 50 Pa,  $v_{50}$  ( $\text{m}^3/(\text{h}\cdot\text{m}^2)$ ), and as the air change rate at 50 Pa,  $n_{50}$  ( $\text{h}^{-1}$ ). The distinction between the historic townhouses (HERT, KONING and VIS) and the contemporary dwellings (SCHOOT, GEEL and BAAL) is not as clear as anticipated. The historic buildings exhibit slightly higher leakage rates, with  $v_{50}$  values ranging from approximately 5.0 to 8.9  $\text{m}^3/(\text{h}\cdot\text{m}^2)$ , whereas the contemporary dwellings range from 2.6 to 4.0  $\text{m}^3/(\text{h}\cdot\text{m}^2)$ . A similar trend is observed for  $n_{50}$ , which varies between 3.6 and 5.8  $\text{h}^{-1}$  for the historic buildings and between 2.1 and 3.2  $\text{h}^{-1}$  for the contemporary dwellings.

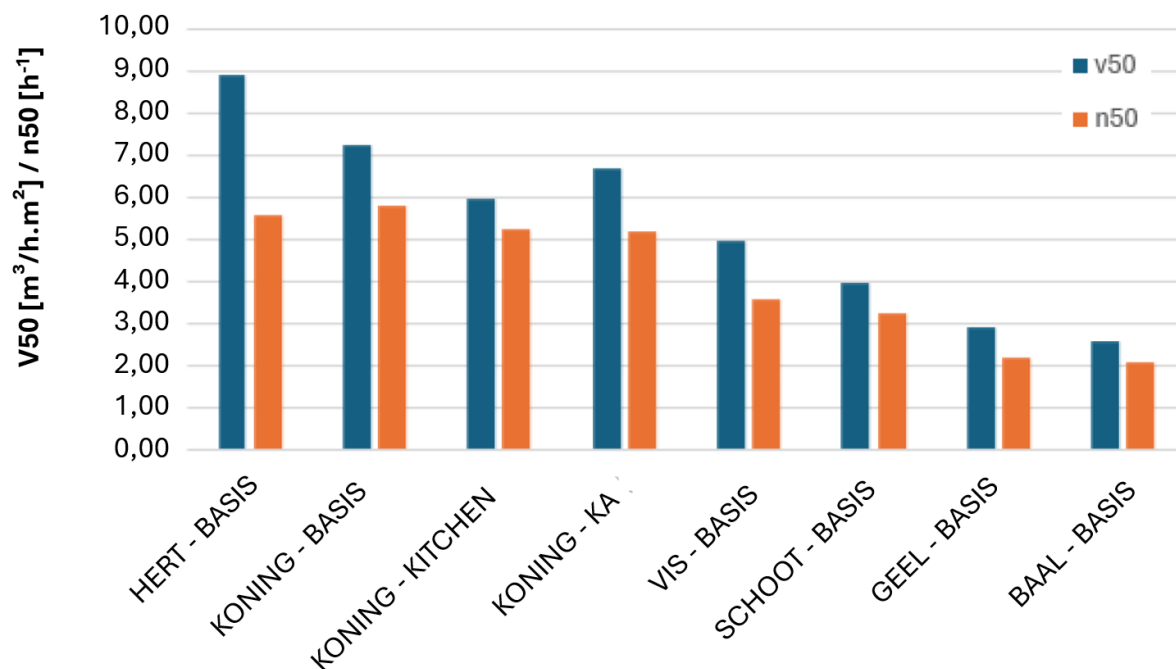


Figure 20 Airtightness measurements on 6 different buildings using the pressurization test

### Repeatability

Repeatability was assessed by comparing consecutive measurements performed under identical conditions within the same building configuration. The blower door test showed excellent repeatability, with an average deviation from the mean of 2.2% and a maximum deviation of 7.1%. The Pulse method exhibited a somewhat larger spread, with an average deviation of 4.8% and a maximum deviation of 12.1%. Despite this higher variability, the results indicate that the Pulse method provides a generally robust and repeatable characterization of building airtightness. No systematic relationship was observed between repeatability and the overall leakage level of the dwelling, suggesting that the method performs similarly across both relatively airtight and more leaky buildings.

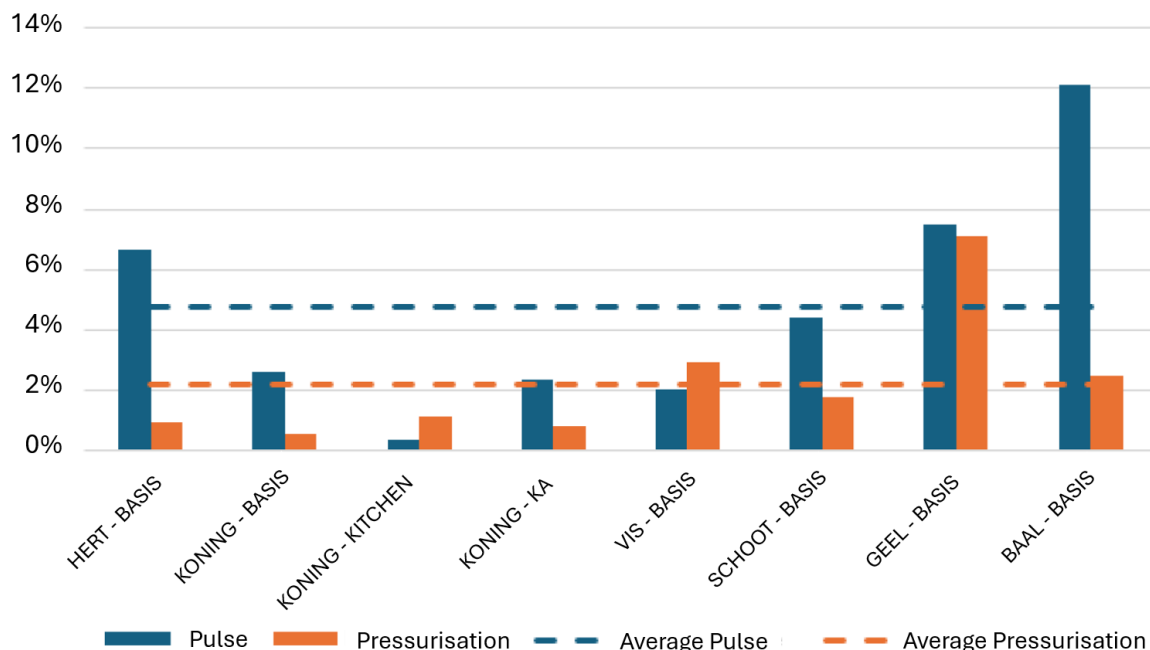


Figure 21 Repeatability and internal variation of pulse test and pressurisation test

### Reproducibility relative to pressurisation test

Reproducibility was evaluated by comparing the Pulse-derived leakage rates, extrapolated to 50 Pa, with the corresponding blower door results. For six of the eight successfully tested building configurations, the difference between both methods remained below 10%, with an average deviation of 5.1%. This demonstrates a generally good agreement between the Pulse method and the established blower door reference procedure. Two buildings, however, showed substantially larger discrepancies, resulting in an overall average deviation of 11.2% when all measurements were considered. Analysis of the corresponding pressure-time curves indicated atypical pressure decay patterns that may be associated with complex internal geometries and non-uniform pressure propagation within the building volume. These findings suggest that building layout may influence the accuracy of the Pulse method and warrant further investigation. Perhaps this may be related to the positioning of the pressure vessel relative to the controller: reflections may have affected the analysis of the pressure wave propagation. In some cases there is no systematic decrease of the pressure after the pulse was generated (see figure 21). The pressure may decrease quickly, followed by a second pressure build-up. Sometimes the airtightness is derived from the first part of the curve, which may not be characteristic of the actual airtightness.

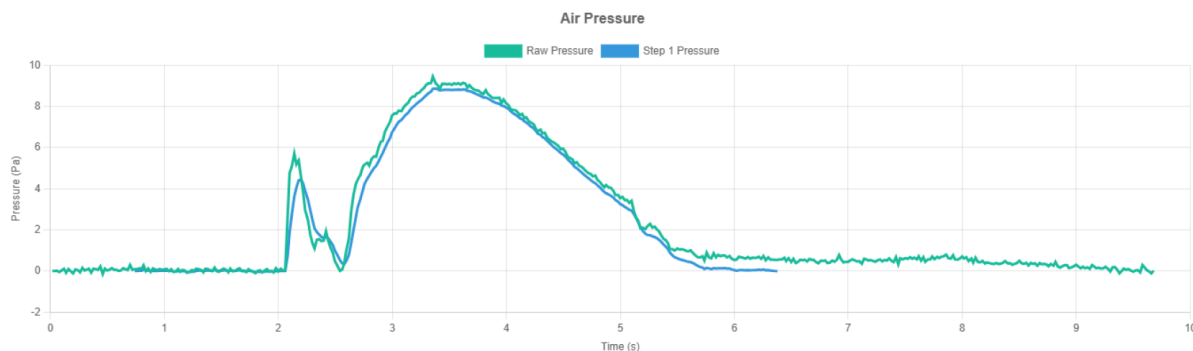


Figure 22 Pressure time series for building BAAL

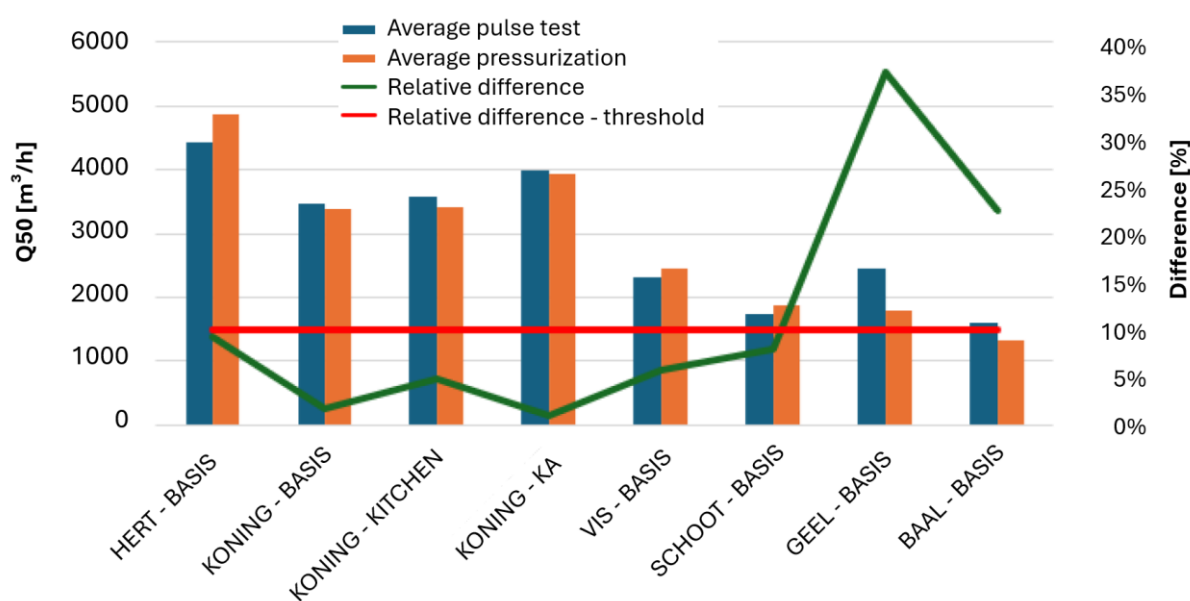


Figure 23 Comparison of pulse tests with pressurization tests

### Practical applicability

From a practical perspective, the Pulse method offers several advantages compared with conventional blower door testing. The equipment is compact, can be positioned within the building, and does not require the installation of a fan system in a door or window opening. Under successful test conditions, the average measurement cycle was slightly shorter than for blower door testing (approximately 12 minutes compared to 14 minutes), while the initial setup time was also reduced.

Despite these advantages, the field campaign revealed a number of practical limitations that currently affect the operational reliability of the method. The overall success rate of the Pulse measurements was approximately 50%, increasing to around 70% when measurements that failed due to technical malfunctions were excluded. By comparison, all blower door measurements were completed successfully.

A substantial fraction of failed Pulse measurements was caused by communication problems between the controller and the pressure vessels. In these cases, the software either reported an "Invalid" result or failed to register a pressure increase despite execution

of the test sequence. These failures occurred independently of the building characteristics and were attributed to communication interruptions between system components. In addition, some tests were affected by freezing of the discharge valve (nozzle) during the rapid release of compressed air. When this occurred, the valve remained open for longer than intended, preventing accurate determination of the injected air volume and rendering the measurement invalid. The pressure vessel then had to warm up and be re-pressurised before testing could resume, increasing the total measurement duration considerably.

Beyond the technical issues, the Pulse method proved highly sensitive to equipment positioning and building geometry. Invalid measurements were frequently associated with poor regression quality ( $R^2 < 0.96$ ) or physically unrealistic flow exponents. In many cases, several equipment locations had to be tested before valid measurements could be obtained. The controller had to be positioned outside the direct influence of pressure-wave reflections, while sufficient clearance was required around the pressure vessels. Consequently, achieving reliable results often required operator experience and multiple trial measurements.

The influence of building geometry was particularly evident in several dwellings where the pressure-time response showed an unusually rapid pressure decay after the initial peak. Buildings with elongated circulation paths, narrow corridors, staircases located at the perimeter of the building, appeared to be more challenging. In such cases, pressure propagation may not have been fully uniform throughout the protected volume, contributing both to measurement failures and to larger deviations from blower door results.

Overall, the field campaign demonstrated that the Pulse method has clear potential as a rapid and non-invasive airtightness testing technique. However, in its current form, the technique remains less robust than conventional blower door testing and is strongly dependent on hardware reliability, equipment positioning, operator expertise and building geometry. Further technical development, particularly regarding communication stability and valve operation, is required before the method can be considered a fully mature alternative for routine testing.

### **Component-level measurements**

A limited number of exploratory measurements were carried out to investigate the feasibility of using the Pulse method for component-level airtightness assessment. The approach consisted of comparing measurements of a room before and after temporarily sealing the tested window with an airtight membrane. The resulting leakage estimates were compared with reference measurements obtained using a Lindab Ltest system at 4 Pa, originally developed for testing the airtightness of ventilation ducts. The results showed large deviations, ranging from 59% to 99%, and in one case even produced a physically impossible outcome in which the room appeared leakier after the window had been sealed. These findings indicate that the differential masking approach is currently unsuitable for accurately isolating the leakage contribution of individual windows. Nevertheless, measurements performed in simple single-room configurations demonstrated excellent reproducibility and a 100% operational success rate, suggesting that the Pulse method itself remains highly reliable in geometrically simple environments. Perhaps the use of the foil on the inside of the window entailed a sudden drop in pressure due to the movement of the foil, in turn yielding a pressure loss that is not realistic.



Figure 24 On site testing of window airtightness using Lindab duct testing equipment

#### 4.1.4.4 Conclusions pulse test

To what extent is the Pulse test a practical and reliable method for characterising airtightness at whole-building level?

The Pulse test proved to be a reasonably reliable method for characterising airtightness at whole-building level. The method showed good repeatability, with an average deviation from the mean of 4.8%, although this was somewhat higher than the 2.2% observed for blower door testing. In practice, the method offered clear advantages in terms of setup and measurement speed. However, the field campaign also revealed substantial practical challenges, including communication failures between hardware components, occasional freezing of discharge valves, sensitivity to equipment positioning, and a relatively low overall success rate. These findings indicate that, while technically promising, the Pulse method is currently less robust than conventional blower door testing and requires careful operation and interpretation of measurement results.

How well do Pulse-test leakage measurements correspond with results obtained using the reference blower door method?

The Pulse method generally showed good agreement with the reference blower door measurements. For six of the eight successfully tested building configurations, the difference between both methods remained below 10%, with an average deviation of 5.1%. This suggests that the Pulse method can provide a reliable estimate of whole-building airtightness under favourable conditions. Larger discrepancies were observed in two buildings with more complex internal geometries, highlighting a possible sensitivity of the method to non-uniform pressure propagation and indicating an area for further research.

Can the Pulse method be used to characterise the airtightness of individual building components, such as windows?

The study found that the Pulse method is currently not suitable for characterising the airtightness of individual building components such as windows using a differential masking approach. Comparisons with reference measurements obtained using the Lindab Ltest revealed large deviations and inconsistent results, primarily due to the influence of the flexible masking membrane and the relatively small leakage contribution of the tested component compared with the overall room leakage. While the Pulse method performed reliably in simple single-room environments, it could not accurately isolate the leakage rate of individual windows.

#### 4.1.5 Conclusions

On site testing of townhouses using a standard pressurization test may allow to quantify the air leakage rate through specific components, if that air flow rate is significantly higher than the measurement uncertainty. For doors and windows frames, it is often challenging to isolate this air leakage during the test by means of foils: continuous visual inspection is required, and as foils are installed on the inside, the building should be put in overpressure to avoid duct tape peeling of during the test. Next to that, it remains difficult to differentiate between the window itself and the window wall interface, as it is not always feasible to install the tape only on the window frame itself. On site testing resulted in performance class 1 and 2 for the windows of 2 town houses, and tests on the front door of 5 town houses indicated that these typically exceed the leakage limit of class 1.

In an optimization study, 24 window configurations of the same window geometry were tested to study the airtightness of original windows, and potential approaches to improve the performance.

Following conclusions were obtained:

- For the leakage rates considered in this study, on site tests with a foil provide a reliable method to quantify the airtightness
- Leakage rates in overpressure and underpressure showed the same trends.
- The original windows entailed an air leakage rate between 15 and 30 m<sup>3</sup>/h.m<sup>2</sup> at 100Pa pressure difference (performance class 1-2).
- Dismantling and transportation of the windows entailed a significant increase in leakage rate: 37-42 m<sup>3</sup>/h.m<sup>2</sup>.
- Standard refurbishment (with gasket) will not lead to improved results: the leakage remained similar.
- Even a new window, replicating the original window configuration, performed only slightly better than the original windows before refurbishment.
- Performance class 4 can be obtained with a double window, as that allows to use modern hardware with a multi-point locking system.

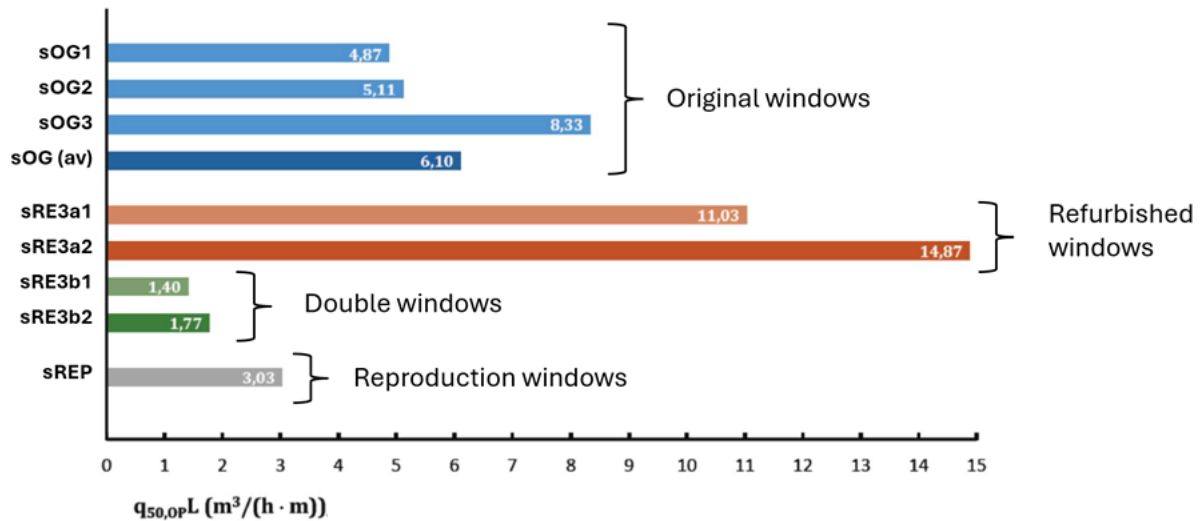


Figure 25 Comparison of air leakage of original, refurbished, and reproduction windows

The research highlights that it is feasible to improve the airtightness of heritage window frames, however;

- Only installing a gasket does not systematically improve the airtightness
- By addressing deformations and checking the actual compression of the gasket the air leakage can be reduced, to obtain better results than the original windows.
- Additional tests showed that the installation of an interior gasket, which allows continuous compression along the perimeter of the sash, allows to obtain performance class 3.

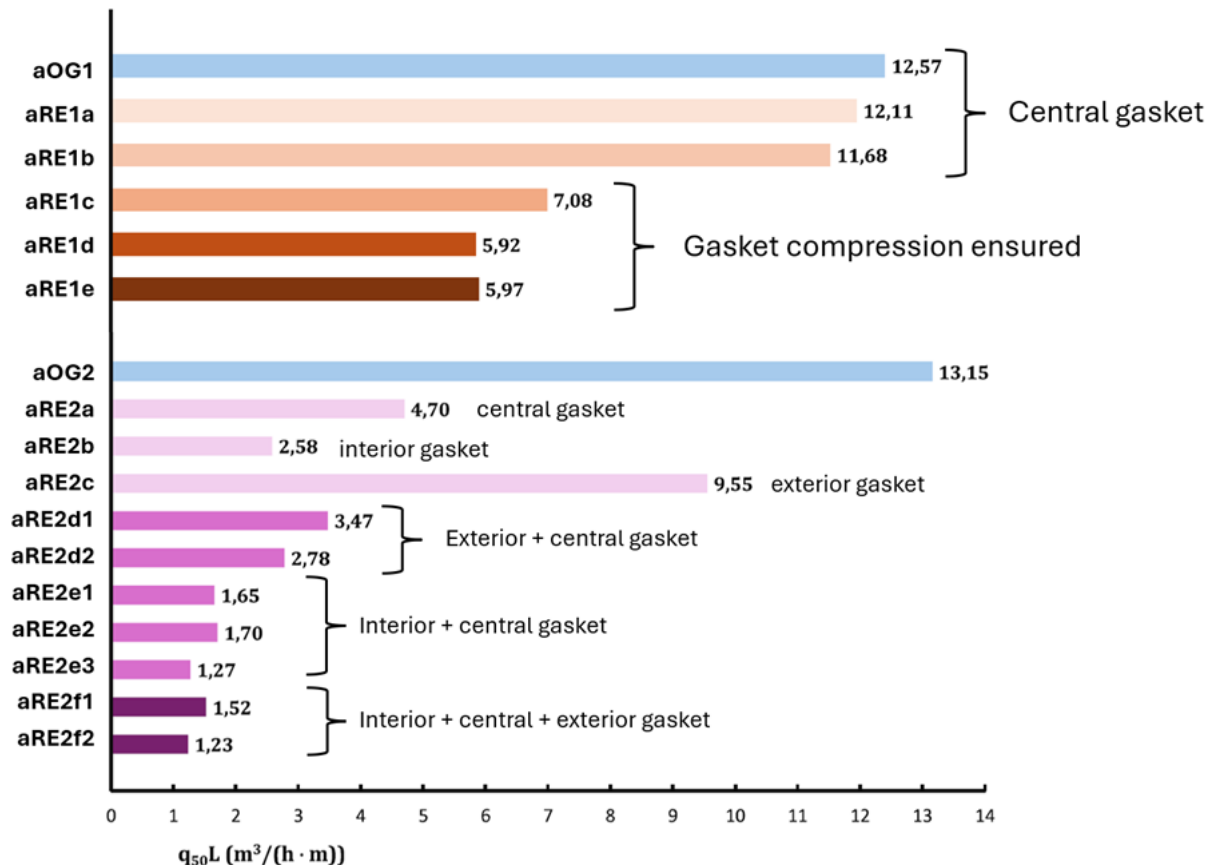


Figure 26 Comparison of different optimization strategies for improving heritage windows

The results indicate that it does not suffice to request the installation of a gasket. When the deformations or tolerances are as extensive as in the windows studied here, the adequate compression of the gasket is not ensured.

Following quality control measures as suggested:

- The gasket needs to be installed both at the perimeter (sash-frame interface) and central stile (frame-frame interface).
- At corners the continuity of the gasket needs to be verified. Welded corners are less susceptible to leaks compared to cut mitre joints.
- The geometric deformation and tolerances must be quantified. A first step in assessing the deformation is measuring out-of-plane deformation. Whether the gasket does make contact can be checked by applying chalk or marker on the gasket and checking for an imprint when opening the window. Also a paper sheet can be placed between the frame and sash to test the sealing pressure.
- Sanding and milling is one approach to address tolerances. Inserting steel plate is more demanding and labor-intensive. Material can be added by means of wood strips, or acryl/epoxy based resins.
- Correcting the geometry by means of hardware is not durable. The continuous stress on the hardware will cause mechanical problems when opening and closing the window, over time leading to damage and incomplete closure of the window, in turn detrimental for the performance.

## 4.2 Estonia

### 4.2.1 General

#### 4.2.1.1 Targeted historic window type

The typical window of the studied Estonian archetypes (see D2.1 and D5.1) of the HeriTACE project consists of double frames both having single pane glazing. Interior frame opens to the inside and the exterior frame to the outside. The interior frames often lack hinges and were originally supposed to be removed for warm seasons.

However, by now – depending on the specific building – modern (from heritage point of view undesirable) windows can significantly outnumber the historic ones. Such modern windows (e.g. PVC or wooden windows with wide frame and uncharacteristic frame distribution) could be replaced in the future, but it would be important to also justify it economically if the new replacement would perform thermally better than the historic types and currently available options. As the protection status of the archetypical buildings usually concerns the exterior, it is possible to improve the thermal performance by replacing the interior frame. It is commonly done by fitting a 2-pane insulated glass unit in the interior frame. However, its performance is limited by the interior frame thickness, as the IGU spacer is quite narrow and the higher performing 3-pane IGU does not fit.

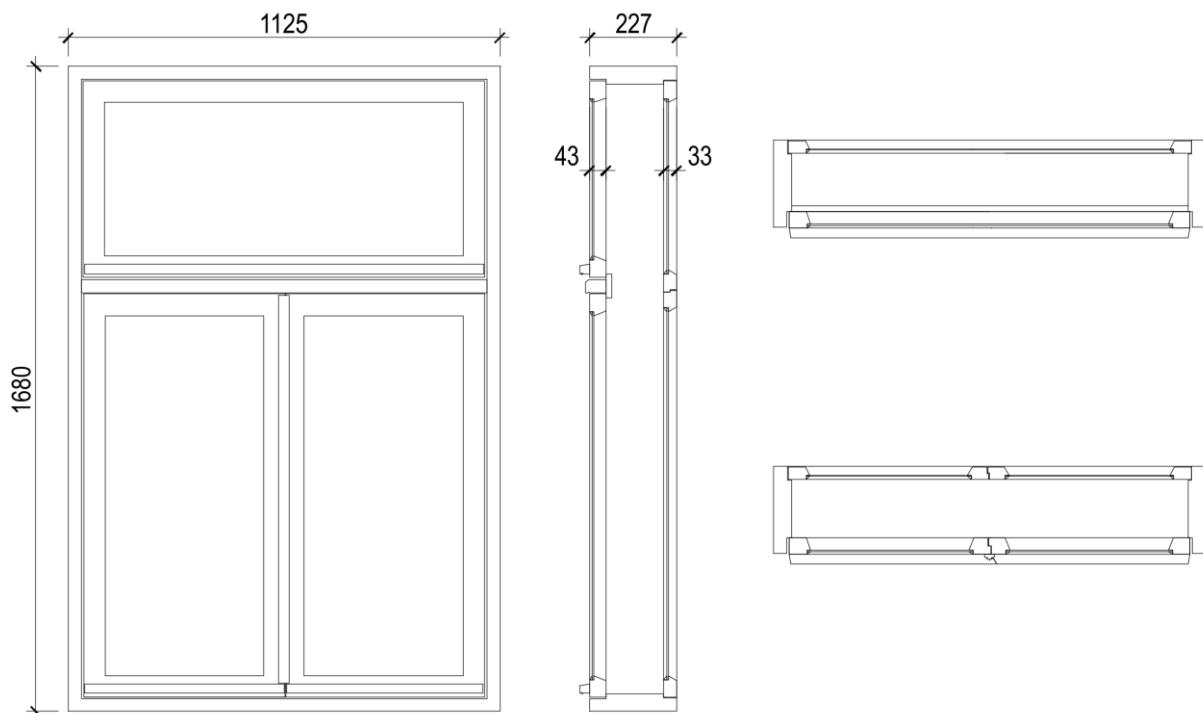


Figure 27 Example of the exterior view (left), vertical section (middle) and horizontal sections (right) of the targeted window type.

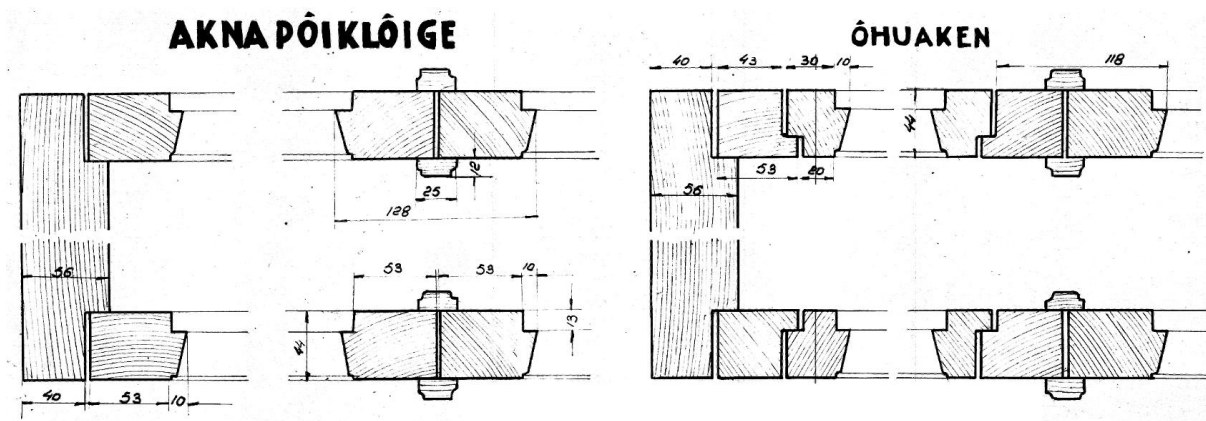


Figure 28 Horizontal sections of Stalinist apartment building windows. The section on the right shows a characteristic smaller window for ventilation purposes.



Figure 29 Examples of different configurations of the targeted window type.

### 4.2.1.2 Energy efficient window prototypes

Here, we prototyped 2 solutions for incorporating a modern 3-pane IGU in the double-frame window while retaining the exterior look. Improved window 1 represents a low profile interior frame where the glazing areas and jamb aligns in both exterior and interior frames. Improved window 2 is possibly more economical option which combines a readily available standard window and part of the historic window (half of the jamb and exterior frame). In the latter case, joining of the two windows could also be achieved by smaller workshops without sophisticated tools.

The prototyped and tested windows were:

1. Historic type window (double frame, 1+1 glass)
2. Standard modern window (single wooden frame, 3 pane IGU)
3. Improved window 1: double frame (3-pane IGU in interior frame, 1-frame in exterior frame)
4. Improved window 2: combination of standard modern window (3-pane IGU) and exterior half of historic window type.

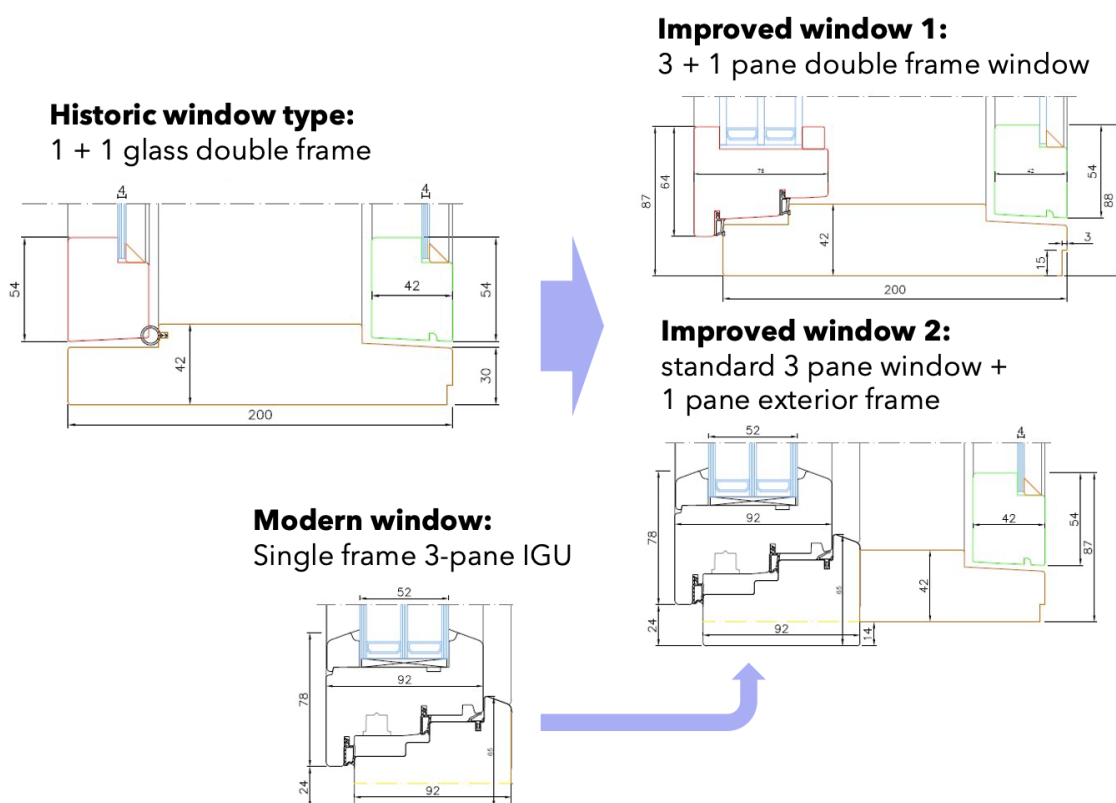


Figure 30 Profiles of the studied historic and improved window prototypes.

Objectives of the studies in Estonia were:

- To measure the as-found baseline airtightness of historic windows and assess the effect of temporary tightening.
- Assess the performance of energy efficient window prototypes.

## 4.2.2 Laboratory studies

### 4.2.2.1 Laboratory airtightness measurements

The lab testing was carried out according to standard EN 1026. Test specimens were fixed into test chamber using wedges, bar clamps and wood. Window - test chamber joint was sealed using appropriate pro clima tapes. Pieces of wood were used to support window from inside and outside to ensure that windows will not move during tests (Figure 31). Prior to testing test chamber and tape air permeability was measured and recorded using airtight window mockup. Test showed that test chamber and tape window mockup average air permeability was  $0.006 \text{ m}^3/(\text{h}\cdot\text{m}^2)$  at 100 Pa pressure difference. Test chamber air permeability is less than 5% of the maximum air permeability permitted throughout the range of the classification that is attributed to the test specimens and will be assumed to be zero.

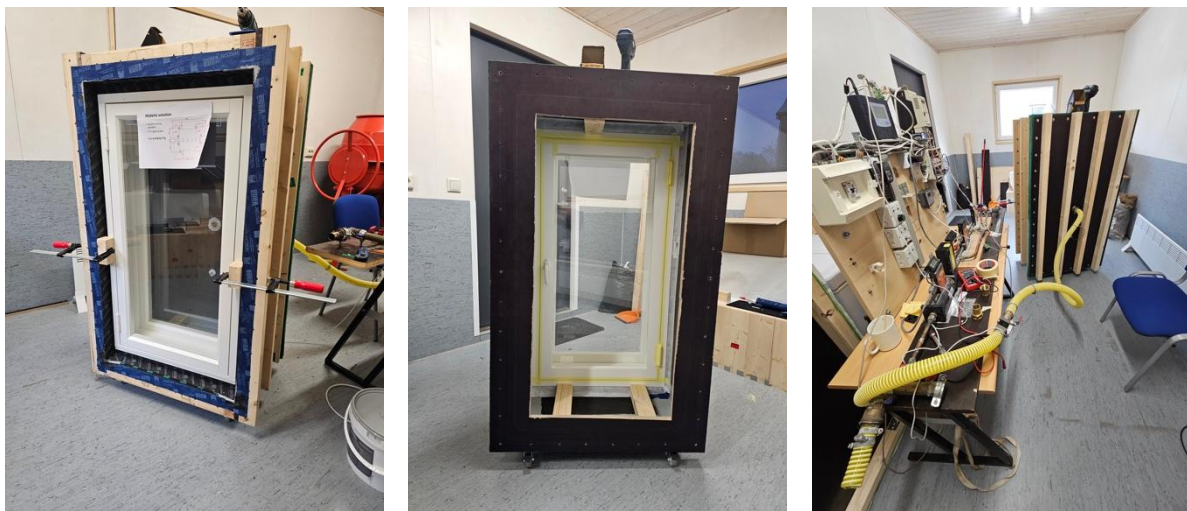


Figure 31 Front view of test chamber with Historic type window fitted and supports (left), back view of test chamber without backplate, paper tape is installed (middle) and test setup (right).

Table 11 Instrumentation used for measuring air leakage rate in lab at TalTech.

| Parameter           | Sensor                           |
|---------------------|----------------------------------|
| <b>Air velocity</b> | Dwyer GFC - 1109 (1 - 5 l/min)   |
|                     | Dwyer GFC - 1131 (0 - 30 l/min)  |
|                     | Dwyer GFC - 1144 (0 - 500 l/min) |
|                     | SMC PMFB7202 (20 - 2000 l/min)   |
| <b>Barometer</b>    | Produal PEL-DK-N                 |

### Historic type window (double frame, 1+1 glass)

Historic type window was tested in 6 different situations: Original seals; Original seals reapplied; Original seals, inside only; Original seals + Tape; D-profile seals and Linen filling. The test specimen was originally fitted with O-profile seals, installed in four sections on the interior frame and three sections on the exterior frame. The sealing methods were selected to represent practical solutions commonly used by building occupants to improve window airtightness.

Test results demonstrate that historic type window can achieve a high level of airtightness and classify as Class 4 window when appropriate sealing method is used. Airtightness

performance is affected by the quality of seal installation, as demonstrated by the difference between “Original seals” and “Original seals reapplied” configuration. Reapplying the original seals reduced air leakage by approximately 54% at a pressure difference of 100 Pa compared with the factory-installed seals.

The use of readily available D-profile seals improved window airtightness by approximately 32% compared to factory-installed seals. The best performance was achieved by applying tape to the window opening joint, which reduced air leakage by approximately 62% compared with the factory-installed seals.

Linen (flax fiber), a traditional material used to fill air gaps, showed the poorest performance (Class 2). The measured air leakage rate was approximately ten times higher than that of the window with factory-installed seals.

In addition to leakage through the gaps, air leakage was also observed around window handle and hinges.

### **Modern window**

Modern window was tested in 5 different situations: Original seals; Original seals + Tape; Original - Outside seals only; Original - Inside seals only; D-profile inside only. The “Original - Inside seal only” and “Original - Outside seal only” configurations were used to simulate complete failure of the exterior and interior seals, respectively, and to evaluate their effect on window airtightness. The original seals consisted of a single continuous seal installed along both the interior and exterior sides of the window frame.

The window showed the best airtightness performance in its factory configuration. Unexpectedly, applying tape to the opening joint resulted in slightly poorer performance than in the original condition. This may have been caused by minor air leakage at the sealing interface between the window and the test chamber. Nevertheless, the window performed as expected and was classified as Class 4.

Simulating complete failure of the exterior and interior seals indicated that the interior seal had a substantially greater influence on the overall airtightness of the window. Removing the exterior seal increased the air leakage rate by 54%. In comparison, removing the interior seal resulted in a 28.7-fold increase in air leakage, from 0.13 to 3.73 m<sup>3</sup>/(h·m<sup>2</sup>) (Class 3). Most of the air leakage was observed around window hinges.

Replacing the interior seal with a D-profile seal, while leaving the exterior seal removed, resulted in 57% poorer airtightness performance compared with the “Original seal – Inside only” configuration. It is important to note that the D-profile seal only barely filled the gap between the frame and sash, which likely limited its effectiveness.

### **Improved window 1**

Improved window 1 was tested in 2 different conditions: Original and Original + Tape. The original seals consisted of a single continuous seals installed along the interior frame and three sections on the exterior frame using O-profile seals.

Test showed that applying tape on the window opening joint improved airtightness by approximately 48%.

In its factory condition, the air leakage is approximately 5 times higher than that of the Modern window (0,6 compared with 0,13 m<sup>3</sup>/(h·m<sup>2</sup>)). However, this difference may have been influenced by the quality of the sealing tape application between the window and the test chamber. Therefore, the two results should not be compared directly.

In addition to air leakage through the gaps, leakage was also detected around the window handle and hinges under the factory-condition test.

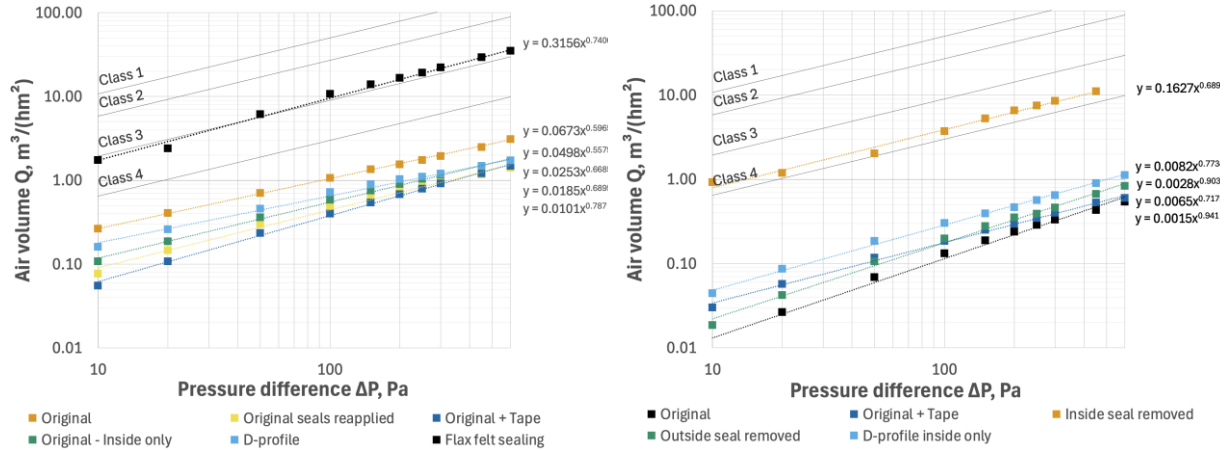


Figure 32 Airtightness measurement results for historic type (left) and modern single frame 3-pane window (right)

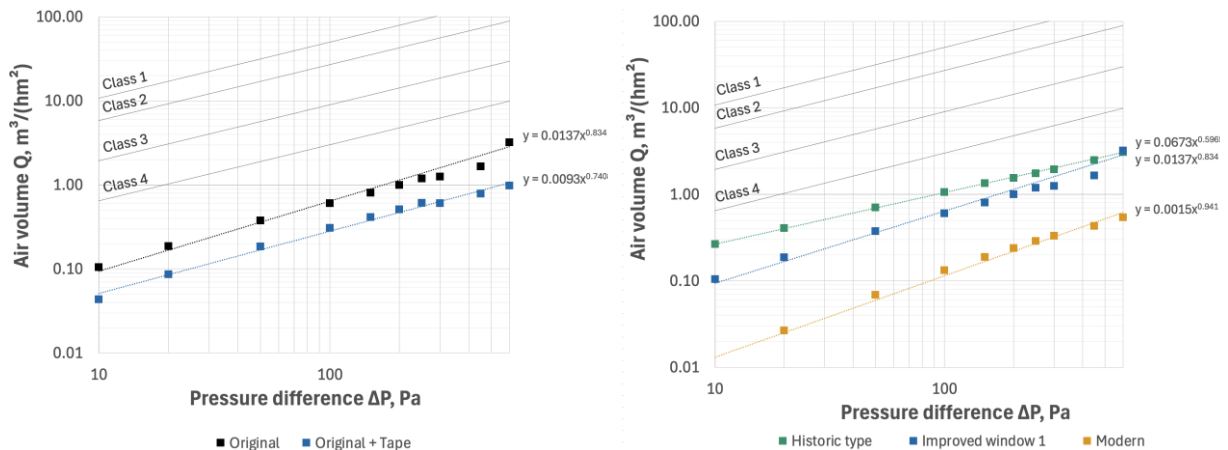


Figure 33 Airtightness measurement results for Improved window 1 (left) and summary of the measurements of windows in their original state (right).

Table 12 Summary of laboratory airtightness measurements of the window prototypes.

| Window            | Sealing method                | $\Delta P, 50 \text{ Pa}$              |                                      | $\Delta P, 100 \text{ Pa}$             |                                      | Class   |
|-------------------|-------------------------------|----------------------------------------|--------------------------------------|----------------------------------------|--------------------------------------|---------|
|                   |                               | $\text{m}^3/(\text{h}\cdot\text{m}^2)$ | $\text{m}^3/(\text{h}\cdot\text{m})$ | $\text{m}^3/(\text{h}\cdot\text{m}^2)$ | $\text{m}^3/(\text{h}\cdot\text{m})$ |         |
| Historic type     | Original seals                | 0.70                                   | 0.15                                 | 1.06                                   | 0.22                                 | Class 4 |
|                   | Original seals reapplied      | 0.30                                   | 0.06                                 | 0.49                                   | 0.10                                 | Class 4 |
|                   | Original seals, inside only   | 0.36                                   | 0.08                                 | 0.58                                   | 0.12                                 | Class 4 |
|                   | Original seals + Tape         | 0.24                                   | 0.05                                 | 0.40                                   | 0.08                                 | Class 4 |
|                   | D-profile seals               | 0.46                                   | 0.10                                 | 0.72                                   | 0.15                                 | Class 4 |
|                   | Linen filling                 | 6.14                                   | 1.30                                 | 10.71                                  | 2.26                                 | Class 2 |
| Modern window     | Original seals                | 0.07                                   | 0.01                                 | 0.13                                   | 0.03                                 | Class 4 |
|                   | Original seals + Tape         | 0.12                                   | 0.02                                 | 0.19                                   | 0.04                                 | Class 4 |
|                   | Original - Outside seals only | 2.03                                   | 0.43                                 | 3.73                                   | 0.79                                 | Class 3 |
|                   | Original - Inside seals only  | 0.11                                   | 0.02                                 | 0.20                                   | 0.04                                 | Class 4 |
|                   | D-profile inside only         | 0.19                                   | 0.04                                 | 0.30                                   | 0.06                                 | Class 4 |
| Improved window 1 | Original                      | 0.38                                   | 0.08                                 | 0.60                                   | 0.13                                 | Class 4 |
|                   | Original + Tape               | 0.18                                   | 0.04                                 | 0.31                                   | 0.06                                 | Class 4 |

## Conclusion

The conducted tests demonstrate that historic-type windows can achieve a high level of airtightness when appropriate sealing solutions are used. The effectiveness of the seals depends both on the type of seal and on the quality of installation. A traditionally used solution, applying tape to the window opening joint for the heating period, can also provide good airtightness performance, but it must be applied carefully. Particular attention should be paid to areas around the window hinges, where achieving a continuous and effective seal can be more difficult. Damaged or missing seals can significantly reduce airtightness performance of a window.

### 4.2.2.1 Thermal transmittance measurements

The thermal performance of the window prototypes was evaluated using a hotbox measurement system (see Table 13 and Figure 34) installed in the nZEB Test Building at TalTech. This setup allowed the windows to be subjected to real outdoor weather conditions while the interior boundary was maintained by a temperature-controlled hotbox, which itself was situated within a separate temperature-controlled room to minimize external thermal interference. The windows were installed within a wall consisting of 200 mm-thick expanded polystyrene (EPS). To calibrate the system and verify the thermal integrity of the installation, reference measurements were performed using a 200 mm EPS block in place of the window opening.

Table 13 Instrumentation used for thermal performance measurement at TalTech.

| Parameter                             | Sensor                                   | Data acquisition                                                      |
|---------------------------------------|------------------------------------------|-----------------------------------------------------------------------|
| <b>Air &amp; surface temperature</b>  | Pt1000                                   | Grant Squirrel SQ2040-2F16, Grant Squirrel SQ2010, Pico PT-104        |
| <b>Heat flux</b>                      | Hukseflux HFP01, greenTEG gSKIN XP 26 9C | Grant Squirrel SQ2040-2F16, Grant Squirrel SQ2010                     |
| <b>Air temperature &amp; humidity</b> | Sensirion SHT35                          | Arduino-based microcontroller, Influx database, Grafana visualization |
| <b>Voltage, current, power</b>        | Texas Instruments INA219                 | Arduino-based microcontroller, Influx database, Grafana visualization |



Figure 34 Windows being tested in the nZEB Test Building of TalTech. Photo from the outside (left) and inside (right): hotbox can be seen installed on the left window, heat flux and temperature sensors are visible on the rightmost window.

The measurements aimed to study the thermal effects of the wide air gap between the window frames and the exterior sealing (to mitigate moisture risks, the bottom exterior seal is omitted). The Improved Window 1 was tested both with and without the exterior frame to quantify the insulating effect of the ca 100 mm air gap. The influence of further sealing the exterior bottom seal was studied on both windows.

Figure 35 presents the measured temperature differences between hotbox-indoor and hotbox-outdoor, while hourly mean thermal transmittances are calculated. To eliminate the influence of solar gains, only data recorded during "night events" (defined as continuous periods of zero solar irradiance) were utilized.

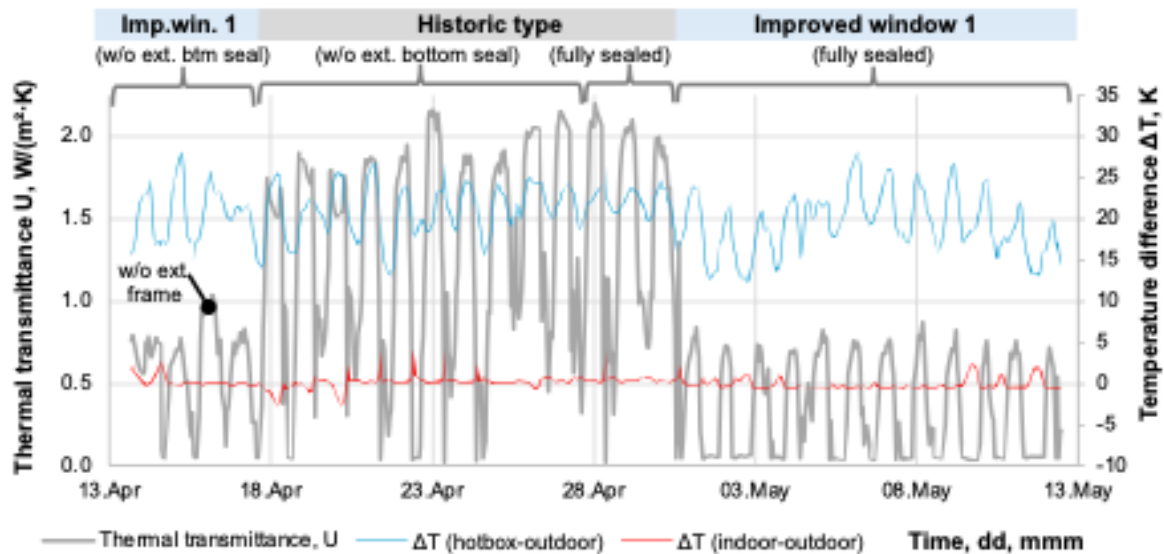


Figure 35 Time series of measured temperature differences and thermal transmittance of different window configurations.

The influence of wind speed is presented in Figure 36. Wind speed affects surface thermal resistances and can increase convective heat transfer in the cavity as the bottom exterior seal is removed. Historic type tests were conducted under higher average wind speeds (1.18-1.60 m/s) compared to the Improved Window 1 tests (0.30-0.48 m/s). The influence of adding the bottom exterior seal does not seem to significantly alter the thermal transmittance as the results without bottom seal fit in the same group as the “fully sealed” measurements. This indicates that omitting the bottom seal to prevent moisture-related issues is a viable strategy that does not severely compromise the overall thermal efficiency.

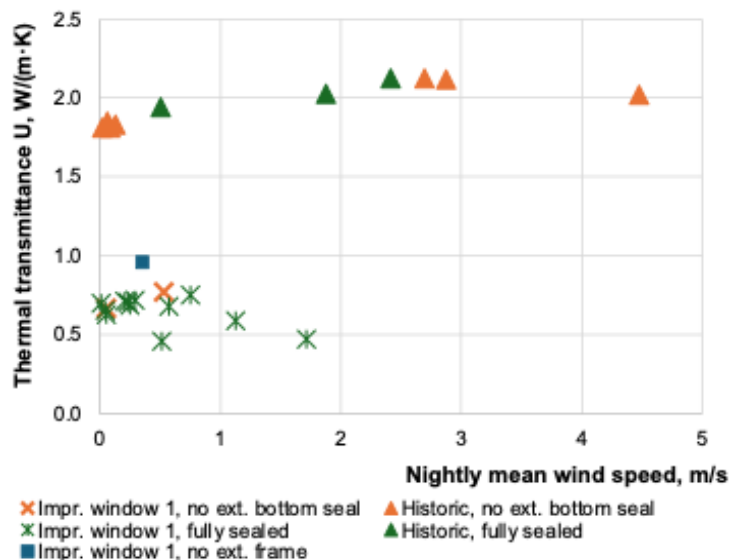


Figure 36 Comparison of nightly mean thermal transmittances dependent on nightly mean wind speeds.

The results of these measurements are further summarized in Table 14. A significant reduction in thermal transmittance was observed when comparing the Historic Type to the Improved Window 1. Even without the benefit of the exterior frame, the Improved Window

1 achieved a U-value of 0.96 W/m<sup>2</sup>·K, representing a nearly 50% improvement over the Historic Type (~1.85 W/m<sup>2</sup>·K). The addition of the exterior frame further reduced the U-value to 0.72 W/m<sup>2</sup>·K, demonstrating that the 100mm air gap provides a significant secondary insulating layer.

Table 14 Summary of thermal performance measurements.

| Window type       | Exterior frame | Ext. frame sealing       | Mean th. transmittance U, W/(m <sup>2</sup> ·K) (±stdev) | Night count | Nightly mean wind speed, m/s (±stdev) |
|-------------------|----------------|--------------------------|----------------------------------------------------------|-------------|---------------------------------------|
| Improved window 1 | No             | -                        | <b>0.96</b>                                              | 1           | 0.36                                  |
|                   | Yes            | W/o exterior bottom seal | <b>0.72 (±0.07)</b>                                      | 2           | 0.3 (±0.33)                           |
|                   | Yes            | Fully sealed             | <b>0.65 (±0.1)</b>                                       | 12          | 0.48 (±0.51)                          |
| Historic type     | Yes            | W/o exterior bottom seal | <b>1.85 (±0.2)</b>                                       | 10          | 1.18 (±1.62)                          |
|                   | Yes            | Fully sealed             | <b>2.03 (±0.09)</b>                                      | 3           | 1.6 (±0.99)                           |

### 4.2.3 On-site measurements

#### 4.2.3.1 General

Field measurements were conducted on 14 windows in 7 buildings. During field measurements technical condition of windows using visual assessment, measured cracks between window frame and jamb joints with leaf caliper and air permeability tests.

#### 4.2.3.2 Technical condition

During visual inspection there were common remarks about windows (Figure 2):

- Missing or malfunctioning fastening elements
- See-through visible cracks
- Not symmetrical window frames and cracks between them. Frame doesn't sit correctly in jamb.



Figure 37 Technical state remarks. See-through cracks (left), missing fastening elements (middle), big gaps between jamb and frame (right)

Since every window is unique, old and handmade - each situation must be viewed separately in the context of preservation and restoration. In ~60% of cases studied it was observed that if the building itself is well-preserved and properly usable and windows are in a proper condition then preserving and restoring should be the first option. But the work

needs to be very precise with both frames and jamb. In the remaining ~40% of cases window replacement is inevitable due to building depreciation what has ended with rotten and crooked window frames and jambs.

#### 4.2.3.3 Air tightness

According to the data measured, not a single window didn't fit into 4 or 3 class and about 50% of cases won't even make to class 2 or 1 (Figure 3).

If windows are tightened and taped, then 46% of windows reach class 4. Therefore, we can say that main leakage comes from between the frame and jamb, not between the frame and glass (Figure 4). The other 54% of windows classify as class 3, 2 or 1 (Figure 3). Higher air permeability on some windows may be caused by tarpaulin placement to the jamb extension rather than window jamb itself, which may lead to excessive measured air permeability between wall and window jamb.

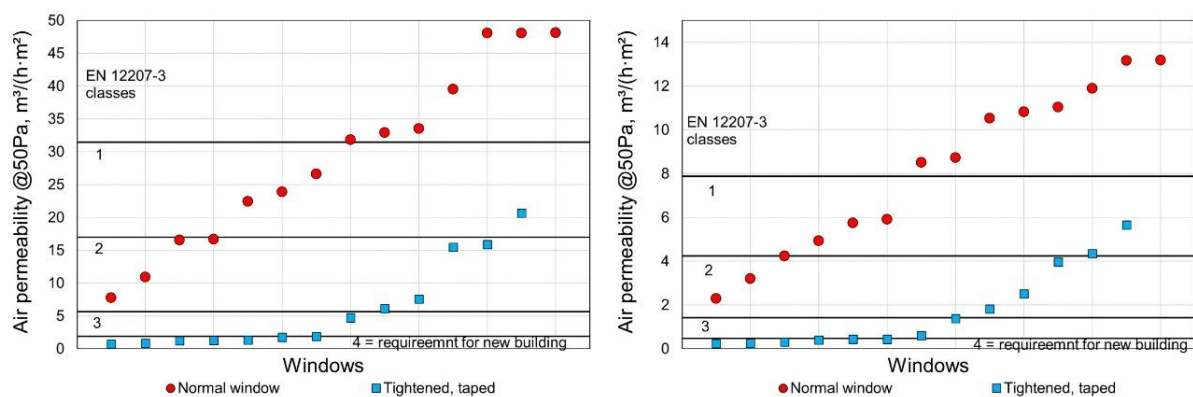


Figure 38 On site test results from Estonia with reference to air permeability related to overall area (left) and opening joint length (right) at 50 Pa pressure difference.



Figure 39 Air permeability at 50 Pa. Original (left) – 32,94 m³/(h·m²). Taped frame-jamb joint (middle) – 1,91 m³/(h·m²). Taped frame-jamb and frame-glass joints – 1,27 m³/(h·m²)

#### 4.2.3.4 Correlating gap width and measured airtightness

To evaluate the airtightness of a window without BlowerDoor test, calculations based on Poiseuille's law were performed. The objective of these calculations is to determine how

closely the calculated results align with measured data and whether this approach could serve as a viable alternative to the time-consuming BlowerDoor method. Air permeability calculation is based on pressure difference between frame and jamb on constant air flow and was calculated by using measured joint data. The calculated results were compared to collected BlowerDoor data of air permeability.

$$r_a = \frac{b^2 * A * \Delta P}{12 * \eta_a * L} \rightarrow \Delta P = \frac{12 * \eta_a * L * r_a}{b^2 * A}$$

Where:

A - crack area (b·d), m<sup>2</sup>

b - crack thickness, m

d - crack width, m

L - crack depth, m

$\eta_a$  - dynamic viscosity of air, Pa·s (N·s/m<sup>2</sup>)

$\Delta P$  - air pressure difference, Pa

$$\Delta P = \frac{(K * \rho * v^2)}{2}$$

Where:

$\rho$  - air density, kg/m<sup>3</sup>

v - air velocity in crack, m/s

K - coefficient

First calculations with 8 windows from 4 buildings show that it is possible to predict the air permeability using measurements of cracks between window frame and jamb (Figure 5). To achieve reliable results, measurements must be precise, as measuring errors as small as - 0.7mm to 0.3mm (Table 15) can alter the calculation outcomes as seen in practice. As previously mentioned, some air permeability measurements also include joints between wall and window jamb, which may distort measurement results and therefore complicate the comparison between calculated and measured data. The accuracy of calculated air permeability compared to measured data is 41% - 142% (Figure 41 & Figure 42). In these calculations there are three calculations that are quite close to measured data, and this gives hope that we can use this method in the future, but this calculation method needs further testing in laboratory to see how reliable it is.



Figure 40 Measuring gap width with leaf caliper.

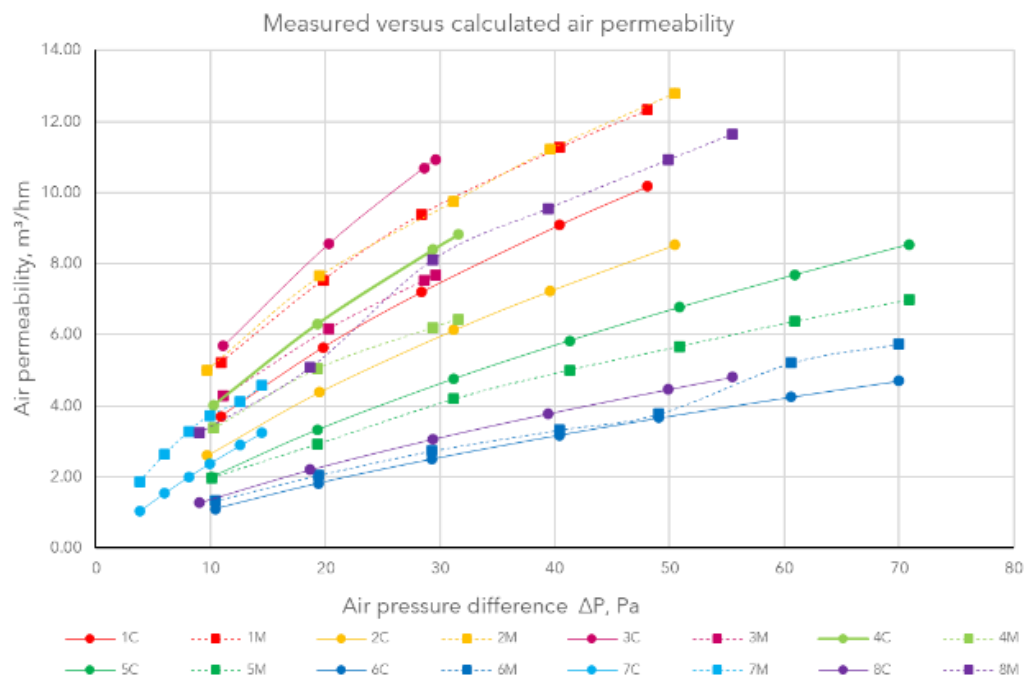


Figure 41 Measured versus calculated air permeability graph over different pressure differences.

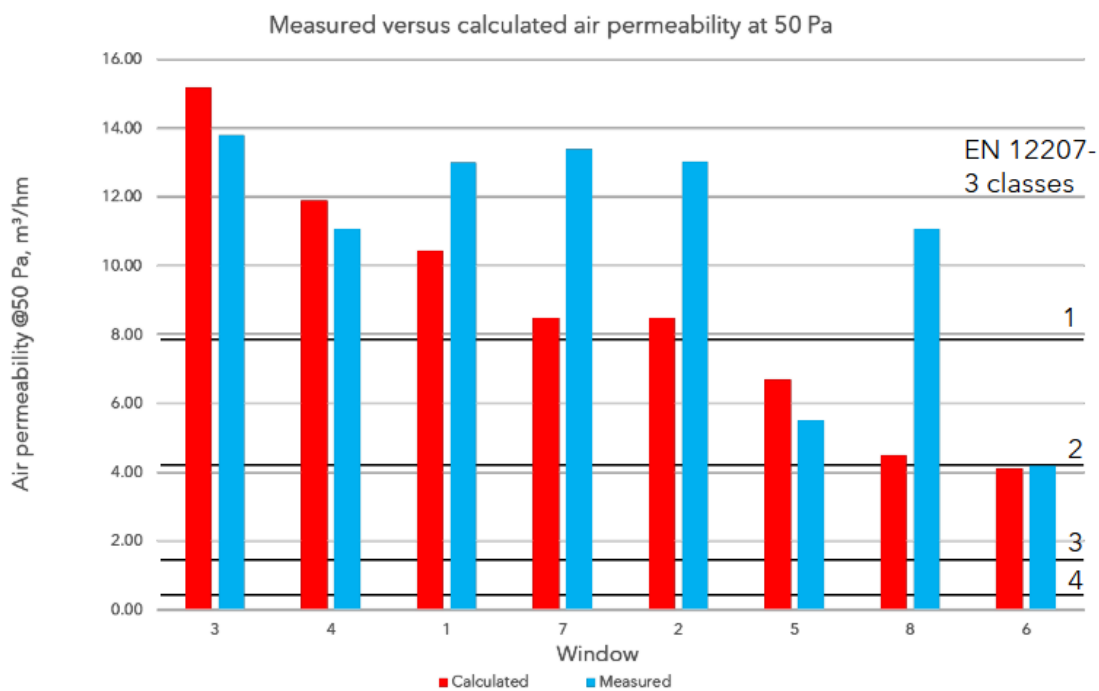


Figure 42 Measured versus calculated air permeability graph at 50 Pa.

Table 15 Average width of measured cracks. The average width of measured cracks is calculated with overall crack area and total crack length.

| Window | Location    | Crack width, mm | Average crack width, mm | Calculated average crack width, mm | Change in crack width in calculations to get measured air permeability |
|--------|-------------|-----------------|-------------------------|------------------------------------|------------------------------------------------------------------------|
| 1      | Outer frame | 0.10-1.80       | 1.26                    | 1.66-1.46                          | +0.2mm                                                                 |
|        | Inner frame | 0.15-1.80       | 1.55                    |                                    |                                                                        |
| 2      | Outer frame | 0.15-1.80       | 1.20                    | 1.70-1.46                          | +0.3mm                                                                 |
|        | Inner frame | 0.20-2.80       | 1.09                    |                                    |                                                                        |
| 3      | Outer frame | 0.30-3.50       | 1.81                    | 1.51-1.38                          | -0.3mm                                                                 |
|        | Inner frame | 0.70-5.40       | 2.39                    |                                    |                                                                        |
| 4      | Outer frame | 0.30-6.00       | 1.66                    | 1.41-1.24                          | -0.2mm                                                                 |
|        | Inner frame | 0.45-4.35       | 2.36                    |                                    |                                                                        |
| 5      | Outer frame | 0.10-2.00       | 0.77                    | 1.15-0.96                          | -0.1mm                                                                 |
|        | Inner frame | 0.80-2.90       | 1.47                    |                                    |                                                                        |
| 6      | Outer frame | 0.10-1.80       | 0.66                    | 0.99-0.89                          | +/-0mm                                                                 |
|        | Inner frame | 0.40-6.00       | 1.13                    |                                    |                                                                        |
| 7      | Outer frame | 0.00-2.00       | 1.08                    | 1.58-1.42                          | +0.2mm                                                                 |
|        | Inner frame | 0.00-2.00       | 0.97                    |                                    |                                                                        |
| 8      | Outer frame | 0.00-3.30       | 1.67                    | 1.45-1.34                          | +0.2mm                                                                 |
|        | Inner frame | 0.40-2.50       | 1.10                    |                                    |                                                                        |

#### 4.2.4 Conclusions

The investigations conducted in Estonia provide insights into the airtightness and thermal performance of historic double-frame windows and possible energy efficient counterparts, which retain their exterior appearance.

On-site inspections and measurements on 14 historic windows in 7 buildings highlighted that ca 40% of studied windows were severely damaged (rotten, deformed). Airtightness measurements showed that no historic windows could be classified to classes 4 or 3 and about 50% failed to reach even the lowest airtightness class 1 in as-found state. If the windows are additionally sealed with temporary tape (as has been traditionally done for heating season), the 46% of windows reach class 4.

The study also explored a non-invasive diagnostic approach by correlating measured crack widths between the frame and jamb with air permeability using Poiseuille's law. Although current calculations ranged between 41% and 142% of the measured BlowerDoor data, the results are encouraging. This suggests that simple geometric measurements may eventually support rapid airtightness assessments, provided that further laboratory validation is conducted to improve the precision and reliability of the method.

Laboratory testing further showed that historic double-frame type windows can achieve high performance levels, including Class 4, when appropriate sealing solutions and

installation quality are prioritized. While using properly fitted seals resulted in low air leakages in class 4, the seasonally applied adhesive tape further enhanced results too, whereas traditional flax felt filling performed poorly. In comparison, modern single-frame windows and the "Improved Window 1" prototype, both featuring 3-pane insulated glass units (IGU), showed superior baseline airtightness. For these modern systems, the interior seal was identified as the dominant factor in overall performance.

Thermal transmittance measurements highlighted a substantial improvement in energy efficiency when transitioning from historic double-frame windows ( $\sim 1.85 \text{ W/m}^2\cdot\text{K}$ ) to the "Improved Window 1" prototype. The double frame window with 3-pane IGU in interior frame achieved thermal transmittance (U) of  $0.72 \text{ W/m}^2\cdot\text{K}$ . Without exterior frame the thermal transmittance was  $0.96 \text{ W/m}^2\cdot\text{K}$ , which also characterizes the performance of a single frame 3-pane IGU window and shows the beneficial value provided by the wide air gap between the double frames of the prototype. Additionally, it was determined that omitting the bottom exterior seal to mitigate moisture risks is a viable strategy that does not severely compromise the overall thermal efficiency.

### 4.3 Italy

The Italian case studies highlight the need for heritage-compatible window improvement strategies that can deliver substantial energy performance gains while reducing the pressure for replacement of original joinery. To this aim within Task 2.5 of HeriTACE measurements were also done on typical Italian windows (even if this was originally not foreseen in the project plan), contributing these to the range of on-site measurements in Belgium and Estonia.

Measurements have been performed (i) on the single renovated windows of the demo case for the archetype “courtyard building” in Mantova, Palazzo Vescovile and (ii) on windows of a building in Bolzano where both renovated and original as well as single and double window configuration was available. Overall measurements on 7 windows in 2 buildings have been performed.

#### 4.3.1 Measurement with Micro Leakage Meter (MLM)

The airtightness was measured with a Micro Leakage Meter (MLM) Measuring System (Blower Door GmbH, 2016) and a spot-made test device around the window. The MLM is often used for tests on duct systems and measures the air flow to the tested component by measuring the pressure difference before and after one of the four disks, each calibrated for a specific pressure difference and air flow range, and can conduct measurements with small air flows of 0.17 to 78.5 m<sup>3</sup>/h and high pressure differentials (up to 250 Pa).



Figure 43 Micro Leakage Meter (MLM) and 4 disks with different size of opening diameter

- 1 Minneapolis Micro Leakage Meter (MLM)
- 2 Connecting hose to the ductwork
- 3 Silicone tube, transparent (10 m) with capillary tube [for determining the pressure in the ventilation duct]
- 4 USB cable [connection DG-700 – laptop]
- 5 Fan control cable [connection DG-700 – fan speed controller]
- 6 Digital pressure gauge DG-700
- 7 Set of silicone tubes, red and blue (3 m each) [connection MLM – DG-700; determining the MLM pressure differential]
- 8 Fan speed controller for DuctBlaster B
- 9 Connecting hose to the DuctBlaster fan
- 10 BlowerDoor fan DuctBlaster B with hose connection plate

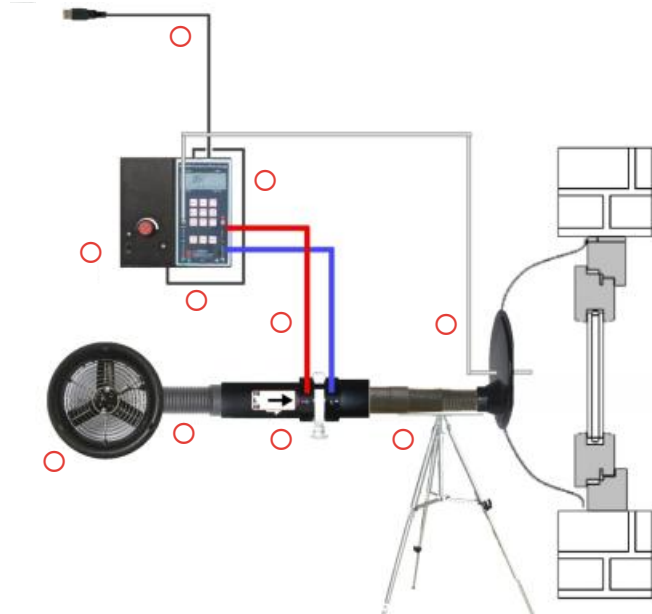


Figure 44 Four disks, calibrated for different pressure differences and volume flows (left) and measurement setup for air-tightness assessment of a component (Blower Dor GmbH, 2016)].

The spot-made device consisted of a plastic sheet, which is attached to the window reveal from the room side, since this is in most cases the logistically easier or even only possible solution. This means that for the inside opening sashes, the measurement under pressure does push the sashes towards the frame, making them potentially more air-tight (closing direction loading, as described in section 4.1.3), while measurement in depression does pull the sashes potentially to open (opening direction loading).

Installing the sheet in the window reveal means that also a potential leakage at connection window-wall and the reveal itself will contribute to the measured air permeability. On the other hand side, an installation of the sheet on the frame itself would have lead to potential obstruction of the air flow, when the sheet would be sucked towards the frame.

The (envisaged) measurement points were 5 Pa, 10 Pa, 14 Pa, 20 Pa, 26 Pa, 37 Pa, 52 Pa, 72 Pa and 100 Pa in accordance to (EN 12114, 2020). The maximum pressure was however not reached, either because of the limited power of the used device or of the limited attachment force of the tape. Maximum pressure difference reached and limiting reason are reported in the following sections together with the results.

The calculation of the air permeability a 50Pa was made using proprietary software TECLOG4, which follows (EN ISO 9972, 2018) allows to correct for the respective temperature and pressure and determines the air permeability with respective uncertainty. The Length of Opening Joints and the Overall Area for the normalisation of the measured air flow to the window size are determined according (EN 1026, 2016) and the classification of windows follows (EN 12207, 2017).

#### 4.3.2 On-site measurement of the single windows at Palazzo Vescovile

The studied windows at Palazzo Vescovile are reconstructions of the single windows, with insulation glazing. They have a size of nearly 4.5 m<sup>2</sup> - with an approximative width of 1.4 m and a height of 3.2 m. The length of joints according EN 1026 results in 14.8 m. The

windows do have a wooden cladding of the reveal which includes also interior shutters. The closure of the latter does not seem airtight, the gaps all around amount to 5 to 10 mm.



Figure 45 Case study Palazzo Vescovile

For a good attachment of the tape, the foil was attached to the wooden reveal.

All tests have been done with closed exterior shutters. Figure 46 shows that these are the typical Italian style with lamellas and considerable open space. As regards the interior wooden shutters, the test has first been performed with shutters. For a second test the interior shutters have been opened - not completely as this would have meant finding a new position for the foil, but with an opening distance of ~200mm in the middle between the two shutters.



Figure 46 Air-tightness measurement build up at Palazzo Vescovile and detail of window showing double glazing and exterior shutters

The measurement with closed interior shutters was performed in depression and pressure leading to a measured air leakage of  $136 \text{ m}^3/\text{h} @ 50 \text{ Pa} \pm 1.4\%$  leading to  $30.4 \text{ m}^3/\text{hm}^2$  resp.  $9.2 \text{ m}^3/\text{hm}$  for depression (i.e. opening direction loading) and  $129 \text{ m}^3/\text{h} @ 50 \text{ Pa} \pm 3.7\%$  leading to  $28.8 \text{ m}^3/\text{hm}^2$  resp.  $8.7 \text{ m}^3/\text{hm}$  for pressurization (i.e. closing direction loading). With open interior shutters the air leakage increases from 136 to  $149 \text{ m}^3/\text{h} @ 50 \text{ Pa} \pm 11.6\%$  corresponding to  $33.3 \text{ m}^3/\text{hm}^2$  resp.  $10.1 \text{ m}^3/\text{hm}$  for depression. Due to time constraints the measurement with open interior shutters was only performed in depression. The above values for 50 Pa have been extrapolated from the measured values, which due to the limited

power of the fan did reach a maximum of 25 Pa respectively 20 Pa. The IR image in Figure 47 shows the air entering all around the shutters and their opening position.

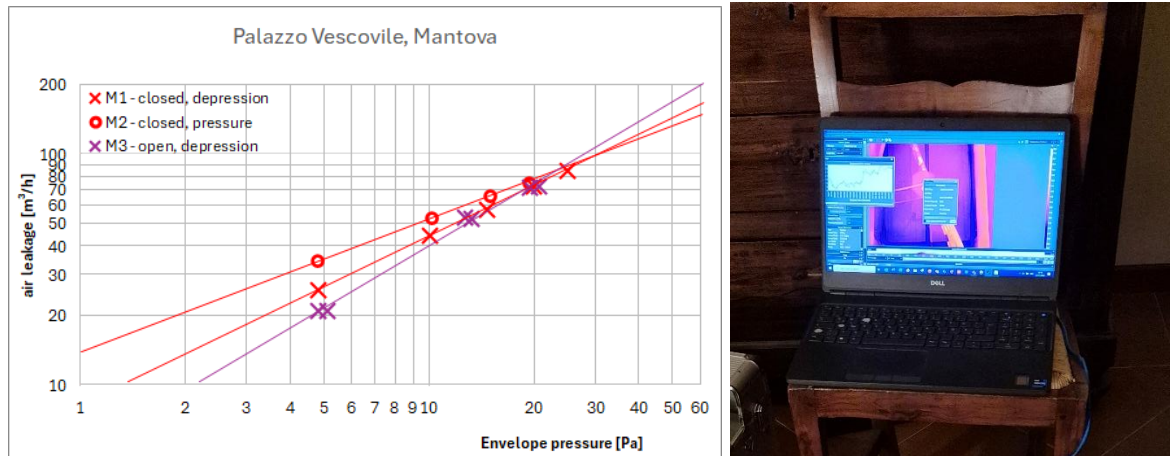


Figure 47 Results of air-tightness measurement at Palazzo Vescovile and IR thermography of the window in open position of the interior shutters

While with closed shutters, the results lead to a classification to class 1 – since the measurement normalised to the surface do not exceed  $31.5 \text{ m}^3/\text{hm}^2$ , with shutters open the limit is exceeded and the window should be classified as class 0, outside the classes defined by EN ISO 12207. With normalization to opening lengths all measurements exceed the limit for class 1 and would result in class 0. The standard, however, explicitly says in clause 4.7 that if the two normalizations give adjacent classes, the specimen shall be classified in the more favorable class is taken.

Table 16 On-site airtightness measurements at palazzo Vescovile, Mantova/IT.

| Window            | shutter        |     | $\Delta P, 50 \text{ Pa}$                |       |                                        |       | Class   |
|-------------------|----------------|-----|------------------------------------------|-------|----------------------------------------|-------|---------|
|                   |                |     | $\text{m}^3/(\text{h} \cdot \text{m}^2)$ | class | $\text{m}^3/(\text{h} \cdot \text{m})$ | class |         |
| Palazzo Vescovile | shutter closed | dep | 30.4                                     | 1     | 9.2                                    | 0     | Class 1 |
|                   | shutter closed | pre | 28.8                                     | 1     | 8.7                                    | 0     | Class 1 |
|                   | shutter open   | dep | 33.3                                     | 0     | 10.1                                   | 0     | Class 0 |

### 4.3.3 On-site measurements of windows with Interlocking rebate (Wolfsrachen)

The Railway Workers House in Bolzano/IT dates from the 1920ies and was constructed by the Italian Railways for their employees when South Tyrol became part of Italy after the First World War. Several construction techniques are typical rather for Norther Italian tradition than for South Tyrol – so is the interlocking rebate (Wolfsrachen; see Figure 48 and Figure 49).

The windows in the flat on 3<sup>rd</sup> floor marked in Figure 48 had been refurbished in 2017: Besides improving them energetically with replacing the single glass in the inner layer with double glazing, an important aspect was that the distorted frames were repaired. The air-

tightness measurements were done in spring 2024, seven years after the retrofit of the windows.

The windows in the flat on ground floor on the other hand side have not yet been repaired and since the flat had not been in use for more than five years they are actually in a bad state (even if less distorted than the one in the above flat before retrofit).



Figure 48 Railway Workers House in Bolzano/IT, with indication of the measured windows. Photos of the refurbished window with “Wolfsrachen” and the sealing of the inner window.

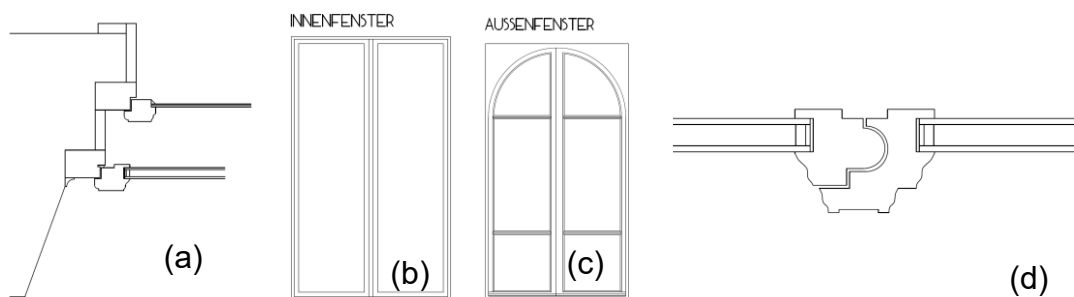


Figure 49 Section of the box type window (a) after retrofit, (b) elevation of the inner window and (c) of the outer window, and (d) interlocking rebate (Wolfsrachen)

In the upper flat three double windows were measured and two single windows (the window in the kitchen and in the bathroom). The double windows do have the sealing in the inner window. All windows except the one in the bathroom do have a size of 2m<sup>2</sup> and joint length of 7.4 m. The measured air-leakage amounts to 5.15 m<sup>3</sup>/h ±3.7% @50Pa for the south window in room2 in depression and 8.33 m<sup>3</sup>/h ±1.7% @50Pa for the second window in the same room. In the first measurement we reached 70 Pa, in the second 50 Pa with Disk 2 and unfortunately due to operator inexperience we did not change to disk 1 which could have allowed to go to even higher pressure difference. The measurement of the second window under pressurization lead to 13.9 m<sup>3</sup>/h ±45.6% @50Pa - limiting factor was in this case the tape detaching at a pressure above 30 Pa. Measurements on the window in room 3 were done by students, and show with 8.5 m<sup>3</sup>/h ±67% @50Pa in depression and 7.5 m<sup>3</sup>/h ±22% @50Pa under pressure more uncertainty (less measurement points, inexperience), but still values which ly in the same order than the measurements in room 2. The air-leakage of the kitchen window, which is a single window, amounts to 11.3 m<sup>3</sup>/h ±3.2% @50Pa for depression. Maximum pressure reaches 30 Pa after which detachment of the tape was observed. Measure under pressure was omitted due to time constraints and the even worse experience with detaching tape in this condition. In the bathroom the air leakage measured in depression amounts to 40.29 m<sup>3</sup>/h ±12.2% @50Pa. This higher value is in line with

observed larger crack width (due to distortion). The results normalized to  $\text{m}^2$  window area and  $\text{m}$  joint length are reported in Table 17.

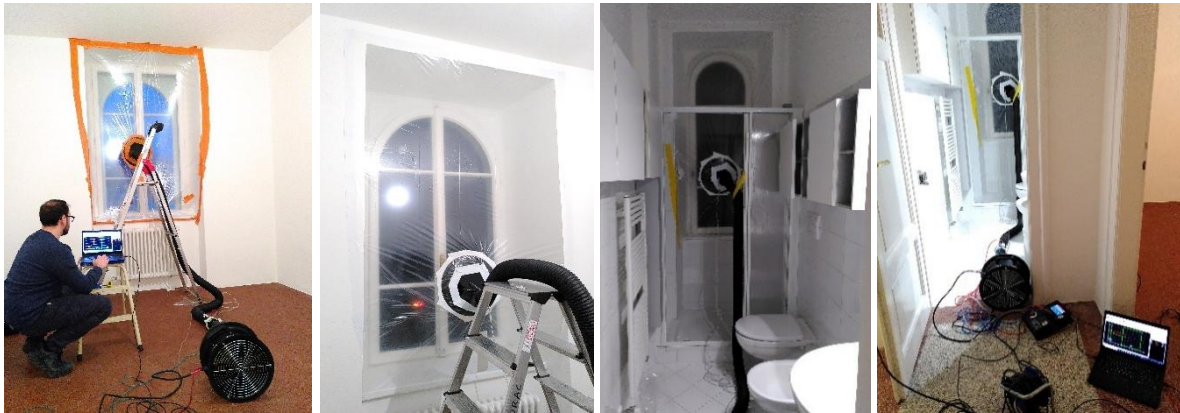


Figure 50 Air-tightness measurement build up at Railway Workers House, Bolzano/IT

In the ground floor flat, the double window was first measured with both windows closed and for a second measurement the inner windows were opened (similar to how the shutters were opened in the case of Palazzo Vescovile in Mantova). In both cases the measured air leaking is very high:  $188 \text{ m}^3/\text{h} \pm 2.4\% @50\text{Pa}$  for depression and  $203 \text{ m}^3/\text{h} \pm 21.9\% @50\text{Pa}$  under pressure for both window layers closed resp.  $248 \text{ m}^3/\text{h} \pm 3.4\% @50\text{Pa}$  for depression for only the outer window closed. The pressure reachable was limited by the for this case too small power of the fan to 14 resp. 10 Pa. The lowest pressure was thus reduced to 4 resp. 2.3 Pa and more interim points were measured in order to increase reliability.

Table 17 On-site airtightness measurements at Railway Workers House, Bolzano/IT.

| Window           | single/<br>double | retrofit<br>or not |     | max<br>$\Delta P$ | n° | $\Delta P, 50 \text{ Pa}$                |       |                                        |       | Class   |
|------------------|-------------------|--------------------|-----|-------------------|----|------------------------------------------|-------|----------------------------------------|-------|---------|
|                  |                   |                    |     |                   |    | $\text{m}^3/(\text{h} \cdot \text{m}^2)$ | class | $\text{m}^3/(\text{h} \cdot \text{m})$ | class |         |
| room 2,<br>south | double            | retrofit           | dep | 70                | 5  | 2.63                                     | 3     | 0.69                                   | 3     | Class 3 |
|                  |                   |                    | pre |                   |    |                                          |       |                                        |       |         |
| room 2,<br>east  | double            | retrofit           | dep | 50                | 5  | 4.25                                     | 3     | 1.12                                   | 3     | Class 3 |
|                  |                   |                    | pre | 30                | 3  | 5.9                                      | 2     | 1.56                                   | 2     | Class 3 |
| room 3           | double            | retrofit           | dep | 20                | 3  | 4.3                                      | 3     | 1.13                                   | 3     | Class 3 |
|                  |                   |                    | pre | 20                | 4  | 3.8                                      | 3     | 1.01                                   | 3     | Class 3 |
| kitchen          | single            | retrofit           | dep | 28.5              | 5  | 5.74                                     | 2     | 1.52                                   | 2     | Class 2 |
|                  |                   |                    | pre |                   |    |                                          |       |                                        |       |         |
| bathroom         | single            | retrofit           | dep | 11                | 3  | 32                                       | 0     | 8.25                                   | 0     | Class 0 |
|                  |                   |                    | pre |                   |    |                                          |       |                                        |       |         |
| ground<br>floor  | double            | no                 | dep | 14                | 4  | 96                                       | 0     | 25.3                                   | 0     | Class 0 |
|                  |                   |                    | pre | 10                | 5  | 103                                      | 0     | 27.3                                   | 0     | Class 0 |
|                  | single            | no                 | dep | 10                | 5  | 126                                      | 0     | 33.4                                   | 0     | Class 0 |
|                  |                   |                    | pre |                   |    |                                          |       |                                        |       |         |



Figure 51 Practical aspect: Transport of MLM equipment with bike trailer is possible

#### 4.3.4 Conclusions

The investigations in Italy, which originally were not foreseen in the project plan, complement the measurements done in Belgium and Estonia.

They enrich the data basis on “measured airtightness” of historic windows with 7 windows in two different buildings.

The measurements confirm that with retrofitted windows with sealing good air-tightness class can be reached – class 3 for the double windows, class 2 for the single window in this case.

The retrofitted window at Palazzo Vescovile just reaching class 1 with closed shutters shows however also, that the sealing has to be well done and maintained. The not retrofitted window in bad state shows as expected the highest leakage – clearly beyond that at Palazzo Vescovile.

The testing method with MLM has proven to be well implementable with some limits: the transport of the equipment to the site does not need particular means, the measurement can also be done on windows of buildings in use without too much hassle for the tenants. Limiting factors are (i) the maximum power of the here used fan – especially for big and leaky windows (Palazzo Vescovile, not retrofitted window at Railway Workers house) and (ii) the observed detachment of the tape especially with measurement under pressure. Attachment was more stable when done on the wall and not in the window reveal. This led, however to a bigger air volume between foil and window and the need to approach the next pressure point gradually and very carefully with manual operation of the equipment.

## 5. Conclusions

This deliverable investigated the airtightness performance of historic windows and the potential for improving their energy efficiency while preserving heritage values. The research combined literature review, laboratory testing, on-site measurements and exploratory investigations of alternative testing methodologies across the Belgian, Estonian and Italian case studies.

The results demonstrate that historic windows are indeed an important source of air leakage in heritage buildings. However, the performance of existing windows varies substantially depending on construction type, maintenance state, geometric deformations and previous renovation interventions. Whole-building measurements showed that uncontrolled air leakage through windows and doors can represent a significant share of the total envelope leakage and should therefore be considered explicitly in energy assessments and renovation strategies.

A key finding of this research is that airtightness improvements cannot be achieved reliably through the installation of gaskets alone. The effectiveness of sealing systems depends strongly on the geometric quality of the frame and sash and on the ability to maintain continuous gasket compression. In many historic windows, long-term deformation and accumulated tolerances exceed the compression range of conventional gaskets, limiting their effectiveness. Consequently, the correction of geometric imperfections through careful restoration works is often a prerequisite for successful airtightness improvement.

The experimental investigations showed that heritage windows can be upgraded significantly without replacing the original joinery. Continuous interior sealing systems proved particularly effective and enabled performance levels corresponding to class 3 according to EN 12207. Even higher performance levels can be achieved through double-window solutions that combine the preservation of the original exterior appearance with modern airtightness technologies. By contrast, standard refurbishment approaches based solely on installing a central gasket generally yielded only limited improvements, and newly manufactured replica windows did not automatically outperform carefully restored originals.

The findings from Estonia further underline the importance of considering the entire window assembly rather than only the operable sash. Field measurements showed that leakage through frame-to-wall interfaces may constitute a major share of the total air leakage, while ca 50% of the studied historic windows failed to meet even class 1 airtightness levels. Simple seasonal sealing measures at these interfaces sometimes resulted in dramatic improvements in measured airtightness. At the same time, the Estonian studies demonstrated that upgrading historic double-window systems can provide 2-2.5x reduction in thermal transmittance while maintaining the architectural character of the original façade.

The Italian case studies confirmed that window replacement remains common practice in many heritage buildings, often driven by thermal performance considerations rather than airtightness concerns. The review of existing window typologies and measured building airtightness indicates that a wide range of performance levels exists within the historic building stock and that heritage-compatible improvement solutions deserve greater consideration as alternatives to full replacement.

The deliverable also evaluated the applicability of the Pulse test as a rapid alternative to conventional pressurisation testing. At building scale, the method demonstrated promising results, with generally good agreement with blower door measurements under favourable conditions. Nevertheless, practical challenges related to hardware reliability, building geometry and pressure-wave propagation currently limit its robustness. For component-level assessment of windows, no reliable methodology could be established within the scope of this work, indicating that further methodological development is required before Pulse testing can be applied to window airtightness evaluations.

Overall, the research demonstrates that substantial energy-performance improvements are possible while retaining historic windows and preserving heritage value. The results challenge the widespread assumption that window replacement is necessary to achieve significant airtightness improvements. Instead, carefully designed refurbishment strategies that address geometric tolerances, sealing continuity and frame-to-wall interfaces can achieve substantial reductions in air leakage while maintaining the authenticity and cultural significance of historic buildings.

The outcomes of this deliverable provide important input for the subsequent HeriTACE activities, including building energy simulations, baseline scenario development, assessment of renovation packages and the formulation of technical guidance for heritage-sensitive building envelope interventions. The results support the broader objective of the project to reconcile heritage conservation and climate neutrality by demonstrating that significant improvements in building performance can be achieved without compromising historic character.

# Bibliography

## Project deliverables

- D2.1** Building envelope characteristics. <https://zenodo.org/records/15656118>
- D2.2** Energy conservation measures inventory. <https://zenodo.org/records/15364987>
- D3.1** HVAC concepts for heritage buildings. <https://zenodo.org/records/15365094>
- D3.2** Comfort and IAQ in heritage townhouses. <https://zenodo.org/records/15640388>
- D4.1** R<sup>2</sup>ES-based energy supply concepts for heritage buildings in historical neighbourhoods. <https://zenodo.org/records/15656204>
- D5.1** Case-study selection at building and neighbourhood levels. <https://zenodo.org/records/15365504>
- D5.2** Cultural heritage analysis and value assessment. <https://zenodo.org/records/15656263>
- D5.3** Cultural heritage building user and owner perspectives. <https://zenodo.org/records/15656286>
- D5.4** Baseline scenarios. <https://zenodo.org/records/15656310>
- D5.5** Map of KPI. <https://zenodo.org/records/15656336>

## References

- ASHRAE Fundamentals Handbook, Chapter 23 “Infiltration and ventilation”, American Society of Heating, Refrigeration and Air Conditioning Engineers Inc., Atlanta, US, 1993.
- A.W. Lawson, M.S. Andrew, V. Andrade, Performance of timber windows. Technical Record 478. Experimental Building Station, Department of Transport and Construction, North Ryde, Australia, 1982.
- Blower Door GmbH (2016). Blower Door Reference Guide. Minneapolis Micro Leakage Meter – Air tightness testing of ventilation duct systems according EN 12599
- O. Daoud, G. Maheshwari, H. Al-Shami, Measured field performance of aluminum windows in Kuwait, Energy and Buildings 17 (1991) 75-85.
- J.F.S. Carruthers, C.J. Newman, The repeatability and reproducibility of test results on windows and wall span elements and the expected results. Paul Rousseau symposium on the testing of wall elements and windows, Vilvorde, Belgium, 1977.
- M. Orme, N. Leksmomo, AIVC Guide 5 – Ventilation modeling data guide. AIVC, Brussels, Belgium, 2002.
- M. Dalaker, Gaskets in window joints, CIB Report No. 11 Weathertight joints for walls. Norwegian Building Institute, Oslo, Norway, 1986.
- T.F. Provan, J.D. Younger, Air infiltration characteristics of windows. Energy and Buildings 9 (1986) 281-292.
- Van Den Bossche N., Janssens A., 2016. Airtightness and watertightness of window frames: Comparison of performance and requirements. Building and Environment 110 (2016) pp129-139
- Weidt, J., Weidt, J. (1980). Air leakage of newly installed residential windows, Lawrence Berkeley Laboratories, Rep. LBL 11111, National Technical Information Service, Springfield, VA.
- Zheng, X., Cooper, E., Mazzon, J. en Wood, C.J., 2019. Experimental and numerical investigation of the Pulse technique for measuring building airtightness. Building and Environment, 161, p.106234.