On the applicability of meta-analysis to evaluate airtightness performance of building components

Abstract

The scientific literature lacks comprehensive and updated information regarding the airtightness of building components, this hindering the development and improvement of models for a robust prediction of their performance. To fill this gap, this paper presents a meta-analysis conducted on literature studies reporting laboratory and in-situ measurements of airtightness for various building components. Meta-analysis is a powerful methodological tool to compare and combine data from previous research, even when they have inherent differences. The results of the meta-analysis allowed to attain three outcomes: a classification of building components related to their airtightness performance; the update and improvement of existing databases of building component airtightness; and, the identification of factors specifically influencing airtightness performances of windows. In addition, the critical appraisal of the findings led to the definition of the requirements for future studies reporting measurements of airtightness of building components. This study offers a step ahead from existing knowledge by improving existing databases and by proposing a methodological framework of analysis that can be extended to several other domains of the built environment.

Keywords: Building Components; Meta-analysis; Airtightness; Air infiltration; Measurements

1. Introduction

Building standards and regulations have made a significant impact in the field of airtightness because of the large influence that air infiltration has on energy demands [1]. Energy policies driven by these regulations considerably increase the number of airtightness tests that need to be performed on buildings and, as a consequence, the number of countries that have implemented qualification schemes for testers [2]. However, considerations related to airtightness should not be limited to energy consumption, since air infiltration also impacts smoke and fire propagation, indoor air quality, and the comfort and well-being of occupants [3]. These implications are largely influenced by the location and distribution of leakage around the building envelope, which is fundamentally associated to the measurement of airtightness at the level of individual components rather than for the whole building.

Various authors have highlighted substantial knowledge gaps in the airtightness performance of building components. Among others, Virtanen pointed out the difficulties, when modelling infiltration, to determine the actual leakage route inside built structures [4]. Liu and Nazaroff emphasised the lack of information regarding leakage characteristics of building components to reliably predict pollutant penetration into buildings [5]. Younes and Shdid explained that the reliability of CFD analysis depends on the capability for the crack data to be a realistic representation that is applicable to the construction techniques and the materials used in practice [6]. Prignon and Van Moeseke stressed the large potential of single component models to predict building airtightness, provided that reliable and updated data are available for the airtightness performance of building components [7].

Currently, there are two databases that are commonly used to characterise building component airtightness: these are provided by ASHRAE [8] and AIVC [9]. These databases have been fed with data coming from studies performed until the early '90s. However, the large impact of new energy policies has made these databases less relevant in current construction practice due to their insufficient reliability for modelling infiltration and airtightness prediction. Consequently, there is an urgent need to update these databases, identifying the impact of individual components on building airtightness, re-computing their airtightness performance, and drawing conclusions based on previous and new studies.

Nevertheless, reviewing the appropriate literature should not be limited to listing relevant studies, and combined results should not be limited to calculation of simple mean averages. In fact, a thorough review of previous research data featuring direct measurements needs to be rigorous and based on solid and well-documented protocols. In addition to computing averages or variation among different components, it should also quantify and investigate the causes of such variation of component performance between studies (e.g., difference in the selected samples or in the experimental design).

Meta-analysis provides a set of tools that could answer the need for a rigorous protocol to compare and combine the results of previous research. A meta-analysis is a set of methods used to consolidate evidence (e.g., effect sizes) of different studies from the literature [10]. This type of analysis is often conducted in clinical research [11], but its application is still rather sparse in the domain of the built environment. This methodological approach could be used as a robust protocol to combine studies reporting measurements of building component airtightness or effects related to these measurements (e.g., the impact of different treatments of an identified leak). The same method could be transferred to the analysis of many other environmental parameters (e.g., indoor air quality, acoustic, lighting or thermal performance), factors influencing occupant comfort, or to compare the energy efficiency of different solutions and strategies in buildings.

In this study, we conduct a meta-analysis in order to compare and combine the results of various studies measuring airtightness of building components. The structure of the paper is as follows. In section 2, we illustrate the steps of a meta-analysis, including the criteria for study selection and the equations to obtain a combined mean, a combined standard deviation, and an inconsistency index (that is, the selected indicator for the variation between studies). In section 3, we provide two outcomes derived from the meta-analysis: a classification of building components related to their airtightness performance and the combined means, combined standard deviations, and index of inconsistency for specific building components. In section 4, we appraise these outcomes and discuss their impacts to both building practice and research. This also includes a critical overview of the results of the meta-analysis, together with a discussion of their limitations with respect to the existing literature and the selected methodology. Guidelines are then drawn for future studies in order to improve the reliability of airtightness measurements, and the application of meta-analysis to other cognate domains of the built environment. Finally, in section 5, we summarise the outcomes of this study and illustrate the further research needed in the measurement of building component airtightness.

2. Methodology

A meta-analysis consists in the weighting of each evidence (e.g., the effect size) based on the reliability of the study: studies with high variability are expected to be less accurate and have less weight in the analysis [12]. Meta-analysis can also be used to combine *single group summaries* (e.g., mean, median, or standard deviation) rather than effect sizes [13]. This is important in this context, and more generally for research in the field of the built environment, since studies hardly report effect sizes. For airtightness of building components, studies reporting measurements commonly provide average leakage data for a given component rather than effect sizes. The role of a meta-analysis is to synthetize data, but also to look at the pattern of studies targeted by the research question [13]. For example, a powerful tool brought by the meta-analysis is the exploration of heterogeneity in the results (i.e., the reasons for variations between studies) [14]. This is important since it can help to investigate and understand the factors influencing the variation in results, which is crucial for their interpretation. For example, variations can be explained by a difference in the selected sample, in the countries where studies are conducted, or in the experimental design. A meta-analysis is made of three main steps: data acquisition; studies combination; and, exploration of heterogeneity. These are presented hereafter, with special focus given to their application in the field of building component airtightness.

2.1. Data acquisition

A meta-analysis aims at combining studies that respond to the same research question. It is, therefore, crucial to formulate an unambiguous research question based on which the relative literature can be reviewed. The protocol used to perform the literature review must be thoroughly described in order to be replicable (e.g., the research terms and platform used should be explicitly stated). Not all studies targeting the research question have to be necessarily included in the meta-analysis, since a badly conducted research can bias the combined effect [12]. However, for each study excluded from the meta-analysis, the reasons and criteria for the exclusion should be clearly stated.

Statistically, there is no restriction about the “required similarity” of studies to be combined in a meta-analysis [13]. However, the studies should be relevant for the defined research question and the results of the combination must be interpreted against the initial objectives. This is illustrated in this paper through section 3: initially, the result of a meta-analysis conducted on studies reporting the measurement of building component airtightness is presented, without looking at different possible treatments for the same component; then, the meta-analysis focuses on the case of windows, including different types of openings and various materials. Both meta-analyses are valid statistically, however interpretation of the results, and the contexts in which these would be relevant, are different.

Once all studies are selected, the outcome of interest must be extracted from each study. As previously explained, this can be effect size or simple group summary (e.g., mean, median, or standard deviation), but it must be consistent with the defined research question on which the systematic review is based. If the studies are addressing similar outcomes expressed in different ways, it is up to the researcher to decide if their combination is meaningful [13]. The selection of inclusion and exclusion criteria for a meta-analysis should be based on the field of research, the objective of the study, and previous research. Without prior knowledge to support decisions, this step can be difficult. Due to their large influence on the combined results, it is important to clearly state these criteria, to justify them, and to discuss their implications. The inclusion and exclusion criteria chosen for this study are presented in section 3.2.

2.2. Combined outcome

Once the outcome of each study is extracted, it must be weighted according to its reliability: high reliability studies have more importance in the combination than low-reliability studies. In meta-analysis, weighting can be based on fixed-effect and random-effect models. Fixed-effect models assume that the true outcome (which is unknown) is the same for all studies. If this assumption is implausible, a random-effect model should be used instead [15]. In the context of building component airtightness, studies are expected to be similar but not identical. The true outcome will vary among studies because of differences in experimental design or selected sample; hence random-effect models should be used.

In random-effect models, the number of studies combined can play a role in the precision of the results. When a small number of studies are combined, the estimate of the error and of result inconsistency (described later in this section) may have large uncertainty. However, there are no good alternatives and the results should be reported with a clear explanation of their limitations [13].

In random-effect models, there are two sources of error: within-study and between-study variations. Both must be considered in the weighting of studies and the observed variance must be decomposed in its two components [13]. A random-effect model is described with Equation 1where T_i, τ_i and ε_i are respectively the outcome, the within-study error, and the between-study error for the i^{th} study, and μ is the true outcome, which is unknown.

Equation 1

$$T_i = \mu + \tau_i + \varepsilon_i$$

These two levels of error induce two steps for the weighting. The first step is the fixed-effect weighting (w_i) and is defined as the inverse of the total variance (combining within-study and between-study deviations). The second step, the random-effect weighting (w_i^*), is more complex to determine since it is the inverse of the sum of the within-study and between-study variance. It can be determined based on the following steps.

First, the total variance Q is calculated based on Equation 2.

Equation 2

$$Q = \sum_{i=1}^{k} w_i T_i^2 - \frac{\left(\sum_{i=1}^{k} w_i T_i\right)^2}{\sum_{i=1}^{k} w_i}$$

Then, the between-study variance (τ^2) is computed by Equation 3, where df is the degree of freedom (number of studies -1) and C a scaling factor (Equation 4) necessary because Q is a weighted sum of squares [15].

Equation 3

$$\tau^2 = \begin{cases} \frac{(Q-df)}{C} & if\ Q > df \\ 0 & if\ Q \leq df \end{cases}$$

Equation 4

$$C = \sum_{i=1}^{k} w_i - \frac{\sum_{i=1}^{k} w_i^2}{\sum_{i=1}^{k} w_i}$$

Lastly, random weights are given by Equation 5

Equation 5

$$w_i^* = \frac{1}{\frac{1}{w_i} + \tau^2}$$

Once weights are computed for each study included in the meta-analysis, the combined outcome is simply the weighted mean (Equation 6) and its standard error is the square root of the variance, that is the inverse of the weights (Equation 7).

Equation 6

$$\bar{T} = \frac{\sum_{i=1}^{k} w_i^* T_i}{\sum_{i=1}^{k} w_i^*}$$

Equation 7

$$\mathrm{SE}(\bar{T}) = \sqrt{\frac{1}{\sum_{i=1}^{k} w_i^*}}$$

2.3. Exploring heterogeneity with subgroup meta-analysis

A statistical heterogeneity is observed when the variation between different studies is above the variation expected by chance. This can be explained by the characteristics of the tested samples, a variation in the treatments, in the execution of the experiment, or in the experimental design [14, 16]. In this context, the calculation of I^2, the index of inconsistency, is suggested. It is interpreted as the proportion of total variation that is due to the heterogeneity between studies (Equation 8) [14, 17].

Equation 8

$$I^2 = \begin{cases} \frac{Q-(k-1)}{Q} \text{ x } 100\% & \text{for } Q > (k-1) \\ 0 & \text{for } Q \leq (k-1) \end{cases}$$

The interpretation of I^2 depends on the field of study and should, therefore, be further investigated for airtightness of building components. Without prior knowledge, the interpretation of I^2 in this study has been based on the same values than those suggested for clinical research: 25%, 50% and 75% respectively for low, moderate, and high inconsistency [16]. Compared to clinical research, there are generally less standardised protocols in sample selection, experimental design, or statistical analysis of the results for data collected in fields related to building physics. As a consequence, a larger deviation between studies, and a larger I^2, is expected in this domain of research. Although this should be stressed when conducting and interpreting the results of a meta-analysis, deeper investigations should be conducted before defining new values for interpretation of I^2 in built environment studies.

One method to explore the heterogeneity derived from between-study variations consists in creating subgroups of studies (e.g., laboratory vs. field measurements) and comparing the heterogeneity of the subgroups with the heterogeneity of all studies [16].

3. Airtightness of building components

This section presents the results of the meta-analysis conducted to combine studies reporting measurements of airtightness of building components. The objective of this combination is to approach the “true” airtightness performance of components (i.e., the mean and the standard deviation of the whole population). As pointed out in the introduction, this can be very helpful for several applications such as infiltration modelling and airtightness prediction.

The relevant studies were identified based on the following keywords and their combinations: “airtightness”, “air infiltration”, “air leakage”, “air permeability”, “building components”, and “building elements”. These were used as search terms in the AIVC publication database [18], Sciencedirect and Google Scholar [19]. For each paper, the abstract and the result section were read to ensure that the study reported the measurements performed on building component airtightness, regardless of the specific methodology applied. In addition, specific research was conducted on papers mentioned in the AIVC [9] and ASHRAE [8] databases focusing on airtightness of building components. In total, 79 relevant studies reporting results of measurements performed between the mid-20’s and today were included in the review. These included journal papers, conference papers, and technical reports. These studies cover around 40 different building components and their treatments.

3.1. Classification of building components airtightness

The first result obtained from this analysis is a list of building components for which airtightness measurements were reported. This list was used to build a 4-level classification of building components related to the way air flows through and around them. This classification provides an overview of the building components that impact airtightness performance. Figure 1 illustrates these components and classifies them in three different types of flows (level 1 classification): partitions and surfaces, junctions between surfaces, and discontinuities.

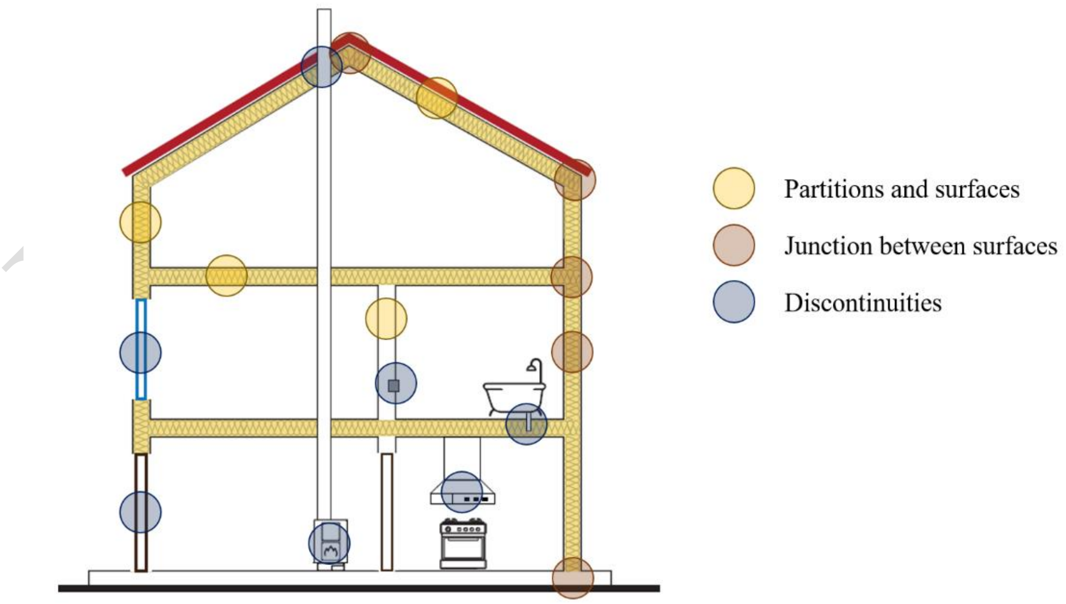

Figure 1 – Illustration of the level 1 classification of building components regarding airtightness. Source: authors.

Each type of flow is further divided in three additional levels: Category of components (level 2); Components (level 3); and, Type and treatment (level 4). Figure 2 shows the complete classification suggested on the basis of this study. The components underlined are those for which a sufficient number of studies could be included in the meta-analysis.

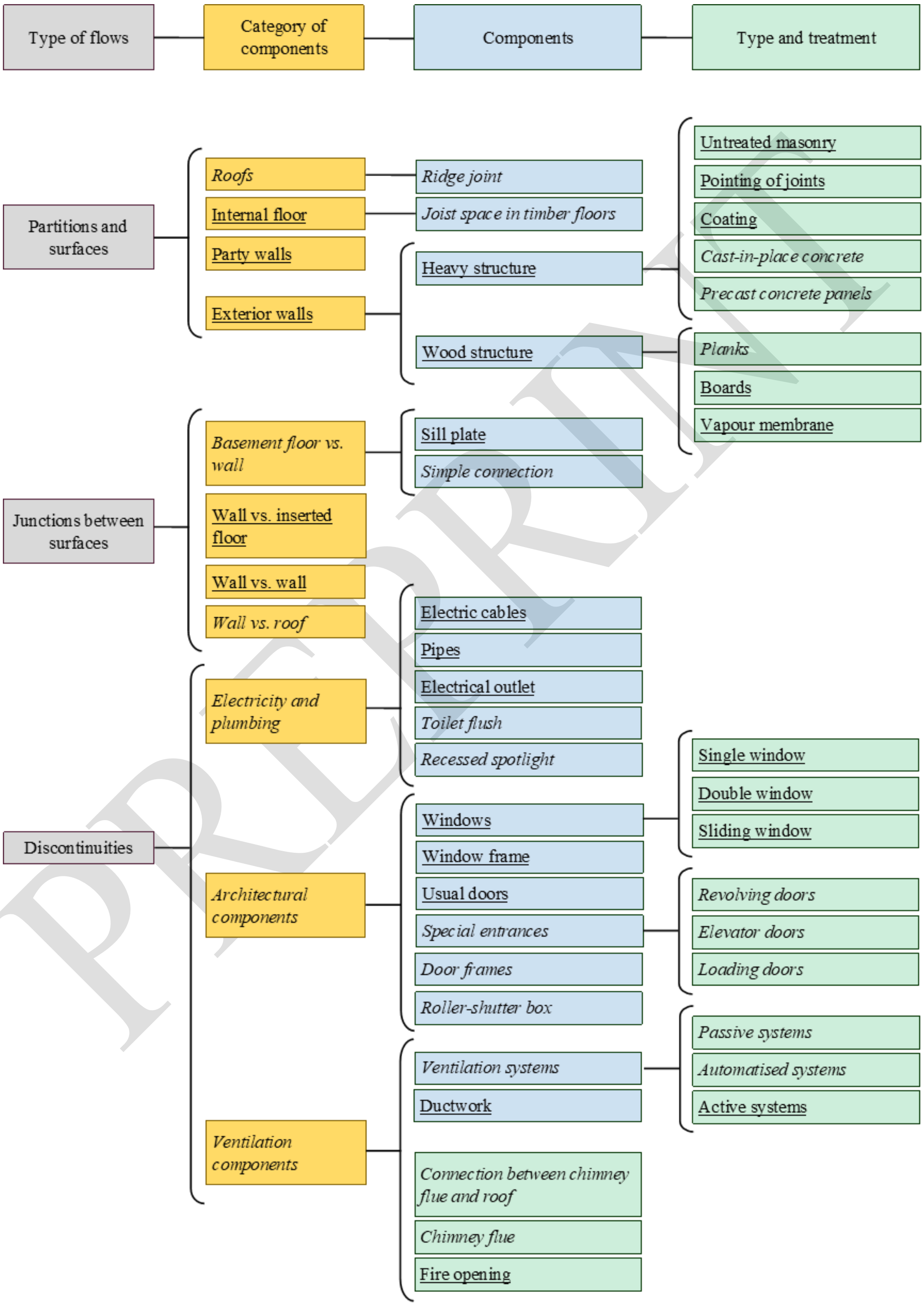

Figure 2 – Four level classification of building components based on studies reporting airflow values. Source: authors.

This classification is expected to expand and improve over the years as the data from new studies reporting measurements of airtightness of building components is included. This is further illustrated in the discussion section (section 4).

3.2. Airtightness performance of building components

Airtightness performance of building components can be expressed in many different units and metrics [20]. However, most can be translated into airflow at 50 Pa (q_{50}), which is largely used in regulations, practice, and research [2, 21]. This translation can be direct (i.e., change of units) or indirect (i.e., using the power-law relation), for which the leakage exponent (n) is needed.

In this analysis, when the metric used could not be directly translated to q_{50}, and n was not reported in the study, a value of 0.65 was assumed [9, 22]. The meta-analysis aimed at determining combined mean, standard deviation, and index of inconsistency for both q_{50} and n. When there was no information available to translate from one normalisation to another, the study was excluded from the meta-analysis. In addition, studies reporting only one measurement, or the mean of multiple measurements without providing information about standard deviation, were also excluded from the meta-analysis since they could not be weighted. Without previous knowledge on meta-analysis in the field of airtightness to support this decision, the choice was made to systematically include studies reporting measurements of airtightness performance if the following two criteria were met:

1) The study reports the outcome in normalised q_{50}, or in a different manner from which it can be calculated directly (i.e., change of unit), or using the power-law with or without an assumption about the leakage exponent.
2) It is possible to determine the standard deviation based on the results reported. This means that the measurements are conducted at least in two cases for each component and that, when all data are not available, standard deviation and mean can be computed from the information available.

Regarding the first condition, the normalisation of q_{50} depends on the component. It is sometimes normalised per unit of length or surface. For components with different normalisation used in different studies (e.g., windows), the most frequently reported was selected for the meta-analysis. This was an arbitrary choice, because the reliability of the meta-analysis depends on the number of combined studies.

The meta-analysis was conducted for each building component that had at least two studies meeting the inclusion criteria. However, to provide a more exhaustive list of building components measured in previous research, the tables presenting the results also include the mean and standard deviation for components that had only one study meeting the inclusion criteria. In these cases, I^2 cannot be computed since the meta-analysis could not be conducted.

Table 1 to Table 14 present the results of the meta-analysis conducted on different components according to the equations presented in section 2.2. These tables provide, for each variable (i.e., the airflow at 50 Pa, q_{50}, and the leakage exponent, n), the number of studies considered in the analysis (N), the combined mean ($\overline{q_{50}}$ and $\bar{n}$), the combined standard deviation (SE($\overline{q_{50}}$) and SE($\bar{n}$)), the inconsistency in the results I^2, and the reference studies used for the meta-analysis. The units used for $\overline{q_{50}}$ and SE($\overline{q_{50}}$) depend on the normalisation of the component.

3.2.1. Leakage through partitions and surfaces

Table 1 presents the results of the meta-analysis performed on roofs, internal floors, party walls and exterior walls. Three studies were excluded from the meta-analysis since they reported only one single measurement [23-26].

Type of partition		**q_{50}**				**n**			**References**
	N	**$\overline{q_{50}}$**	**SE($\overline{q_{50}}$)**	**I^2 (%)**	**N**	**$\bar{n}$**	**SE($\bar{n}$)**	**I^2 (%)**	
Roof	1	95.8	55.4	-	1	0.63	0.18	-	[27]
Internal Floor	3	1.4	1.5	36.7	1	0.59	0.10	-	[28-30]
Party wall	2	2.9	0.6	0.0	-	-	-	-	[29, 31]
Exterior wall	11	1.6	0.5	88.6	5	0.76	0.06	29.6	[28, 29, 31-38]

Table 1 – mean, standard error and inconsistency for airflows at 50 Pa (in m³/(h.m²)) and leakage exponent calculated through the meta-analysis of studies measuring leakage by partition.

The high mean air leakage through the roof (95.82 m³/(h.m²)) was expected since the study refers to tile roofs only, with nothing to prevent air leakage between tiles [27]. Similar performance is found on internal floors (1.4 m³/(h.m²)) and exterior walls (1.6 m³/(h.m²)) but with different standard deviation (1.5 m³/(h.m²) on internal floors and 0.5 m³/(h.m²) on exterior walls). Party walls are found to be leakier (2.9 m³/h) than exterior walls, probably due to less attention paid in construction practice. This is because party walls have a lower impact on energy consumption than exterior walls and will often have no impact on the results of fan pressurization measurements. The leakage exponent is found to be lower than the average building exponent (0.65) for roofs (0.63) and internal floors (0.59), but it is higher for exterior walls (0.76).

The large inconsistency between studies focusing on exterior walls (88.6%) was expected because many different types of leakage are measured on exterior walls and different studies probably investigated different airflows. In addition, results are expected to strongly vary between construction types (heavyweight vs. timber construction) and measurement methods (laboratory vs. in-situ measurements).

Joist spaces in timber floors and ridge joints are studied in [39] and [40], respectively. These components should be a subsection of the internal floors and roofs categories, but since both studies reported only one measurement, they were excluded from the meta-analysis.

Table 1Table 2 presents the results of the meta-analyses performed on external wall surfaces for heavyweight structures (untreated masonry, masonry with pointing of the joints, masonry with coating, cast-in-place concrete, and precast concrete panels) and timber-frame structures (boards, planks and vapour membrane). In total, six studies were excluded from the meta-analysis because only one measurement was performed [25, 34, 39, 41-43].

Type of surface	q_{50}				n				**References**
	N	$\overline{q_{50}}$	SE($\overline{q_{50}}$)	I^2 (%)	N	$\overline{n}$	$SE(\overline{n})$	I^2 (%)	
Untreated masonry	5	11.3	5.8	93.3	5	0.78	0.04	82.2	[44-48]
Pointing joints	2	1.0	0.7	0.0	1	0.81	0.10	-	[46, 49]
Coating	6	0.1	0.1	15.7	4	0.94	0.07	70.2	[36, 44, 46-49]
Cast-in-place concrete	1	2.4	2.4	-	1	0.61	0.14	-	[32]
Precast concrete panels	1	1.4	0.5	-	1	0.68	0.18	-	[25]
Boards	6	0.0	0.0	31.6	3	0.98	0.01	15.1	[49-53]
Planks	1	16.9	15.4	-	1	0.76	0.08	-	[53]
Vapour membrane	2	0.1	0.1	0.0	2	0.76	0.08	0.0	[53, 54]

Table 2 – mean, standard error and inconsistency for airflows at 50 Pa (in $m^3/(h.m^2)$) and leakage exponent calculated through the meta-analysis of studies measuring leakage through external wall surfaces.

Untreated masonry reached high airflow values (11.3 $m^3/(h.m^2)$), which can be substantially reduced by pointing the joints (1.0 $m^3/(h.m^2)$) and by coating one or both sides of the wall (0.1 $m^3/(h.m^2)$). Cast-in-place concrete and precast concrete panels showed higher leakage than expected (2.4 $m^3/(h.m^2)$ and 1.4 $m^3/(h.m^2)$), but these also showed large standard deviation (2.4 $m^3/(h.m^2)$ and 0.5 $m^3/(h.m^2)$), which implies a large 95% confidence interval for the mean value. Leakage exponents for heavy constructions were found to be higher than the buildings mean value. This was expected, since air flows through surface are a mixture of air flowing through cracks and air flowing through the material itself, which is characterized by an airflow assumed as fully laminar (flow exponent of 1.0) [55]. This becomes especially evident when coating is added, since it covers the cracks in masonry joints.

A large heterogeneity was found in untreated masonry (93.3%), which can possibly be explained by the differences in the type of masonry (e.g., clay-brick or hollow concrete block), the wall thickness, and workmanship quality.

Timber structures can be divided into two different behaviours: boards and planks. On one hand, boards – which include fibreboard, particle board, plywood, OSB panels and asphalt impregnated fibreboards – have a mean airflow at 50 Pa below 0.1 $m^3/(h.m^2)$ with a standard deviation of 0.1 $m^3/(h.m^2)$. On the other hand, planks showed much higher leakage (16.4 $m^3/(h.m^2)$) and standard deviation (15.4 $m^3/(h.m^2)$). A large difference was also observed in mean leakage exponents (0.98 on boards and 0.76

on planks). These differences suggest that air mostly leaks through the material rather than through board cracks, but also through the space between plank elements. However, a study [53] showed that adding a gypsum board to plank walls made them as efficient as board walls.

With respect to board walls, junctions between boards and faults of the board itself can lead to large leakage. Table 3 shows the results of two studies that focused on these faults [52, 56]. These could not be combined because of the different fault types that were studied. Table 3 reports therefore the results of individual studies.

Type of defect	$\overline{q_{50}}$	SE($\overline{q_{50}}$)	References
Tongue and groove joint ($m^3/(h.m)$)	1.4	1.6	[52]
Double-board corner joint ($m^3/(h.m)$)	6.7	9.5	[52]
Triple-board corner joint (m^3/h)	3.7	3.1	[56]
Hole in gypsum boards (between 5 and 55 mm of diameter) (m^3/h)	12.4	7.3	[56]
Space between boards (between 0.5 and 2.5 mm) ($m^3/(h.m)$)	4.1	4.3	[56]

Table 3 – Mean and standard deviation of defects in boards reported by Hall and Hauser [56] and Langmans et al. [52].

In timber constructions, vapour membranes are often used to avoid condensation and hygrothermal issues with the insulation. These membranes are found to have good airtightness performance (Table 2 – 0.1 $m^3/(h.m^2)$) and can therefore compensate eventual faults on the boards. Two studies went further and looked into how the installation, or a defect in the vapour membrane (either in the membrane itself or at the connection between two parts of the membrane), can affect its performance at 50 Pa [56, 57]. As in Table 3, Table 4 reports the results from individual studies.

Type of defect	$\overline{q_{50}}$	SE($\overline{q_{50}}$)	References
Screws ($m^3/(h.screw)$)	0.1	0.1	[57]
Staples ($m^3/(h.staple)$)	0.2	0.2	[56]
Loose clamped joint ($m^3/(h.m)$)	0.1	0.2	[57]
Missing tape at vapour connection (m^3/h)	0.7	0.3	[56]
Cut in the foil ($m^3/(h.m)$)	2.2	0.9	[56]
Hole in the foil (m^3/h)	4.5	3.8	[56]

Table 4 – Mean and standard deviation for defects in vapour membrane reported by Hall and Hauser [56] and Gullbrekken [57].

Although Table 3 and Table 4 do not present new values obtained from meta-analysis, reporting them here allows to compare these results with those featured in Table 2.

3.2.2. Leakage through junctions between surfaces

Table 1Table 5 presents the results of the meta-analysis performed on the following junctions: basement floor vs. wall, wall vs. internal floor, and wall vs. wall. Wall vs. roof junctions were not reported in this table since all studies reported only one measurement and were therefore excluded from the meta-analysis [40, 52, 56, 58]. With respect to other junctions, seven studies were excluded because only one measurement was performed [23, 56, 59-63]. Study [62] measures typical construction joints including, without distinction, junctions between metal panels, wall to ceiling/floor, and wall to wall. This study was excluded from the analysis since it did not focus on one specific component. Airflow through window-wall or door-wall connections (i.e., window-frames and door-frames) are featured in the "discontinuity" category and are investigated in following section.

Type of surface	q_{50}				n				**References**
	N	$\overline{q_{50}}$	SE($\overline{q_{50}}$)	I^2 (%)	N	$\overline{n}$	$SE(\overline{n})$	I^2 (%)	
Basement floor vs wall, sill plate (BF/W)	4	0.2	0.0	0.0	2	0.69	0.17	95.2	[26, 40, 64, 65]
Basement floor vs. wall, simple connection (BF/W)	1	17.9	25.0	-	1	0.71	0.20	-	[66]
Wall vs. internal floor (W/IF)	2	1.2	0.8	0.0	1	0.78	0.03	-	[40, 67]
Wall vs. wall	2	0.5	0.1	0.0	1	0.71	0.09	-	[26, 40]

Table 5 – Mean, standard error and inconsistency for airflows at 50 Pa (in m³/(h.m)) and leakage exponent calculated through the meta-analysis of studies measuring leakage through junctions between surfaces.

Junctions between surfaces can account for large airflows, especially basement floor vs. wall for simple connection detail (17.9 m³/(h.m)) and wall vs. internal floor (1.2 m³/(h.m)). However, when the detail of the basement floor vs. wall junction includes a sill plate, it subsequently reduces airflows (0.2 m³/(h.m)). Regarding the leakage exponents, these stand between 0.69 and 0.78, which is a higher value than the mean leakage exponent.

The large heterogeneity found in the leakage exponent in basement floor vs. wall junctions (95.2 %) can be explained by the fact that both studies investigating leakage exponents [26, 64] focused on different treatments of the sill plate detail, which potentially leads to different flow regimes and, therefore, to different flow exponents.

3.2.3. Leakage through discontinuities in the air barrier

This section focuses on the purpose-provided openings applied to the air barrier during the construction process. These can entail partial penetration in the wall (e.g., electrical outlets) or total penetration of the wall (e.g., pipes, doors or windows) and induce intentional (e.g., ventilation systems) or adventitious airflows. These discontinuities to the air barrier are subdivided in 3 types: electricity and plumbing; ventilation; and, architectural components.

3.2.3.1. Electricity and plumbing

Table 6 presents the results of the meta-analyses performed on the following electricity and plumbing components: electric cables (below 20 mm of circumference), electrical outlets, and pipes (more than

130 mm of circumference). Two studies on pipes were excluded: one because it reported only one measurement [68], and one because it measured the pipe penetration and the bath enclosure at once [58]. A study on electrical outlets [60] was excluded because it provided the mean of 65 tests, without information about the standard deviation of the results. Studies [69] and [68] were excluded because results were reported in total leakage per house and not per electrical outlet. In addition, 6 results in study [70] were not considered since they measured airflow through part of a ventilated wall, including an electrical outlet, with an external vapour membrane. Therefore, the measured airflow was related to the leakage through the wall including the electrical outlet, rather than through the electrical outlet itself. Lastly, study [26] reported only one measurement of bathtub vs exterior wall connection ($q_{50} = 4.3$ m³/(h.m) and $n = 0.74$)and, therefore, had to be excluded from the meta-analysis.

Type of surface	q_{50}				n				**References**
	N	$\overline{q_{50}}$	$\mathrm{SE}(\overline{q_{50}})$	I^2 (%)	N	$\bar{n}$	$SE(\bar{n})$	I^2 (%)	
Electric cable	2	0.1	0.1	96.4	-	-	-	-	[43, 56]
Pipes	3	1.6	1.1	0.0	1	0.66	0.08	-	[26, 43, 56]
Electrical outlet	4	2.7	0.9	0.0	1	0.69	0.13	-	[26, 56, 70, 71]
Toilet flush	1	21.0	5.9	-	-	-	-	-	[56]
Recessed spotlight	1	10.6	13.3	-	-	-	-	-	[56]

Table 6 – Mean, standard error and inconsistency for airflows at 50 Pa (in m³/h) and leakage exponent calculated through the meta-analysis of studies measuring leakage through electricity and plumbing components.

These results highlighted a good sealing performance of the electrical outlets and pipe penetrations since these can induce large airflows (1.6 m³/h and 2.8 m³/h respectively) and are often found in buildings. However, these results are expected to vary as a function of the wall type. In addition to the type of wall, the standard deviation observed on pipes (1.1 m³/h) can be explained by the variation in diameters, especially when it is not properly sealed [43], and by differences in sealing methods. Toilet flush and recessed spotlight showed large airflows, but their relevance depends on their location in the building and the possible presence of a second air barrier behind them. For example, recessed spotlights are often penetrations through the false ceiling, but the air leakage can, in this instance, be stopped by the ceiling or by the internal floor.

The large inconsistency (96.4 %) among studies reporting measurements performed on electric cables can be explained by their experimental design. . One study reported the measurement of the penetration through a board [43] and the other through a foil [56], which can tear around the penetration in case of large deformations.

3.2.3.2. Ventilation

Ventilation components should not be considered in the same manner as other building components since they do not intend to be airtight when in use. In fact, they induce or extract air intentionally to provide proper ventilation. These components are still interesting since they highly impact the building's global airtightness. This section divides them in three types of components: ventilation systems; ductworks; and, chimneys.

Ventilation systems

Ventilation can be obtained through passive (e.g., ventilation grilles or ridge), automatised (e.g., self-regulated or humidity-sensitive grilles), or active (e.g., exhaust fans) systems.

For passive systems, the airflow induced depends on the size of the opening and the need for ventilation. All the values reported for this component came from single-measurement studies and were, therefore, not included in the results [56, 62, 72, 73]. However, it is of interest to mention that one study found that even though window ventilation grilles were closed, they still induced air leakage [72].

Table 7 reports the results of studies on automatized and active ventilation systems. Results from [72] about self-regulated grilles were excluded from the meta-analysis since only one measurement was reported. For active systems (i.e., extractors in Table 7), one study reported only one measurement and it was excluded from the meta-analysis [56].

Type of ventilation system	q_{50}				n				**References**
	N	$\overline{q_{50}}$	SE($\overline{q_{50}}$)	I^2 (%)	N	$\overline{n}$	$SE(\overline{n})$	I^2 (%)	
Humidity-sensitive grilles	1	61.4	39.2	-	1	0.58	0.11	-	[72]
Self-regulated grilles	1	37.0	0.4	-	-	-	-	-	[74]
Extractors with damper close	1	11.5	5.8	-	-	-	-	-	[69]
Extractors with damper open	3	52.3	14.0	0.0	-	-	-	-	[69, 75]
Junctions between the fan and the wall	1	9.6	11.4	-	-	-	-	-	[71]

Table 7 – Mean, standard error and inconsistency for airflows at 50 Pa (in m³/h) and leakage exponent calculated through the meta-analysis of studies measuring leakage through ventilation systems.

Automatised systems are an alternative to passive systems with an opening varying as a function of the pressure difference (self-regulated) and relative humidity (humidity-sensitive). The leakage of automatised systems was found to be lower than those of open passive systems (61.4 for humidity-sensitive and 37.0 m³/h self-regulated). The large standard deviation in humidity-sensitive grilles can be explained by the variation of the opening with the relative humidity of the building: measurements were conducted with different relative humidity [72]. For self-regulated grilles, the leakage exponent was not constant during a fan pressurisation test since the flow regime, and therefore the leakage exponent, may vary with the pressure difference. This is also expected in humidity-sensitive grilles if the building's humidity varies during the test.

Even when switched off, active systems can induce large airflows (52.3 m³/h) when a pressure difference of 50 Pa is applied on both sides. However, these systems are often used with a damper to improve airtightness performance, resulting in a substantial decrease of leakage (11.5 m³/h). In addition to leakage through the extractor, its junction with the wall or the false ceiling is also found to be responsible for air infiltration (9.6 m³/h). However, large standard deviations were observed for that component (11.4 m³/h).

Ductwork

As for other building components, poor ductwork airtightness induces an increase of heating and cooling demands. In addition, the fan must compensate for any leakage through the duct system in order to supply enough airflow in different rooms, which has an impact on fan energy use and noise [76, 77]. This explains the recent increasing concerns about ductwork airtightness and why some countries consider including their performance in energy regulations [78]. Ductwork performance can be divided in four classes according to the European standard [79]. Table 8 provides an overview of the air leakage limit for each class, as well as its corresponding value in airflow at 50 Pa per hour to remain consistent with this analysis.

Ductwork class	f_{max}	$q_{50,max}$
Class A	$0.027 * \Delta p^{0.65} * 10^{-3}$	1.24
Class B	$0.009 * \Delta p^{0.65} * 10^{-3}$	0.41
Class C	$0.003 * \Delta p^{0.65} * 10^{-3}$	0.14
Class D	$0.001 * \Delta p^{0.65} * 10^{-3}$	0.05

Table 8 – Air leakage limit in m³/(s.m²) and in airflow at 50 Pa (m³/(h.m²) for each class of ductwork according to the European standard. Table adapted from [79].

In fact, the meta-analysis included only two studies that report ductwork measurements by m³/(h.m²) [80, 81]. A large study (more than 1200 measurements) was excluded since it expressed the results as a percentage of measured ductwork in each class [82], two studies were excluded since they expressed the results in total leakage (m³/h) rather than per ductwork square meter [69, 83], and one study was excluded since it reported only one measurement [60]. Since the same number of studies reported the results in m³/(h.m²) and in m³/h, and in m³/(h.m²), this criterion was selected for the reported result to remain consistent with the European standard [79]. The meta-analysis on both studies selected showed a mean airflow of 0.8 m³/(h.m²), a standard deviation of 0.9 m³/(h.m²), and an inconsistency in results of 0.0 %. Regarding the leakage exponent, the analysis resulted in a mean value of 0.59, a standard deviation of 0.04, and an inconsistency of 0.0%.

Both studies reported field measurements, but a large inconsistency would have been expected for a meta-analysis combining in-situ and laboratory measurements since the absence of joints in some elements of the ductwork is often observed *in-situ* [84]. In addition, ductwork often does not reach the expected performance once installed on site since some joints might be missing [82]. This highlights the need for *in-situ* measurements of ductwork airtightness.

Chimneys

Study [85] showed that the airtightness performance of chimneys should be divided in three types of airflows: airflow 1 at the connection between the chimney flue and roof; airflow 2 through the chimney flue; and, airflow 3 at the opening itself. These are schematised in Figure 3.

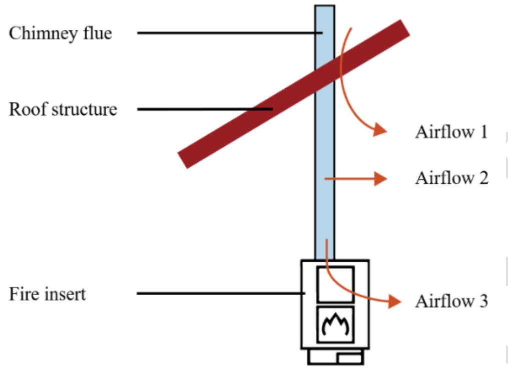

Figure 3 – Types of airflows encountered in chimneys. Sources: authors.

Table 9 presents the results of the analysis conducted on the three different types of airflows in chimneys. Three studies were excluded because they reported only one measurement [58, 60, 86].

Type of airflows	q_{50}				n				**References**
	N	$\overline{q_{50}}$	SE($\overline{q_{50}}$)	I^2 (%)	N	$\overline{n}$	$SE(\overline{n})$	I^2 (%)	
Connection with roof	1	37.2	108.5	-	1	0.81	0.16	-	[85]
Connection with roof + chimney flue	1	35.3	42.5	-	1	0.78	0.13	-	[87]
Chimney flue	1	14.1	16.8	-	1	0.72	0.06	-	[85]
Fire opening	3	141.9	57.8	95.6	-	-	-	-	[56, 69, 75]

Table 9 – Mean, standard error and inconsistency for airflows at 50 Pa (in m³/h) and leakage exponent calculated through the meta-analysis of studies measuring leakage through chimneys.

Chimneys were found to be very leaky, whatever the airflow considered. All these airflows showed large standard deviation, especially airflow 1. This is due to the difference between the untreated detail (345.9 m³/h) and treated detail (mean of 8 reported results is 3.3 m³/h), which are both considered in the calculation of the standard deviation. In the case of airflow 3, one of the studies found surprisingly low standard deviation (1.4 m³/h [56]) compared to others (23.1 [75] and 45.7 m³/h [69]), which explains the large inconsistency between results (95.6 %). Since this standard deviation was calculated from only two measurements, it showed a large uncertainty [88] that in turn resulted in large uncertainty for I^2 and SE($\overline{q_{50}}$) when combining studies. Another reason that can possibly explain this large inconsistency among studies is the difference in measurement methods (*in situ* vs. laboratory) and the differences in sample characteristics (e.g., presence of dampers and fire inserts).

Values of leakage exponents were found to be higher than average (0.81, 0.78 and 0.72 for airflows 1, 1+2 and 2). No study investigated the leakage exponent of airflow 3, which is expected to be close to 0.5 because of the large opening (the flow regime is more likely turbulent), especially with an open damper and no insert.

3.2.3.3. Architectural components

Table 10 presents the results of the meta-analyses performed on windows, window frames, and doors. Six studies were excluded for windows [62], window-frame [58, 63, 68, 89], and doors [68]. Two studies were excluded for roller-shutters [68, 74] because they reported only one measurement. This resulted in only study meeting the inclusion criteria, therefore preventing the meta-analysis. In addition to this, four studies focusing on windows were excluded because results were expressed per square meter of window area [90, 91] or per window [58, 92] rather than per opening length.

Type of architectural component	q_{50}				n				**References**
	N	$\overline{q_{50}}$	SE($\overline{q_{50}}$)	I^2 (%)	N	$\overline{n}$	$SE(\overline{n})$	I^2 (%)	
Windows	12	2.0	0.6	36.3	3	0.69	0.07	52.0	[30, 56, 71, 74, 93-100]
Window frame	4	0.3	0.2	81.0	-	-	-	-	[39, 40, 101, 102]
Roller-shutter box	1	6.0	1.4	-	-	-	-	-	[56]
Doors	8	137.6	46.7	87.3	3	0.62	0.16	0.0	[30, 56, 58, 60, 74, 75, 92, 99]
Elevator door	1	1049.6	156.7	-	1	0.59	0.12	-	[32]
Revolving door	1	1908.0	1294.2	-	1	0.71	0.04	-	[103]

Table 10 – Mean, standard error and inconsistency for airflows at 50 Pa (in m³/(h.m) for windows and window frames and in m³/h for doors) and leakage exponents calculated through the meta-analysis of studies measuring leakage through architectural components.

Windows and window frames

There are numerous windows in buildings, which make this component very important for achieving the building's airtightness requirements. The mean value (2.0 m³/(h.m)) appeared to be large compared to what would be acceptable for new constructions today. The leakage exponent was found to be close to the mean observed in buildings. This component is further investigated via subgroup meta-analysis in section 3.2.3.4.

Another type of leakage related to window elements is the connection of the window with walls, generally referred to as window frame. This leakage was found to be of lower importance than the air leakage through the windows themselves (0.3 m³/(h.m)). One possible reason of the large inconsistency between these results (81.0 %) could be represented by variations in junction treatments, type of window, material and wall type.

Roller-shutter boxes also showed large leakage (6.0 m³/h), but the variation among results was lower than expected (1.4 m³/h). Larger variation was anticipated since the performance can strongly change depending on the model. The study reported in Table 10 measured only 2 cases focusing on airtight models of roller-shutters, while other studies, which were excluded, reported results of different models (10.2 and 517.4 m³/h). Further investigation of roller-shutter boxes should be performed in order to characterise the airtightness performance of these components.

Doors and door frames

Usually, there are few doors around the measured volume of a building, but these are responsible for large leakage (137.6 m³/h). In this meta-analysis, no distinction was made between internal doors, external doors, sliding glass doors, and trap doors (e.g., doors providing access to an attic or crawl space), which are expected to have different airflows because of different sizes and treatments. This is a possible explanation of the large standard deviation of air leakage (46.7 m³/h) and the large inconsistency (87.3%) between results (induced by the sample characteristics). In addition, these studies combined different testing methods, including laboratory and *in-situ* measurements. For doors, the leakage exponent (0.62) was slightly below the mean in buildings.

There are three types of doors that were considered differently because of their function: revolving doors (1908.0 m³/h), elevator doors (1049.6 m³/h), and sectional doors (one study with one measurement obtaining a value of 9504.0 m³/h [73]). These doors were found to be much leakier and should be positioned in a location where they do not entail pollutant penetration, discomfort, or increased energy demands, or they should be carefully treated to substantially improve their performance. However, all these values were based on single study analyses.

No study investigated directly door frames, but these were considered in many "combined studies" as explained hereafter.

Combined studies

Many studies report architectural components mixed with other components; these have been categorised as "combined studies". Among these, four were excluded from the door + window frame [52, 61, 75, 89] and one from windows + doors [23] due to a single measurement. In the case of windows + doors, one study was excluded because the results were reported in total leakage for one house rather than per crack meter [30]. Table 11 presents the results of the meta-analysis and single relevant studies performed on windows + window frames, window frames + door frames, and windows + doors.

Type of architectural component	q_{50}				n				**References**
	N	$\overline{q_{50}}$	SE($\overline{q_{50}}$)	I^2 (%)	N	$\overline{n}$	$SE(\overline{n})$	I^2 (%)	
Windows + window frame	2	4.3	2.6	0.0	-	-	-	-	[56, 63]
Window + door frame	1	0.0	0.0	-	-	-	-	-	[104]
Windows + doors	1	8.1	8.9	-	-	-	-	-	[58]

Table 11 – mean, standard error and inconsistency for airflows at 50 Pa and leakage exponent calculated through the meta-analysis of "combined studies" of architectural components.

Two studies performed in-situ tests using direct technique on the window and the window-wall junction at once (7.8 m^3/h) [56, 63]. One study looked at typical window frames and door frames joints treated with PUR (Polyurethane rigid foam) in timber structures (0.0 $m^3/(h.m)$) [104]. Lastly, one study reported results without making a distinction between windows and doors (8.1 $m^3/(h.m)$) [58]. The results obtained were of the same order of magnitude than the results observed in the other un-combined studies presented in this section.

3.2.3.4. Exploring heterogeneity of windows airtightness

Windows represent the most studied and reported architectural element, with larger samples than for other components. This is due to multiple reasons: the standards of laboratory measurement of windows [105, 106]; the large impact of windows on airtightness; and, the ease to measure window airtightness on site compared to other building components. The higher number of studies available makes it possible to investigate more in depth heterogeneity among studies and variables influencing window airtightness.

Table 12 provides details about the studies used in the meta-analysis on windows. For each study, the table provides the authors, the year of publication, the size of the sample (N), the type of measurement performed (i.e., laboratory or *in-situ*), the material (timber, aluminium, or unspecified materials) and the type of windows measured (double window, single window, sliding window, or unspecified type).

Ref	Author(s)	Year	N	Type of measurement	T	A	Um	DW	SW	SL	Ut
[30]	Tamura	1975	17	In-situ	x			x	x	x	
[93]	Lowinski	1979	6	Laboratory	x			x	x		
[94]	Almeida et al.	2017	23	In-situ	x	x		x	x	x	
[95]	Weidt et al.	1979	192	In-situ	x	x		x	x	x	
[96]	Larson et al.	1930	14	Laboratory	x			x		x	
[97]	Van den Bossche and Janssens	2016	437	Laboratory			x	x	x	x	
[98]	Carruthers and Newman	1977	131	Laboratory	x				x		
[74]	Pinto et al.	2011	3	In-situ			x			x	
[99]	Ward and Sharples	1982	10	In-situ			x			x	
[56]	Hall and Hauser	2003	10	Laboratory	x				x		
[100]	Persily and Grot	1984	18	In-situ			x				x
[71]	CMHC	1991	6	Laboratory			x				x

Table 12 – List of publication used for the meta-analysis on windows, including the authors, the year, the sample size (N), the type of measurement, the material (T= Timber, A = Aluminium and Um = Unspecified material) and the type (DW = Double window, SW = Single window, SL = Sliding window and Ut = Unspecified type) of window measured.

Figure 4 illustrates the results of the meta-analysis conducted on these 12 studies. Black lines represent the 95% confidence interval ($\overline{q_{50}} \pm 2 * \text{SE}(\overline{q_{50}})$) around the mean value ($\overline{q_{50}}$, black dot). The last line (in blue) represents the total 95% confidence interval, while the red dashed line indicates the mean value for the combined results.

This figure shows that the combined mean value (2.0 m³/(h.m)) falls outside the 95% confidence interval for one study [71]. The reason for the low mean leakage and standard deviation of [71] is probably due to the sample characteristics. In fact, study [71] tested only inoperable windows, while other studies looked at different types of operable windows. This hypothesis is strengthened by the inconsistency index (I^2) obtained from the meta-analysis conducted without this study ($\overline{q_{50}} = 2.5$m³/(h.m), SE($\overline{q_{50}}$) $=$ 0.5m³/(h.m) and $I^2 = 0.0\%$). Therefore, the following investigations are conducted on the pool of 11 studies. In addition, two studies found much higher mean values [94, 99] but these are less weighted in the combination since their standard deviation was higher.

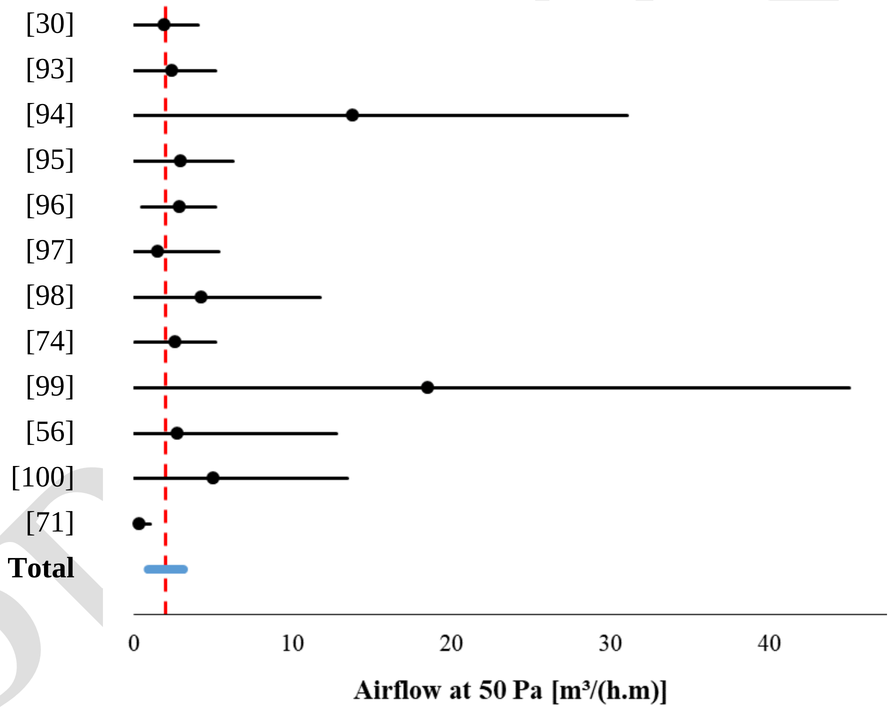

Figure 4 – Forest plot obtained from the meta-analysis conducted on windows study presented in Table 10

Subgroup meta-analysis can be used to explore reasons for heterogeneity, but it also provides an insight on how the variables influence the measurement of airtightness of windows. Table 13 shows the results of the subgroup meta-analysis conducted for three variables: measurement methods, type of windows, and materials. It is important to keep in mind that subgroup meta-analyses are conducted on fewer studies compared to whole group meta-analysis and, therefore, have higher uncertainty with respect to the calculation of I^2 and SE($\overline{q_{50}}$).

Subgroup analysis		N	$\overline{q_{50}}$	SE($\overline{q_{50}}$)	I^2 (%)	**References**
		q_{50}				
Measurement method	In-situ	6	2.5	0.7	0.0	[30, 62, 74, 95, 99, 100]
	Laboratory	5	2.5	0.8	0.0	[56, 93, 96-98]
Type of windows	Single windows	7	1.8	0.5	50.7	[30, 56, 93-95, 97, 98]
	Double windows	6	2.0	0.5	0.0	[30, 93-97]
	Sliding windows	7	3.2	0.7	18.9	[30, 74, 93-95, 97, 99]
	Unspecified	1	5.0	4.2	-	[100]
Window materials	Timber windows	7	2.4	0.6	0.0	[30, 56, 93-95, 98, 99]
	Aluminium	2	4.1	1.5	0.0	[94, 95]
	Unspecified	4	2.5	1.0	0.0	[71, 74, 97, 99, 100]

Table 13 – Sample size, mean, standard error (in m³/(h.m)) and inconsistency for airflow at 50 Pa for three subgroups meta-analyses based on the measurement method, the type of window, and the window material.

These subgroup meta-analyses highlight that differences should be expected among various types of windows and window materials (different means and standard deviation), but not between measurement methods (*in-situ* vs. laboratory). These three variables are further investigated in the following sections. Other variables could have been relevant in this context (e.g., year of implementation for windows measured *in-situ*) but could not be included due to lack of information in the studies analysed.

For the first variable, all studies used either laboratory or *in-situ* measurements (i.e., none of them looked at the difference between both). The results obtained with the subgroup meta-analysis suggested that the differences detected considering this variable were not significant. This was confirmed with an independent t-test, which showed that there was no statistical (*p*-values) nor practical (effect size) evidence of differences between mean values calculated in studies performing *in-situ* and laboratory measurements ($t = 0.017$; $p = 0.988$; $g = 0.01$). The Hedge's g coefficient was preferred over other indicators (e.g., Cohen's d and Glass's) because the standard deviation of independent groups and their sizes were different [107].

Multiple studies compared different types of windows and a meta-analysis could be conducted to determine a combined difference in means among various window types. Since none of the studies reported effect sizes, these must be calculated based on the data provided. In this context, the raw mean difference is appropriate since the outcome is reported in a meaningful scale (airflows in m³/h). Raw mean difference can be used because studies reporting results in other type of outcomes (i.e., excluded from the meta-analysis conducted in 3.2.3.3) did not investigate the impact of window type on air leakage [90-92]. The main advantage of using this measure of effect size rather than standardized differences (e.g., Cohen's d or Hedge's g) is that the result of the meta-analysis is intuitively meaningful [13].

The combination of relevant studies reported in Table 14 shows that double windows were leakier than single windows, and that both single and double windows were tighter than sliding windows. However, for the three cases, a large inconsistency was found between studies, pointing out the need of additional research looking at these specific types of windows.

	D				References
	N	**D**	**SE(D)**	I^2 (%)	
Double - Single	5	0.98	0.73	94.8	[30, 93-95, 97]
Single - Sliding	5	-1.58	0.75	95.6	[30, 94, 95, 97, 98]
Double - Sliding	4	-0.37	0.37	70.5	[30, 94, 95, 97]

Table 14 – Mean, standard deviation and inconsistency for the raw difference of means of different types of windows

Likewise, as for the type of windows, three studies looked at different window materials [94, 95, 97], and a similar methodology can be used to conduct the meta-analysis. However, one of the studies did not report sufficient details and results regarding differences between window materials to include them in the meta-analysis [97].

The meta-analysis conducted on two studies showed a higher mean airflows for timber windows ($D = 4.8$ m³/(h.m)) than aluminium windows but with a high standard deviation ($SE(D) = 9.1$ m³/(h.m)) and high inconsistency among studies ($I^2 = 71.3\,\%$). This makes this conclusion quite uncertain, in addition to the need for further research to explore the heterogeneity between these studies.

4. Discussion

A thorough review of studies measuring airtightness performances of building components, and the meta-analysis of reported measurements, resulted in three different outcomes: 1) a classification of building components related to their airtightness performance (section 3.1); 2) "new" means and standard deviations and inconsistency indices of building components' performance calculated on the basis of a weighted combination of studies (3.2) the identification of variables influencing airtightness performances of windows (section 3.2.3.4).

These three outcomes bring novelty to the literature in the field of building airtightness and, more generally, within the domain of the built environment.

The classification provides a comprehensive list of building components studied in previous research due to their impact on building airtightness. The proposed 4-level classification allows to understand the different type of flows (level 1), the different components category for each type of flow (level 2), the components falling into each category (level 3), and the possible treatments or type of each component (level 4). Having this 4-level structure can be of great support in building practice, to understand how to deal with which component, and in research, to consistently compare the performance of different components (e.g., it is often more relevant to compare a component with others of the same category).

Updating and improving existing databases of airtightness performance of building components is also of significant interest because of three important additions to current knowledge:

- Consideration of the studies conducted between the mid-90's and today, which is very important because of the changes in construction practice driven by recent energy policies;
- Relevance of a weighted combination of studies, which gives more importance to studies with higher accuracy and, therefore, with larger sample size and / or more rigorous experimental design;
- Evidence of the inconsistency between different studies, which is an additional information for the user regarding possible additional errors in the combined values.

Exploring heterogeneity among studies focusing on window airtightness also responds to questions related to the impact of window type and window material on airtightness performance. The analysis presented shows that only the type of window has a practically relevant impact on window airtightness, although large inconsistencies appear among studies when looking at raw mean differences.

In addition to these three outcomes related to the field of airtightness, this paper has explored the transfer of meta-analysis methods to the domain of the built environment (e.g., using mean or raw differences rather than effect sizes). This is of a great interest for research, since this approach can offer a robust protocol to combine evidence from different studies based on an estimation of their accuracy.

Nevertheless, some limitations should be acknowledged in the review of studies and in the meta-analysis. Among these: the low number of studies available; the lack of studies focusing on the treatment of components; some missing information on the tested components; and, the lack of statistical evidence when reporting some of the results. Consequently, the outcomes obtained should be considered in light of these limitations.

The low number of studies available impacts the three outcomes in different ways. First, in the classification, many third level blocks are missing since these are not studied in literature. Second, more studies would reduce the uncertainty of I^2 and $\mathrm{SE}(\overline{q_{50}})$ for meta-analysis and subgroup meta-analysis. Finally, a larger number of studies would increase the potential of subgroup meta-analysis when exploring heterogeneity by making it less likely to have subgroups created from only one study.

The lack of studies investigating treatments also impacts the three outcomes. First, it would lead to additional blocks at the fourth level of classification. Second, looking at different treatments individually could reduce the standard deviation observed in the results of meta-analysis, since different treatments might induce different airtightness performance. Therefore, looking at each treatment individually would result in a smaller range of measured airflows and lower standard deviation. Lastly, studying different treatments is only feasible if the number of studies looking at the treatments of one specific component is larger than the number of treatments investigated.

The lack of information reported in the tested component is a limitation for the subgroup meta-analysis since it reduces the possibilities of selecting subgroups to explore heterogeneity among studies. For example, the absence of information regarding the year of implementation of windows for *in-situ* measurements in some studies prevents conducting subgroup meta-analysis, which is expected to have an impact on airtightness performance.

These limitations not only influence the outcomes of the meta-analysis but can also affect the results of any study reporting measurements of building components. This is a potential reason for the relatively sparse literature available on the airtightness performance of building components, despite its large potential in improving infiltration models and airtightness prediction. However, increasing the number of studies would not be helpful unless their experimental design, and the methods to report results, is appropriate for the application of meta-analysis methodologies. To improve the statistical power, reliability, and the potential applicability of meta-analysis approaches based on the limitations here identified, future studies should meet four requirements:

- Each study should measure at least two different cases for each component and provide a standard deviation in addition to the mean value. Moreover, a larger number of measurements would result in a more accurate calculation of the standard deviation and, therefore, a more accurate weighting in the combination of studies.
- The characteristics of the measured sample should be thoroughly described based on previous research for future analysis (e.g., materials of the component, year of testing, year of implementation, etc.). The sample description should refer to the classification suggested in this paper as an improvement (new component), to increase precision (new treatments), or to reinforce evidence for an existing case (already identified in the classification).
- The airtightness performance of building components must be reported with the leakage exponent and the information required for the different normalisations encountered for the component (e.g., area-to-length ratio for windows). This would increase the number of studies to be considered in the meta-analysis.
- Studies comparing different treatments of windows should report the effect size of the observed difference between treatments to make them comparable with previous studies even if these have inherent differences (e.g., differences in outcomes or measurement methods).

5. Conclusion

This paper presented the results of a meta-analysis conducted on a critical synthesis of literature studies reporting measurements of building component airtightness.

Its main conclusions can be summarised in three different outcomes: a 4-level classification of building components based on their airtightness performance (i.e., type of flows, category of components, components and type/treatments); an update of existing airtightness databases; and, a thorough investigation of factors influencing airtightness performance of building components.

A critical appraisal of these findings, and of the limitations encountered, led to the definition of requirements that future studies should meet to improve the reliability of meta-analyses.

These outcomes offer a step ahead from existing knowledge by adding new evidence to existing industry references and providing a framework for future research. In this context, meta-analysis – a study procedure commonly used in clinical research – is a rigorous method that can allow to compare data from previous studies, even when they have inherent differences. Other than a strong need for additional studies reporting measurement of airtightness performance of building components, the application of meta-analysis protocols revealed that some aspects of the methodology should be further investigated in future studies (e.g., the index of inconsistency or the desired number of studies for each meta-analysis) to improve its potential use. Nevertheless, this can be of substantial interest to many practitioners and researchers due to its possible application to many other domains of the built environment.

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