Regression Techniques under ISO 9972 – A Comparative Analysis

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Abstract

Building airtightness is increasingly important for enhancing energy efficiency, indoor air quality, and ensuring regulatory compliance. The commonly used Ordinary Least Squares (OLS) regression approach, recommended by ISO 9972 Annex C, inadequately addresses uncertainties inherent in real-world testing conditions, particularly under the influence of wind and at low pressures.
This study evaluates various regression methods—Ordinary Least Squares (OLS), Weighted Least Squares (WLS), and the Weighted Line of Organic Correlation (WLOC)—to improve uncertainty estimation in building airtightness testing. Analyzing over 6,000 blower door tests across 127 distinct building configurations, this research compares the predictive accuracy and uncertainty estimation capabilities of these regression approaches. Furthermore, the study introduces a simplified variant, WLOC_2.
Findings indicate that all regression methods provide similar predictive accuracy at the standard test pressure of 50 Pa. However, at a realistic infiltration pressure of 4 Pa, WLS and WLOC_2 significantly reduce prediction error by up to 6 percentage points compared to traditional OLS. Confidence interval analysis reveals that at 50 Pa, OLS covers the reference airtightness values for only 25% of the data, while WLOC_2 achieves 42% and WLS 91%. At the lower 4 Pa pressure, OLS confidence intervals cover merely 21% of measurements, whereas WLS demonstrates overly conservative uncertainty, covering all measurements, and WLOC_2 provides a balanced performance with 82% coverage.
These results strongly advocate incorporating weighted regression methods like WLS and WLOC_2 into airtightness measurement standards, as they better account for variability and uncertainty, particularly at low-pressure conditions relevant for realistic infiltration assessments.

Introduction

Building airtightness is a critical factor in ensuring energy efficiency (Sherman and Chan, 2006), indoor air quality (Kempton et al., 2022), and occupant comfort (Rodrigues et al., 2021). As buildings become increasingly energy-optimized, controlling unintended air leakage through the building envelope becomes essential to achieve designed thermal performance and ventilation effectiveness.
From a regulatory standpoint, airtightness has become an important performance requirement in many building codes worldwide. Countries such as France, Germany, or the United States have embedded specific airtightness thresholds into compliance frameworks (Moujalled and Mélois, 2023; Rolfsmeier and Rienhardt, 2024; Walker et

al., 2024). These regulatory developments increase the demand for reliable, repeatable airtightness measurements to verify compliance.
Moreover, as airtightness targets tighten, the accuracy of the measurement itself becomes more critical**.** Deviations due to environmental conditions like wind, or improper uncertainty handling during testing, can lead to incorrect pass/fail judgments with financial or legal consequences.
In this context, improving the robustness of airtightness measurement methods—and particularly the reliability of associated uncertainty calculations—is crucial not only for scientific accuracy but also for practical, everyday decision-making in the building sector.

Fan Pressurization Method and ISO 9972

To reliably measure building airtightness, the fan pressurization method (<known as the blower door test) has emerged as the global standard, described in detail by (ISO 9972, 2015). The blower door test involves installing a calibrated fan, usually mounted in a temporary airtight panel placed in an external doorway. This fan artificially creates a measurable pressure difference between the interior and exterior environments of a building. By systematically varying the fan speed and measuring the resulting airflow rates and pressure differences, a set of data points is generated that characterize the building's leakage behavior.
The standard ISO 9972 approach prescribes collecting multiple airflow measurements at incremental pressure differences. These measurements are then analyzed through regression to estimate two key parameters C and n of the power-law equation:

$$\mathrm{q} = \mathrm{C}\Delta\mathrm{p}^{\mathrm{n}} \tag{1}$$

where q is the airflow rate through the building envelope (m³/h), $\Delta\mathrm{p}$ is the indoor-outdoor pressure difference (Pa), C is the flow coefficient, indicating the magnitude of air leakage and n is the pressure exponent, describing the flow characteristic of leakage paths.
Conventionally, ISO 9972 employs a regression method known as Ordinary Least Squares (OLS) applied to logarithmically transformed values of airflow rates and pressure differences. While straightforward, this regression approach implicitly assumes that uncertainty in pressure measurements is negligible, treating the pressure as error-free independent variables, an assumption known to be unrealistic, particularly under real-world testing conditions influenced by environmental factors such as wind and stack effect (Delmotte, 2013; Prignon et al., 2020).
In recent years, the reliability and accuracy of this standardized OLS method have increasingly come into question, particularly regarding its handling of uncertainty and its practical applicability under non-ideal testing conditions. Wind (Carrié and Leprince, 2016) and stack-induced pressures (Carrié et al., 2021; Kölsch et al., 2024) can significantly affect indoor-outdoor pressure measurements, causing fluctuations that lead to inconsistent data points and larger scatter at lower pressures. Because infiltration in real buildings occurs naturally at much lower pressures (often around 4 Pa or even less), correctly characterizing building airtightness under realistic conditions demands regression methods that remain stable when extrapolating to these lower-pressure scenarios.
Consequently, research efforts are now examining alternative regression approaches, such as Weighted Least Squares (WLS) or Weighted Line of Organic Correlation (WLOC), which explicitly account for uncertainties inherent in both airflow and pressure measurements (Delmotte, 2017; Kölsch and Walker, 2020; Prignon et al., 2020). Such

methods aim to increase the reliability and practical relevance of airtightness tests carried out according to ISO 9972, ensuring that measurements are both scientifically sound and directly applicable to regulatory verification and building diagnostics.

Purpose of this Work

The purpose of this paper is to evaluate and compare how uncertainty is addressed within ISO 9972 (Annex C) and the German Annex to ISO 9972 (DIN EN ISO 9972), using a larger dataset of more than 6,000 blower door tests. Specifically, this study aims to:

- Analyze the treatment of uncertainty in the ISO 9972 Annex C approach.
- Examine the regression and extended uncertainty framework introduced by the German National Annex of ISO 9972.
- Identify the practical strengths and shortcomings of both approaches when applied across a wide range of field conditions.
- Introduce a possible alternative, more robust regression technique—specifically the Weighted Line of Organic Correlation (WLOC)—that can better capture uncertainty in real-world measurements without overcomplicating practical workflows.

While a detailed mathematical treatment of these regression methods is beyond the scope of this paper (as covered in (Delmotte, 2013; Kölsch et al., 2025; Prignon et al., 2020)), the focus here is on their practical applicability, uncertainty behavior, and potential for standardization improvements.

Current Standard Approaches to Uncertainty

Uncertainty Calculation in ISO 9972

To characterize the leakage behavior, the ISO 9972 relies on the power-law relationship (Eq. (1)) between airflow (q) and pressure difference ($\Delta\mathrm{p}$). This relationship is linearized using a logarithmic transformation, resulting in the form:

$$\ln(q) = \ln(C) + n\ln(\Delta p) \qquad (2)$$

The parameters leakage coefficient C and pressure exponent n are then estimated through Ordinary Least Squares (OLS) regression on the transformed data. Annex C of ISO 9972 provides a procedure for calculating the uncertainty of the derived parameters, including the computation of the standard deviations of n and $\ln(C)$. These standard deviations are used to construct confidence intervals, relying on the Student's t-distribution for a given confidence level. The Annex shows the derivation of a 95% confidence interval around a predicted airflow q at any given pressure Δp, based on the propagation of uncertainty from the fitted regression parameters.

Despite its statistical completeness, this approach has several practical limitations. It focuses exclusively on the statistical scatter of the measured data points around the fitted regression line, without accounting for uncertainty contributions from the measurement equipment itself. Instrument tolerances—such as the calibration accuracy of the manometer or the airflow sensor—are not explicitly included in the uncertainty budget. As a result, the total uncertainty reported by this method may be considerably underestimated in practical testing scenarios.

Moreover, the regression model treats pressure difference as an error-free independent variable. This assumption neglects the fact that pressure measurements, particularly under windy conditions or in unstable environments, can exhibit significant variability due to wind-induced pressure fluctuations and shifting baseline pressures. This leads to overly optimistic confidence intervals, especially at lower pressures, where measurement uncertainty is most pronounced.

German Annex DIN EN ISO 9972

To address the limitations of ISO 9972 Annex C, particularly the neglect of measurement-device errors and wind-induced pressure fluctuations, the German National Annex (DIN EN ISO 9972, 2018) introduces a more practical approach for estimating airtightness and its associated uncertainty. This method is based on a Weighted Least Squares (WLS) regression and an expanded uncertainty budget that reflects real-world influences often encountered during field tests.
The regression modifies the fitting process by assigning a weight to each data point proportional to the square of the measured airflow:

$$q_i = q_{env,i}^2 \tag{3}$$

This counteracts the logarithmic transformation bias of the standard OLS method, which overemphasizes low-pressure points that are typically more prone to wind and noise. The method retains the log-transformed linear form, but replaces the standard unweighted calculations with weighted counterparts, as detailed in Annex NC.2 of DIN EN ISO 9972.
For uncertainty estimation, the German Annex introduces a structured and conservative error model. The total uncertainty s (in %) is defined as:

$$s = \max\left(\sqrt{a^2 + b^2 + e^2}, d\right) + g \tag{4}$$

Here, a is the uncertainty from the airflow measurement device (typically around 3%). b represents the contribution from pressure measurement uncertainty, which includes both reference pressure error and the error due to zero-flow pressure difference—calculated using wind-induced fluctuations or the difference between baseline pressures before and after the test. The component e accounts for the uncertainty introduced by air density corrections (2% if barometric pressure is measured, 5% otherwise). The statistical contribution d is derived similarly to ISO 9972 Annex C but is applied to the WLS regression fit. Finally, g accounts for possible asymmetry in valve effects and is typically 0% if both pressurization and depressurization are conducted.
Of particular note is how the German Annex incorporates wind effects into the pressure uncertainty. The zero-flow pressure uncertainty $e(\Delta p_0)$ is estimated as the greater of half the baseline drift or half the dynamic pressure from wind:

$$e(\Delta p_0) = \max\left(\left|\frac{\Delta p_{0,1} - \Delta p_{0,2}}{2}\right|; \frac{1}{2} \cdot \frac{\rho}{2} v^2\right) \tag{5}$$

This formulation enables the method to account for wind-induced pressure noise without requiring direct wind measurement instrumentation, making it particularly suited for field applications. While the standard does not prescribe how to convert this total uncertainty into a confidence interval, in this study, we apply the following expression assuming a 95% coverage factor $k = 2$:

$$CI\left(q_{ref}\right)_{WLS} = q_{ref} \pm k \cdot s \cdot q_{ref} \tag{7}$$

Comparative Analysis and Limitations of Current Methods

Given the importance of accurate uncertainty estimation in airtightness testing, it is essential to critically examine how well the current standard ISO 9972 Annex C

(OLS) and the German Annex DIN EN ISO 9972 (WLS) methods perform under real-world measurement conditions. Table 1 summarizes and compares key characteristics of these two standard approaches, highlighting their main differences relevant for practitioners.
The uncertainty estimation procedure outlined in Annex C of ISO 9972 has significant limitations, notably the systematic underestimation of true uncertainties. This arises because Annex C's approach relies exclusively on statistical scatter of the measured data, entirely neglecting instrument calibration errors and environmental factors such as wind-induced measurement biases. Consequently, confidence intervals derived from this method may be deceptively narrow, especially under conditions involving wind or at lower pressures where these factors become particularly influential.
The practical implications of these underestimated uncertainties are substantial. Technicians, auditors, and regulatory bodies may mistakenly interpret test results, potentially leading to incorrect compliance decisions.

Table 1: Comparison of Uncertainty-Treatment Features: ISO 9972 Annex C vs. German Annex DIN EN ISO 9972

Aspect	ISO 9972 Annex C (OLS)	German Annex (WLS)
Regression method	Ordinary Least Squares (OLS)	Weighted Least Squares (WLS)
Regression weighting	None (all points equal in log–log space)	Down-weights low-pressure points (s. Eq. (3))
Instrument errors	Statistical scatter only	Explicit a, b, e terms (flow, pressure, density)
Wind influence	Implicit (only if it increases scatter)	Term $e(\Delta p_0)$
Confidence-interval logic	Pure regression CI (Student-t)	Overall error s
Typical effect	May **under-estimate** CI, esp. at 4 Pa and in wind	May **over-estimate** CI, esp. at 4 Pa

The German Annex addresses several OLS shortcomings by explicitly including instrument calibration errors and wind-induced pressure variability. However, this method may tend toward overly conservative uncertainty estimates, particularly at low-pressure extrapolation.

Improved and Alternative Approach

Weighted Line of Organic Correlation (WLOC)

Recognizing the limitations inherent in both the ISO 9972 Annex C (OLS) and the German Annex DIN EN ISO 9972 (WLS), alternative regression methods such as the Weighted Line of Organic Correlation (WLOC) have gained attention. This method is particularly suited to airtightness measurements where significant uncertainties exist in both airflow and pressure measurements.
Unlike OLS, which assumes uncertainty predominantly in airflow measurements, or WLS, which primarily weights data points based on airflow magnitude alone, the WLOC method simultaneously accounts for uncertainties along both axes. Practically, this means WLOC acknowledges potential errors in pressure measurements, a critical consideration under windy conditions or at lower pressures. As a result, WLOC tends

to produce more balanced and realistic uncertainty estimates, especially beneficial when extrapolating test results down to natural infiltration pressures around 4 Pa.
Conceptually, WLOC calculates a regression line by minimizing weighted perpendicular distances from measurement points to the regression line rather than merely vertical distances as in OLS (Delmotte, 2017). Each measurement point is assigned a weighting factor inversely proportional to its combined measurement uncertainty. Thus, points with higher reliability (lower uncertainty) more strongly influence the regression fit, whereas points characterized by greater uncertainty—often low-pressure measurements—exert proportionately less influence. This balanced approach prevents either airflow or pressure measurement errors from disproportionately affecting the regression outcome.
A new variant, termed "WLOC_2," was developed in (Kölsch et al., 2025) to streamline the weighting methodology based on data typically available during standard tests. This new method calculates uncertainties for pressure differences and airflow measurements by considering three main components: the standard deviation reflecting measurement fluctuations during testing, device uncertainty consistent with ISO 9972 specifications, and uncertainty due to variations in façade pressure, approximated from zero-flow pressures measured before and after tests.
Specifically, the uncertainty for the pressure difference $u(\Delta p_i)$ is calculated as:

$$u(\Delta p_i) = \sqrt{\sigma^2(\Delta p_{\mathrm{m},i}) + u^2(\Delta p_{\mathrm{m},i}) + \left(\frac{\Delta p_{0,1}+\Delta p_{0,2}}{2}\right)^2} \tag{8}$$

Here, $\sigma(\Delta p_{\mathrm{m},i})$ is the standard deviation of pressure measurements at each station, with station meaning the series of measurements taken at a given pressure difference. Device uncertainty (maximum permissible measurement error) is defined according to standard specifications.
Similarly, the uncertainties in airflow for pressurization $u(q_{\mathrm{env},p,i})$ and depressurization $u(q_{\mathrm{env},d,i})$ are defined respectively as:

$$u(q_{\mathrm{env,p},i}) = u_\mathrm{c}(q_{\mathrm{m,p},i}) \cdot \frac{T_\mathrm{int}}{T_\mathrm{e}} = \sqrt{\sigma^2(q_{\mathrm{m},i}) + \left(u(q_{\mathrm{r},i}) \cdot \sqrt{\frac{T_\mathrm{e}}{T_0}}\right)^2} \cdot \frac{T_\mathrm{int}}{T_\mathrm{e}} \tag{9}$$

$$u(q_{\mathrm{env,d},i}) = u_\mathrm{c}(q_{\mathrm{m,d},i}) \cdot \frac{T_\mathrm{e}}{T_\mathrm{int}} = \sqrt{\sigma^2(q_{\mathrm{m},i}) + \left(u(q_{\mathrm{r},i}) \cdot \sqrt{\frac{T_\mathrm{int}}{T_0}}\right)^2} \cdot \frac{T_\mathrm{e}}{T_\mathrm{int}} \tag{10}$$

The 95% confidence interval is then defined as (with $k = 2$):

$$CI(q_\mathrm{ref})_\mathrm{GUM} = q_\mathrm{ref} \pm k \cdot u_\mathrm{c}(q_\mathrm{ref}) \tag{11}$$

The combined standard uncertainty $u_\mathrm{c}(q_\mathrm{ref})$ accounts for uncertainties in both the pressure exponent and airflow coefficient, including their mutual correlation:

$$u_\mathrm{c}(q_\mathrm{ref}) = \sqrt{\begin{array}{c}\left(\frac{\partial q_\mathrm{ref}}{\partial n} \cdot u_\mathrm{c}(n)\right)^2 + \left(\frac{\partial q_\mathrm{ref}}{\partial \ln(C_\mathrm{env})} \cdot u_\mathrm{c}(\ln(C_\mathrm{env}))\right)^2 + \\ 2 \cdot \frac{\partial q_\mathrm{ref}}{\partial n} \cdot \frac{\partial q_\mathrm{ref}}{\partial \ln(C_\mathrm{env})} \cdot u_\mathrm{c}(n) \cdot u_\mathrm{c}(\ln(C_\mathrm{env})) \cdot r(n, \ln(C_\mathrm{env}))\end{array}} \tag{12}$$

Methodology and Data

Dataset Overview

The analysis presented in this paper is based on a comprehensive experimental dataset originally collected at the Alberta Home Heating Research Facility (AHHRF) in Edmonton, Alberta, Canada. The AHHRF consists of six dedicated unoccupied test houses, each uniquely constructed to represent various typical building characteristics. Extensive details regarding the facility, the specific test houses, and the data collection procedures are documented in previous studies by (Walker et al., 2013).

The dataset encompasses nearly 7,500 airtightness measurements, systematically conducted under 127 distinct building configurations. These configurations were varied by manipulating construction elements such as flue openings, sliding window positions, and passive ventilation adjustments, resulting in diverse airtightness scenarios representative of typical construction practices. Each scenario included between 5 and 140 individual blower door tests, providing robust statistical representation. Among all tests performed, approximately 39% were conducted under pressurization mode and 61% under depressurization mode. Measurement data, including airflow and pressure readings, were recorded at regular 15-second intervals. Importantly, parallel meteorological data capturing external environmental conditions were collected, including ambient temperatures ranging from -32 °C to +34 °C and wind speeds varying from 0 m/s up to conditions exceeding 10 m/s. Following data collection, a filtering process was applied to ensure the dataset's quality and compliance with ISO 9972 requirements. The criteria and further details are specified in (Kölsch et al., 2025).

Comparative Procedure

To systematically evaluate and compare the uncertainty-handling capabilities of different regression methods—specifically Ordinary Least Squares (OLS), Weighted Least Squares (WLS), and Weighted Line of Organic Correlation (WLOC)—a structured comparative procedure was consistently applied across the extensive dataset comprising 6,197 airtightness tests.

Two distinct implementations of the OLS method were used: OLS_1 corresponds strictly to the ISO 9972 Annex C procedure, utilizing statistical scatter alone for uncertainty estimation, while OLS_2 incorporates an enhanced uncertainty calculation in line with the Guide to the Expression of Uncertainty in Measurement (GUM) (Joint and Committee for Guides in Metrology, 2008), accounting explicitly for correlations between uncertainties.

Similarly, the WLOC method was analyzed in two variants: WLOC_1, employing the comprehensive weighting scheme originally proposed by Delmotte and Prignon, and WLOC_2, a simplified variant specifically developed for this study.

Each airtightness test within the dataset was analyzed independently using OLS (both OLS_1 and OLS_2), WLS (German Annex DIN EN ISO 9972), and WLOC (both WLOC_1 and WLOC_2). For each method, key leakage characteristics—including the flow coefficient, pressure exponent, and predicted airflow rates at standardized pressure levels (50 Pa and 4 Pa)—were determined.

For airflow predictions at the regulatory standard pressure of 50 Pa, each regression method's accuracy was evaluated by comparison against reference values established under stable environmental conditions (minimal wind speeds). This step provided insights into how accurately each method could approximate true building leakage characteristics under standardized test scenarios.

Recognizing the practical importance of accurately estimating infiltration rates at low pressures, the analysis also assessed the reliability of extrapolations down to approximately 4 Pa. The predictions at this lower pressure were compared against reference measurements, highlighting each regression method's ability to provide reliable airflow estimates relevant to typical building infiltration conditions.

Finally, the reliability and practical accuracy of each regression method's uncertainty estimates were evaluated through the coverage rates of their respective 95% confidence intervals (CI). This evaluation determined how frequently actual reference airflow values fell within the predicted CIs. Ideally, a method providing nominal 95% CI coverage would include approximately 95% of reference values; lower coverage would indicate an overly optimistic (underestimated) uncertainty estimation, whereas excessively high coverage would indicate overly conservative uncertainty estimates with excessively broad confidence intervals.

Results

Accuracy Comparison at 50 Pa and 4 Pa

Figure 1 evaluates the efficacy of the five regression methods in predicting airflow at two distinct pressure differences: 50 Pa (left) and 4 Pa (right). The horizontal axis represents wind speed, ranging from 0 m/s to 10 m/s, while the vertical axis shows the Percentage Difference (PD) between the measured and the reference airflow values. Each data point indicates the average PD calculated for measurements within each 1 m/s increment of wind speed. Because OLS_2 employs the same regression approach as OLS_1, their results overlap entirely in the graphs.

At the standard testing pressure of 50 Pa, all regression methods demonstrate similar accuracy in predicting the reference airflow, with mean PDs remaining within approximately -6%, even at higher wind speeds. This consistency suggests that at this pressure difference, the specific regression method chosen has a limited impact on the accuracy of predicted airflow values. Moreover, the error bars—representing the standard deviation of PDs within each wind speed interval—are similar across all methods, further emphasizing minimal differences among them at 50 Pa.

For both pressure differences (50 Pa and 4 Pa), the mean PD remains close to zero for wind speeds up to approximately 3 m/s. This indicates that wind-induced errors are minimal at lower wind speeds and that the observed variability is predominantly due to random measurement uncertainties or other minor sources of error. However, as wind speeds exceed approximately 3 m/s, a clear negative bias emerges, particularly pronounced at the lower extrapolation pressure of 4 Pa. This negative bias represents an underestimation of leakage flow rates, primarily caused by the underlying assumption within all regression methods that leakage occurs through a single equivalent opening, a simplification known to systematically underestimate actual airflow under significant wind-induced pressure fluctuations.

At higher wind speeds (above approximately 3 m/s), the negative bias at 4 Pa is notably higher. Specifically, the OLS (OLS_1 and OLS_2) and WLOC_1 methods demonstrate larger negative PDs compared to WLS and WLOC_2. Quantitatively, at higher wind speeds approaching 10 m/s, the mean negative PD for OLS and WLOC_1 is approximately 4 percentage points greater than for WLS and the WLOC_2 method.

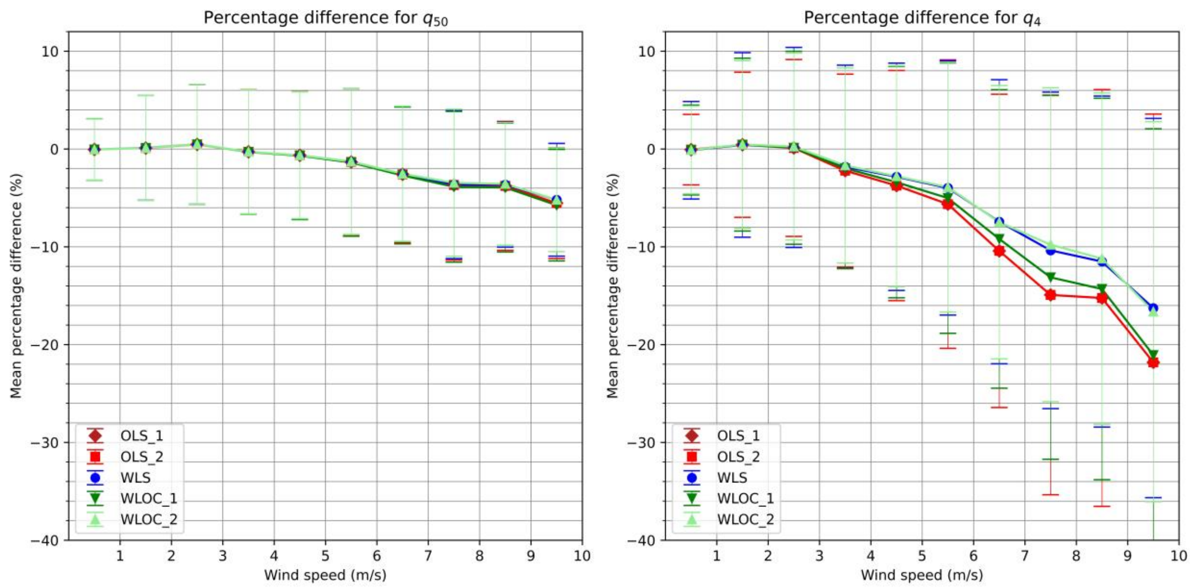

Figure 1: Mean values for increasing wind speeds of the percentage difference (PD) for calculated airflows at pressure differences of 50 Pa (left) and 4 Pa (right) and a reference value at these pressures with error bars representing the standard deviation

Confidence Interval (CI) Coverage Assessment

Beyond evaluating accuracy, an important aspect is understanding how reliably each regression method's uncertainty calculation captures the actual variability observed in airtightness measurements. Figure 4 summarizes this by presenting the percentage of calculated airflows at both 50 Pa and 4 Pa that fall within the respective 95% confidence intervals (CIs), thereby directly comparing the relative performance of each regression technique across the dataset.

The WLS method demonstrates notably high overall coverage, achieving approximately 91% at 50 Pa and essentially perfect coverage (100%) when airflow is extrapolated to 4 Pa. Among the alternative methods evaluated, the simplified WLOC_2 approach emerges as particularly promising at lower pressure extrapolations, maintaining confidence interval coverage above 80%.

However, the WLOC_2 method exhibits significantly lower effectiveness at 50 Pa, where coverage remains below 50%. This limited performance indicates an underestimation of actual uncertainty by WLOC_2 at this standard testing pressure.

A principal reason why uncertainty calculations fail to achieve nominal 95% coverage is that existing regression models typically do not fully account for all uncertainty sources. A notable factor, as previously shown in Figure 1, is the systematic error introduced by increasing wind speeds. This systematic bias arises from the simplifying assumption common to all current models that air leakage can be represented by a single equivalent leak. Such simplification leads to underestimated leakage predictions as wind increases, a factor that the current uncertainty frameworks do not explicitly consider. Although this error is systematic for any particular building scenario, its unpredictability across diverse building types effectively makes it appear random from the perspective of uncertainty estimation.

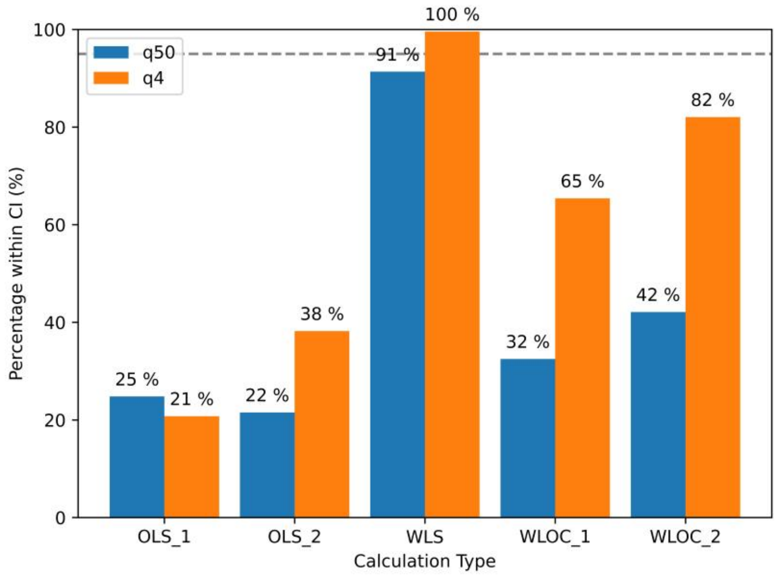

Figure 2: Total percentage per regression method where mean calculated airflows at 50 Pa and 4 Pa fall into the 95% confidence interval

Given this challenge, a practical recommendation emerging from this study is to explicitly incorporate a model-induced uncertainty component into regression uncertainty calculations. Previous research by (Carrié and Leprince, 2016) and (Delmotte, 2021) provides a potential methodological foundation for quantifying and incorporating this additional systematic error into confidence intervals. Such integration could improve the reliability of uncertainty estimates, enhancing their practical value to technicians, auditors, and regulators responsible for interpreting airtightness test results under realistic field conditions.

Conclusions

Based on this evaluation, practitioners are encouraged to adopt regression methods that more accurately reflect real-world testing uncertainties. For tests aiming at estimating infiltration airflow at pressures around 4 Pa, testers should prioritize using WLOC or the German Annex's WLS method, as both methods significantly enhance uncertainty reliability compared to traditional OLS.

To improve consistency and reduce complexity in field practice, standardized calculation templates or software tools incorporating simplified uncertainty assumptions, as demonstrated by WLOC, should be widely adopted by technicians and measurement service providers. Finally, caution should be exercised when interpreting results obtained via standard OLS regression methods under realistic field conditions, due to their demonstrated tendency to systematically underestimate measurement uncertainties.

To address current limitations in ISO 9972 Annex C and enhance the accuracy and reliability of airtightness tests, future revisions of the standard should explicitly incorporate advanced regression techniques that account for realistic measurement uncertainties. Specifically, future ISO 9972 revisions should clearly integrate weighted regression methods such as WLS or WLOC, explicitly acknowledging uncertainties in airflow and pressure measurements, including those resulting from instrument calibration errors and environmental conditions like wind.

Future studies should focus on systematic validation of uncertainty estimation methods in controlled laboratory environments (Mélois et al., 2024), enabling precise isolation and quantification of individual uncertainty sources such as instrument calibration, wind-induced pressures, and pressure measurement variability. Additional field studies should be extended to include multi-story buildings and complex building geometries, where effects such as stack-induced pressure differences and spatial variability in leakage paths significantly influence measurement uncertainties. Investigations focusing on improving wind-effect models, particularly through refined characterization of façade-specific wind pressures, would greatly enhance uncertainty estimation under windy testing conditions.

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