Factors Influencing Airtightness and Airtightness Predictive Models: A Literature Review

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Abstract

In recent decades there has been a growing awareness regarding energy consumption in buildings. Unfortunately, at a time when all building actors should get involved in the challenge to reduce energy consumption, designers cannot rely on effective tools to help them in their decision making process concerning airtightness. This literature review allows the identification of two important issues: new airtightness predictive models are complex to develop and existing airtightness predictive models do not meet the needs of designers and contractors. This paper is divided into three main parts in addition to the introduction and the conclusion. The first part deals with the key concepts of infiltration and airtightness, the second part with influencing factors and the third part with airtightness predictive models. These different chapters highlight a need for standardization regarding the metrics used for data presentation, parameters definition and statistical quantification. The lack of standardization hinders the development of a new airtightness predictive tool for designers and contractors. Along with the problem of standardization, supervision and workmanship are parameters that are difficult to model. Their significant impact can explain why designers and contractors find some existing models unreliable. This paper concludes that none of the existing models can be used in their present form as design tools. Further work should focus on the standardization of data presentation and on the development of a new airtightness predictive model. The first step in the development of such a model is to draw an appropriate classification of "air paths."

Keywords: Airtightness review; Airtightness models; Airtightness influencing factors; Blowerdoor Test; Infiltration.

Highlights

- Deduces the airtightness influencing factors from references
- Reviews the predictive models and analyzes their ability to be used as design tools
- Emphasizes the need for the standardization for the data presentation

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- Suggests future research as classification of "infiltration paths"

1. Introduction

A few years ago, worldwide political leaders recognized the need to set ambitious challenges in energy consumption. Europe [1, 2], the United States [3] and Russia [4] developed energy strategies for the next decades. The building sector plays a large role in final energy consumption and thus requires particular attention. The European Commission adopted the 2010 Energy Performance of Buildings Directive [5] and the 2012 Energy Efficiency Directive [6]. Today, energy challenges concern the entire building sector, from field workers to researchers. Air infiltration can be responsible for up to 30% of the heating demand in winter [7, 8, 9] and it impacts insulation thermal performances, hygrothermal performances, occupant comfort, ventilation system efficiency and acoustic insulation [10, 11, 12, 13, 14, 15, 16, 17]. Furthermore, industry members and organizations highlight the responsibility of air leakages in many types of building failures [18]. Despite its impact on energy consumption, air infiltration phenomenon remains poorly developed by researchers and equally mastered by designers and contractors.

Airtightness is the main envelope property impacting infiltration [19]. Most national regulations require minimum performances for new buildings. Up until now, the experience of designers and contractors, and practical guides were enough to ensure acceptable airtightness [20, 21, 22]. Airtightness requirements have been strengthened over the last few years. Today, their implementation is expensive and time-consuming due to the lack of knowledge and tools. Researchers need airtightness predictive models to model the infiltration phenomenon and designers and contractors need such models to control costs and time in implementing the regulations. Why, when designers and contractors need new tools, aren't predictive tools being developed that would be suitable for practical use ?

This literature review reveals two issues: the lack of standardization hinders the development of new airtightness predictive models and existing airtightness predictive models do not meet the needs of designers and contractors. The lack of standardization is discussed in the first and second chapters while existing models are discussed in the third chapter. The first chapter deals with infiltration and airtightness key concepts, the second with airtightness influencing factors and the third with existing predictive models.

2. Key Concepts

Authors develop in this chapter four key concepts: the air infiltration phenomenon, the difference between infiltraton and airtightness, the measurement methods, the theory about flow through cracks and, finally, the nomenclature and metrics. This last section highlights an inconstancy between authors regarding the metrics.

2.1. *Air Infiltration Phenomenon*

Infiltration is the mass of air passing through cracks or other unintentional envelope openings. This airflow is driven by pressure difference across the envelope [23]. In buildings, such pressure difference occurs because of stack effect and wind pressure. The stack pressure difference is a gradient over the building height caused by a temperature difference. The wind pressure is caused by air flows around the building. It depends on location, geometry, air density, wind speed and wind direction [24]. Infiltration modeling is important since it is a key to understand and predict airtightness. Nevertheless, this literature review focuses on airtightness and not on infiltration.

2.2. *Differences Between Infiltration and Airtightness*

Airtightness should not be confused with infiltration. On the one hand, infiltration is a physical phenomenon: under a pressure difference, air infiltrates the building through envelope cracks or unintentional openings. On the other hand, airtightness is the main envelope property impacting infiltration and is defined as the flow of air infiltrating the building at a pressure difference of 50 Pa. The infiltration phenomenon depends on wind speed, temperature and location while airtightness is intended to be independent of climate variations. Climate influence is reduced by taking a 50 Pa pressure difference [19].

Although airtightness and infiltration are different, they can be mathematically linked. The first empirical relation is known as "rule of thumb." It simply consists in the assumption that the infiltration in a building is $1/20^{th}$ of its airtightness [25]. This relation does not take into account numerous parameters impacting the infiltration. In 1987 Sherman developed the well-known model: "LBL (Lawrence Berkeley Laboratory)" model. Sherman suggested correction factors to take into account the building height, the wind exposure and the type of cracks [26]. Another existing empirical model is the "AIM-2 (Alberta air Infiltration Model)" developed by Walker and Wilson in 1990. This model assumes that the total airflow is a function of the stack flow and the wind flow [27].

2.3. *Airtightness Measurement Methods*

For airtightness, measurement is crucial. Sadauskiene et al. show that energy performance calculations seem only reliable after verifying the building airtightness [28]. To our knowledge, correlated with Relander et al. [29], none of the references argue that estimations could replace measurements.

The most popular tests to measure airtightness is the fan pressurization method or blowerdoor test. It consists in the successive building pressurization and depressurization with a fan placed in an opening (door or window) [24]. Sensors record airflow required to maintain a given pressure difference. Q-ΔP couples are recorded and n and C (equation 2) can be determined. Norm EN 13829 [30] suggests the use of the least square method to determine mean building value for n and then to determine C. Okuyama and Onishi [31] questioned this methodology. In their paper, Okuyama and

Onishi suggest a weighted least-squares method, a correction of the parameter estimation equation and the deduction of the uncertainty propagation equation. In our view, although these authors present an improved method, it should be trialed in more field studies before drawing solid conclusions. Such investigations would be useful to reduce uncertainties which are an important issue for blowerdoor test measurements [32].

Other methods are much less used since another device is needed, on the top of the measurement device, to fix the pressure difference between in- and outside at 50 Pa. In recent years acoustic methods have emerged. These methods try to quantify airflow based on the ultrasound reduction recorded between a wave transmitter on one side of the envelope and the wave receiver on the other side. Further development of these techniques would be useful to create an effective component leakage measurement method. Unfortunately, even though these methods are effective to localize air leakage, they are not yet validated to quantify air leakage [33, 34]. Other new measurement techniques have been developed to determine airtightness in specific cases. One of them is the sudden expansion from a compressed chamber used to measure airtightness in rooms [35, 36]. The tracer gas method does not measure airtightness, but it must be still mentioned as the most common method to measure infiltration [37, 38]. Tracer gases are also sometimes combined with the fan pressurization method to localize air leakages.

2.4. Flows Through Cracks

Air flows (Q) through cracks is due to a pressure difference (ΔP) between both sides of the crack. The relation between Q and ΔP depends on the type of crack. Q is proportional to ΔP in cracks dominated by laminar flows and Q is proportional to $\sqrt{\Delta P}$ in cracks dominated by turbulent flows [19, 39]. In practice dominating flows in cracks are neither completely laminar nor completely turbulent. Thus, Etheridge suggested in 1977 a relation (quadratic) where both type of flows are separated (Eq. 1) [40].

$$\Delta P = \alpha Q + \beta Q^2 \tag{1}$$

The power law (Eq. 2) is much more encountered in literature and practice. The exponent n chatacterize the type of flow dominating the crack. Exponent is 1 for laminar flows and 0.5 for turbulent ones.

$$Q = C(\Delta P)^n \tag{2}$$

Researchers widely discussed the use of one or other expression. In 1987, Baker et al. [41] developed the case of parallel plates. He suggested that the quadratic form represents the experimental datas better than the power law. In 1992, Sherman [42] showed that both representation can be interchanged in the case of short pipes. In 1998, Walker et al. validated the use of power law in standards and measurement procedures. This validation was based on theoretical analysis, laboratory measurements and in situ testing [43]. They prove that power law represents better the relation between Q and ΔP in many cases. Nowadays, authors almost always use the power law.

The issue of flow through cracks and openings is important. These last years research focus often on global building airtightness. Nevertheless, some papers focus on the air flow through components: duct leakage studied by LBNL [44, 45] and leakage through wood-frame houses component by Relander et al. [46, 47, 48].

2.5. Nomenclature and Metrics

An important metric used is the Effective Leakage Area (ELA). ELA is based on the orifice equation (Eq 3) where C_d is the discharge coefficient, A the orifice area and ρ the air density.

$$Q = AC_d\sqrt{\frac{2\Delta P}{\rho}} \tag{3}$$

ELA is defined in ASHRAE as "the area of an orifice [...] that would produce the same amount of leakage as the building envelope at the reference pressure" (Eq 4) [24].

$$ELA = \frac{Q\sqrt{\frac{\rho}{2\Delta P}}}{C_d} \tag{4}$$

NLA is sometimes used also. NLA is a derived quantities of ELA. It is simply defined as ELA divided by the area across which pressure difference occurs.

Other metrics have been used, in norms and regulations. Terms used in European standard can sometimes be confusing and are then not used in this review paper. The table 1 makes a list of terms, units and mathematical relation linking different metrics.

Paper notation	European norm [30]	Unit	Mathematical relation
$Q_{\Delta P}$	/	m^3/h	none
ACH	/	h^{-1}	$ACH = Q_{real}/V$
ACH_{50}	n_{50}	h^{-1}	$ACH_{50} = Q_{50}/V$
q_{50}	q_{50}	$m^3/(h.m^2)$	$q_{50} = Q_{50}/A_E$
w_{50}	w_{50}	$m^3/(h.m^2)$	$w_{50} = Q_{50}/A_F$

Table 1: Paper nomenclature, European norm, units and mathematical relations of air tightness variables

$Q_{\Delta P}$ is used to define the airflow entering the building by infiltration at a given pressure difference. Q_{real} is used for infiltration flow to avoid confusion in subscripts, but it is never used neither in literature nor in practice. ACH is the Air Change Rate in actual conditions. It is the ratio between infiltration and building volume. ACH_{50} is the air change rate at a 50 Pa pressure difference. q_{50} is the building air permeability: ratio between infiltration flow and envelope area. w_{50} is the building specific leakage: ratio between infiltration flow and floor area.

The metric used depends on the author, the country or the goal of the project. This huge lack of uniformity makes results difficult to compare and conclusions difficult to draw. Urquhart et al. already highlight the need of metric standardization [49]. A standardized metric should: (i) have a simple physical meaning ; (ii) allow the comparison of buildings of different size ; (iii) be related to regulations and ; (iv) give an information to the user about main leakage paths in the building. In their paper, Urquhart et al. recommend the use of NLA as a standard metric. ELA has a simple meaning but do not fulfill other requirements. NLA has a simple meaning and allows the comparison of buildings of different size, but is not related to regulation. ACH_{50} and q_{50} are directly linked to regulations but have no simple meaning.

In our point of view, none of the current metric could be used as a standardized metric. We think that more than one metric should be used to describe the building airtightness. For example the main metric could be ELA since it gives a simple meaning. Three complementary metrics could then be added: the airflow at 50 Pa could be divided once by the enclosure area (q_{50}), once by the total length of linear air leakage paths and once by the number of punctual air leakage paths. An experienced designer would be able to extract information from the comparison of these three complementary metrics. Tables of typical values for different building sizes would help less experienced designers or contractors to choose an appropriate retrofit to achieve good airtightness.

3. Factors Influencing Airtightness

To understand or develop a predictive model, factors impacting airtightness must be known and understood. This part deals with impacting factors identified in literature and tries to understand how such factors impact airtightness. This section reveals and discusses other standardization problems.

3.1. References

For years, many authors have performed blowerdoor tests. These works can be compared to understand how factors impact airtightness. Table 2 summarizes main information about references analyzed. A (*) symbol means that the significance is not assessed in the paper but test results are available and this review paper made a statistical analysis. A huge recent database is not mentioned in the table because it has not yet been analyzed, but Bailly et al. recently gathered results of 65.000 blowerdoor tests [50].

Ref	Year	Country	# of Unit	Significance analysis
[51]	2016	Netherlands	300	Multiple regression analysis
[52]	2016	Czech Republic	150	Spearman's Rank correlation
[53]	2016	Spain	45	ANOVA test
[54]	2014	Belgium	153	t-test
[55]	2015	Finland	226	t-test
[56]	2013	US	134.000	multiple regression analysis
[57]	2012	Italy	20	none *
[58]	2012	Ireland	28	none *
[59]	2011	Uk	53	none *
[60]	2010	France	251	multiple regression analysis
[61]	2010	Uk	287	multiple regression analysis
[62]	2008	Greece	20	regression analysis
[7]	2007	Estonia	32	t-test
[63]	1984	Canada	200	none *

Table 2: Summary of the different references performing air tightness measurements to identify influencing factors. * = references without statistical analysis, but such analysis is made in this paper based on available test results.

A residential leakage database (ResDB) was created In US in mid 1990's. ResDB has been updated several times and now contains data from about 147.000 homes [64]. Various analysis of ResDB were performed in 1994 [65], 2002 [66], 2005 [67], 2006 [68], 2007 [69], 2012 [70] and 2013 [56]. Only the last analysis is presented in table 3. This analysis covers the largest number of measurements and seems the most relevant in the context of this review paper.

3.2. Parameters

These references discuss many different parameters. Sometimes authors use different names for the same variable and sometimes the same name can have different definitions. In this review, parameters are divided into four categories: Geometry, Technology & Materials, Guidance & Supervision and External. Table 3 summarizes results. The parameter ranking is shown in the leftmost column. This ranking is an indicator of the impact significance. It is a value between 0 (not significant), 1 (significant) and 2 (highly significant). (*) is used for parameters not enough discussed in references and (?) for parameters not directly linked to the infiltration. This ranking must be carefully used and it should always be compared to the number of cross-references leading to these conclusions.

Parameters and ranking		Significant	Not significant
Geometry			
?	Number of stories	[7, 63, 57, 62, 60]	[55, 53]
?	Envelope area	[58, 61, 63]	[53, 57]
?	Floor area	[53, 60, 56]	[61, 57, 51, 63]
?	Volume	[53, 58, 62]	[57, 63]
*	Window and frame area	[53]	[57]
*	Frame length	[53, 62]	[57]
*	Number of penetrations	[61]	
Technology and materials			
2	Envelope structure	[51, 55, 59, 60, 61]	[54]
2	Building method	[55, 51, 7]	
2	Ventilation system	[7, 55, 54]	
1	Dwelling type	[59, 61]	[51, 58]
*	Insulation type	[55]	
*	Foundation type	[56]	
*	Insulation position	[60]	
*	Duct location	[56]	
*	Ceiling type	[55]	
0	Roof type		[51]
0	Heating system		[60]
0	Window material		[57]
0	Floor structure		[55]
Guidance and supervision			
2	Design target	[54, 58, 61]	[51]
2	Supervision and workmaship	[55, 54, 58, 61, 7, 63, 59]	
2	Feedback and guidance	[59]	
Other			
0	Climate variation and surroundings		[52, 61, 57, 62]
?	Climate zone	[56]	[53]
?	Construction year	[60, 56, 51]	[55, 58, 57]

Table 3: Factors influencing building airtightness with references dealing with it and results from the crossing of references.This ranking is an indicator of the impact significance. 0 = not significant. 1 = significant. 2 = highly significant. * = not enough discussed. ? = parameters not directly linked to infiltration phenomenon

3.2.1. Geometry

Most geometry parameters are available and are often presented in studies even if they are not always related to the infiltration phenomenon. In these parameters, one can observe an important inconsistency among papers. This is probably due to the indirect link between these parameters and infiltration. For example, volume is sometimes found correlated to airtightness. If the volume of a building increases, weak joints are multiplied. The increase of leakage is not directly linked to the volume increase but it a correlation could be found in some cases. Unlike areas or junctions, the volume is not an air path.

Usually the number of story is defined according to two categories (one story and multi-story houses), but authors define more categories. One-story houses are shown to be more airtight than multi-story houses in many papers. One of the papers showed no significant differences in averages, but authors found a statistically significant relation for the ACH_{50} values in the case of concrete and masonry houses [55]. They did not find this significance for q_{50} values. The difference between q_{50} and ACH_{50} is due to the evolution of the volume-area ratio. The increase of volume and area leads to the decrease of ACH_{50} and q_{50} values, but not in the same way. For example, in timber-framed houses the number of stories has a significant impact on q_{50} values. The multiplication of weak ceiling-wall joints with the increasing number of stories explains this significant impact. This significance is not found in ACH_{50}. Indeed, the decrease of ACH_{50}, due to the rise of the total volume, counterbalances its increase linked to the multiplication of weak joints. In the case of q_{50}, it doesn't decrease enough with the increase in area to counterbalance the increasing number of weak joints. such situations reinforce the need for metric standardization.

Envelope area and floor area are interesting parameters linked to infiltration phenomenon. Air can infiltrate in the building through porous surfaces and should then be related to the different envelope surfaces. However, due to air barriers in walls, the leakages through surfaces are negligible compared to junction leakages at 50 Pa. This is why most of the researchers found the impact of this parameter not significant. Nevertheless, the increase of the envelope area can be correlated to the increase of leakage junction and can lead to an "indirect" correlation with airtightness in addition to the weak direct correlation.

Authors almost always know the volume and then give it in their results table. But unlike envelope and floor areas which are both indirectly and directly linked to air infiltration, volume is only indirectly linked to it.

The area of window frames, the number of significant envelope penetrations (windows, doors) and the frame length are rarely discussed but must be further investigated. Indeed, wall-window junctions are often identified as weak points in building airtightness.

3.2.2. Technology & Materials

Parameters in this category are linked to the building "quality" instead of its geometry. These parameters are discussed in many references, but never with a clear definition.

The best example of this issue is the most studied parameter in this category: the envelope structure. In [55], Vinha et al. select seven types: timber-framed, logs, blocks of autoclaved aerated concrete, lightweight aggregate concrete, bricks, concrete blocks and concrete elements. The research shows major differences between "concrete & blocks" and "timber-framed & log houses." The second group is found more porous than the first one. Inside the "timber-framed & log" group, log is found more porous than timber-framed. The subgroups of "concrete & blocks" were too small to draw a conclusion. In [54], Laverge et al. found a statistically significant difference between massive and wood frame. The results presented in [59] show that wet/mechanically plastered masonry seems more airtight than dry-lined masonry and steel framed constructions. In [60] the structure is divided into light structures (wood or steel frame constructions) and heavy structures (concrete, bricks or masonry). Light structures appear to be less airtight than heavy structures, and the difference is found statistically significant. In [61] the structure of the envelope (called build method) considers four types: traditional masonry, reinforced concrete, timber frame and precast concrete panels. The differences between these types were found statistically significant, except between reinforced concrete frame and traditional masonry. These two are less airtight than timber frame which is less airtight than precast concrete panel. Lastly, in [51] the envelope structure is divided into concrete, steel, timber and masonry. As it can be seen with this parameter, the lack of standardization makes these references very difficult to compare.

Building method is also defined differently from one paper to another, but key points can be extracted from references: a significant difference can be found between prefabricated buildings (more airtight) and on-site constructed building. In [61], prefabricated constructions are discussed in envelope structure.

Three papers discuss the ventilation system and draw the same conclusion: mean ACH_{50} values between ventilation systems with heat recovery have been found to be statistically different to other systems (natural ventilation and mechanical exhaust). In [54], Laverge et al. explain this difference by the test method standards: the stacks have to be closed with existing shutters (not often present) while ventilation ducts are sealed during the test. Before drawing any conclusion, this explanation should be more investigated.

When papers discuss dwelling types, flats are often significantly more airtight than houses. But apartments are often constructed with different envelope structures and building methods. [61] observe no significant differences between subcategories (end-terraced, mid-terraced, detached and semi-detached for houses and ground floor, mid-floor and top floor for apartments).

The roof type, the heating system, the floor structure and the window materials have been studied by only one reference and each one showed no significant impact on airtightness.

All other parameters presented in table 3 (insulation type, insulation position, foundation type, duct location and ceiling structure) shows an impact on airtightness in only one reference. For these parameters, further investigation should be performed to confirm the first observation. For insulation type, the lowest air change rate is found for polyurethane insulation. Concerning insulation position, insulation from the interior seems to provide the higher level of airtightness. Five foundation types are observed in [56]: unconditioned basement, vented crawlspace, unvented crawlspace, conditioned basement and slab foundation. Ducts are divided in four locations: conditioned space, unconditioned basement, unconditioned attic and vented crawlspace. Concrete-framed ceilings are more airtight than timber-framed ones.

Results here are much more consistent than geometry variables. It highlights that the "quality" of the element has probably more impact than its geometry. Constructive modes are still gathered based on characteristics not directly linked to airtightness. Structures or elements should be gathered based on elements responsible for airtightness (e.g. presence/absence of an air barrier).

3.2.3. Guidance & Supervision

Parameters in this category are important: almost all references agree that they have a significant impact on airtightness. Unfortunately, these parameters are difficult to define and to take into account in a predictive model. The importance of this section can partially explain the different conclusions drawn by authors for other parameters.

Some authors observed the impact of the design target in different ways. This parameter is closely related to the next one: Supervision & workmanship. [54] compares two groups: the first is made of randomly selected cases while the second is made of dwellings intended to be airtight already during the design phase. The difference between both samples is highly statistically significant. The conclusion in [58] highlights the positive influence that airtightness testing can have on building energy performances. In [61], the correlation between the maximum q_{50} value allowed and the final airtightness obtained is found to be significant. Only [51] observe that there is no correlation between design target and airtightness. The work of Meiss and Feijó-Muñoz [8] is not in the table due to the low number of measured units but it can still be interesting in this context. It studies the airtightness of buildings submitted to three different Spanish standards. Results show important differences in ACH_{50} values between the different standards.

Many references study the supervision & workmanship impact, and most conclusions highlight the importance of this parameter in airtightness performances. For this parameter, authors often compare different contractors or compare houses constructed with and without professional supervision.

The impact of feedback & guidance is only discussed in [59]. Johnston et al. did their research in three phases. Two different sets of tests are performed, in the first and third phases. Buildings in the first phase are constructed before the "feedback & guidance" phase (phase 2) while buildings in the third phase are constructed after the second phase.

3.2.4. External

This category deals with a number of parameters which are not directly related to the building itself but to the construction context: construction year or surroundings.

Climate variation & surroundings are expected to have no influence on airtightness since the test norms are made in order to be independent from these parameters. All references confirm this expectation. Nevertheless, [56] studied different climate zones and found statistically significant differences. This observation is probably due to the construction techniques varying from one to another climate zone.

The construction year is discussed in many papers and is the source of many debates. Some authors observed correlation between construction year and airtightness while others did not. This difference is due to the changes in construction techniques and regulations. It can then vary a lot from one building sample to another. An interesting point -not directly studied as an influence factor- is the deterioration of envelope airtightness performance over time. Measurements from Bracke et al. [71] and Vanwelde and Dartevelle [72] show an increase of ACH_{50} over time up to 28% between one and five years after the building was erected.

3.3. Conclusion

A first point highlighted by the analyze of references is the huge lack of consistency between parameters definition and significance evaluation. For instance, the number of stories is chosen between one or more in some papers and between one, two, three and four in others. Sometimes the same name is given for two different parameters, for instance the building method is the envelope materials in [28] and the use of prefabricated elements in [7]. The correlation between parameters and airtightness is sometimes only observed based on averages and sometimes deals with a p-value from ANOVA or t-test. Some correlations found by authors cannot be compared to other dataset because of the lack of consistency. A standardization could increase the contribution of research by the comparison with other research. The lack of standardization hinders the generalization of tendency observedin papers performing measurements on a small number of measurements.

Despite the lack of consistency, some trends can be observed between references. Some factors are pointed out as having an impact on airtightness: the number of stories, the building method, the envelope structure, the ventilation system, the design target and the supervision. The choice of simple design with prefabricated elements and good supervision can achieve good airtightness, while the same building with complex design and bad supervision can lead to bad performances. However, even if many influencing factors are observed, a very good airtightness can be reached in almost every situation and regardless of the technological choices, materials, geometry or external factors [55]. Disagreements between authors can be attributed to many parameters (e.g. the country, the sample of buildings tested, the measurement equipment). According to Wei Pan, interactions linking different influencing factors can also explain the difference between authors [61]. For example, the ventilation system can be linked to the design target or, as Ramos et al. [73] develop, to the human behavior which is a poorly understood issue.

The huge influence of supervision and workmanship is also an interesting point highlighted in this chapter. This parameter is difficult to integrate in a mathematical model and its importance can explain why designers and contractors found some existing models unreliable.

3.4. Standardization

As mentioned in section 2.5, the lack of standardization regarding used metric was highlight by Urquhart et al. To our knowledge, nobody tackled the issue of lack of standardization neither in parameter definition nor in the significance evaluation. In this section we suggest some direction for this issue.

Parameter definition and classification should be done carefully. A good classification must deal with the infiltration phenomenon: the air flows through areas (walls, roofs, windows,...), through junctions between elements (wall-floor, wall-roof, window-wall,...) and through small individual points (electricity, plumbing,...). Figure 1 schematically represents these three different kinds of air paths.

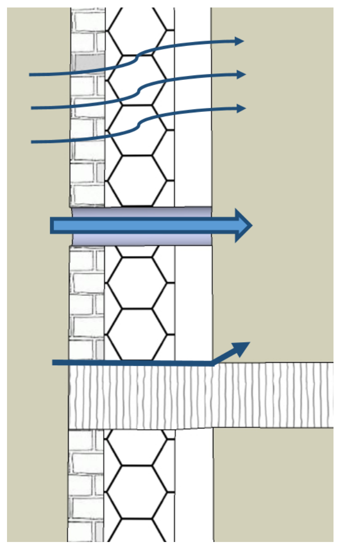

Figure 1: Three examples of different type of air paths

This paper suggests an example of the relation dealing with these three types of air paths (equation 5), with newly defined "quality coefficients."

$$Q_{50} = \sum_{\alpha=1}^{areas} A_\alpha C_{qs,\alpha} + \sum_{\beta=1}^{junctions} L_\beta C_{ql,\beta} + \sum_{\gamma=1}^{penetrations} C_{qp,\gamma} \quad (5)$$

Q_{50} is the total air flow passing through the envelope at a pressure difference of 50 Pa in m^3/h, A is the area of an envelope part in m^2, L is the length of junctions in m, C_{qs} is the surface quality coefficient in $m^3/(h.m^2)$, C_{ql} is the linear quality coefficient in $m^3/(h.m)$ and C_{qp} is the point quality coefficient in m^3/h. This equation is divided in three terms: first for surface air losses, second for linear air losses and third for point air losses.

A number of cases encountered in practice would be classified as "hybrid cases" because of their nature. These have to be classified in one of the equation terms, depending on their dominant behavior. An example of hybrid case is shown in figure 2. One must choose if this example is a point loss (regarding the external membrane) or a surface loss (regarding the internal membrane). In our view, internal membrane should be taken as a reference since a good practice is to set the air barrier in the wall closer to the inside in order to avoid internal condensation in mild and cold climates. The example would be then considered as a surface loss.

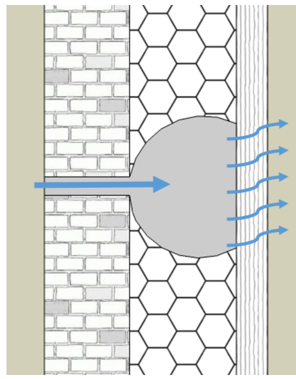

Figure 2: Example of a hybrid air path

Except for the third term of the equation, each has a "geometry" variable and a "quality" variable. Parameters identified in this section stand behind all these variables. Important parameters to include in the classification can be directly determined from this equation. Table 4 describes these parameters.

Influencing Factor	**Variable Type**	**Losses Type**
Already discussed parameters		
- Envelope area (m^2)	Geometry	Surface losses
- Frame length (m)	Geometry	Linear losses
- # of stories (one or more)	Geometry	Linear losses
- # of penetration (number)	Geometry	Point losses
- Construction method (prefabricated or on site construction)	Quality	Linear losses
- Envelope structure (materials and air barrier)	Quality	Surface losses
- Supervision & workmanship (contractor description)	Quality	All losses
- Design target (required performances)	Quality	All losses
New suggested parameters		
- Length of wall-roof junction (m)	Geometry	Linear losses
- Type of penetration (electric, plumbing, ...)	Quality	Point losses

Table 4: classification of important parameters regarding infiltration phenomenon

The table is divided in two parts, in the first are parameters already discussed in literature while in the second are new parameters. The ventilation system should probably be added to this list (as quality variable in point losses), but the issue of test standards discussed in section 3.2.2 must first be investigated. The envelope structure is an important parameter, but in our point of view the definition used in different papers is not appropriate for infiltration. It is considered as an "already discussed parameter" in table 4 but its definition has been modified.

To quantify the impact of parameter on airtightness, standardization should be done regarding a statistical indicator. P-values are often used in literature to determine a level of significance (0.05 is usually chosen as the limit between significant and not significant values). These values are easy to understand and well-known by researchers. The difficulty arises when authors must choose a statistical tool to compute p-values. Numerous statistical tools exist and the choice depends on the situation. One can determine P-values by comparison of means (t-test or one-way ANOVA test), by variable interaction study (two-way ANOVA) or by correlation study (r-Pearson). The choice of the most suited tool is an important task in the standardization of results but depends a lot on the variables studied. It is important that in each work, authors clearly mention and explain the statistical tools used to perform their analysis in each work.

Standardization is important to compare data and to have a better understanding of airtightness. With such a standardization, the idea of collecting worldwide data to draw a single conclusion would be tempting. However, structure type, construction technique, building technologies or other influencing factors vary from one country to another. Single conclusion could probably not be drawn from such a database, but different countries and techniques could be compared.

4. Predictive Models

With the strengthening of airtightness requirements, good supervision and design are not always enough to achieve required airtightness. Predictive tools for contractors or designers are more necessary than ever. This section aims to describe existing predictive models, divided in four categories: theoretical models, empirical models, building characteristic models and single component models. Regarding these models, particular attention will be paid on their drawback, their intended use and how they deal with influencing factors.

4.1. Theoretical Models

Theoretical models are based on equations expressing the flow through individual cracks and openings as described in section 2.1 (equations **??**, **??** and 2). These equations can be used to model each crack individually or the entire building. Indeed, the building can be seen as an aggregation of numerous cracks. Mean values for C and n are usually obtained with blowerdoor tests. If the airtightness has to be predicted before construction, one can find these two parameters in literature. But without testing, these coefficients lead to huge simulation inaccuracy [39]. They can be found in a building with similar location, geometry, techniques or materials but such a model does not deal with supervision and workmanship quality.

If cracks are studied individually, governing equations must be used to model each crack or opening. This can be done by using CFD (Computational Fluid Dynamics). Besides the literature databases, numerical method (CFD, Computational Fluid Dynamics) can be used to predict air flows, heat and mass transfers after the problem discretization [74]. CFD can be very precise or not, depending on theoretical hypothesis. For example, a simple model would consider only one virtual huge crack (which would be the sum of each real crack) while a complex model would consider each crack individually. Younes and Shdid recently discussed the use of CFD in this field, highlighting the fact that they are not suited for practical use [75]. Main CFD drawback is its important computation time. Wang and Chen explain that for a building in steady-state conditions, calculations can take from several hours to several days [76]. While not impossible, the use of CFD in practice is often limited by the important computation time and calculation power necessary to obtain reliable models. Nevertheless CFD could be used to create a suitable tool instead of being used as a predictive tool. It can also be used to study the influence of specific parameters by theoretically freezing other influencing factors to avoid interactions.

4.2. Empirical Models

Empirical models are based on huge sets of blowerdoor data. This paper presents two types of empirical models: the regression analysis and the artificial neural network. The regression analysis is a statistical tool used to evaluate the relation between variables. Such models establish mathematical relations between airtightness and numerous parameters [77]. Regression analyses on airtightness have been performed by Chan et al. in 2005 [67] and in 2013 [56], Montoya et al. in 2010 [60], Pan the same year [61] and more recently Fernàndez-Agüera et al. [53] in 2015 and Bramiana et al. [51] in 2016. Regression models are accurate in describing buildings close to the set used for the analysis. Consequently, these models are usually used to describe and analyze the building stock. They can also be used as predictive tools but are only accurate for buildings close to the data used for the original analysis.

Artificial Neural Network is a model with human capabilities: learning and adaptation. It consists of a few simple processing units and many connections. These connections lead to modifications of units in order to adapt them if new data are obtained [78]. Krstic et al. [79] recently tested the neural network to predict the airtightness of a building set in Croatia. One year later, a second paper validated this methodology by its application on another set of buildings from the republic of Serbia [80]. This powerful estimation tool shows strong capabilities but still requires an important validation work.

Hybrid models can be mentioned in this section. These models are not yet used for airtightness prediction, but can be a path to explore. Hybrid models are based on both empirical relations and theoretical considerations. An example is the formula established by Dietz used to determine ACH. It deals with temperature difference and wind speed, driving forces of infiltration, and other parameters as the generalized house leakiness factor or the terrain sheltering [81]. Nowadays, hybrid models are only valid for a reduced set of data when uncertainty of parameters is important [82].

4.3. Building Characteristic Models

This type of model is the most suitable for designer use: based on building characteristics, airtightness can be determined by using simple mathematical formula or calculation sheets. Such formula has been presented first as the SBR method 1 [83]: Q10 (in [L/s]) is calculated by multiplying coefficients depending on the type of construction, the type of roof, the workmanship and the building envelope area. De Gids further develops this method in 2010 [84] to take into account the facade and the building form in addition to previous coefficients. Relander underlines that this method is not accurate for new sets of buildings [29]. With AIVC worksheets a designer can determine the ACH_{50} of a building. Starting with a basic value depending on the building type, a bonus/penalty increase based on parameters (construction technologies or materials) lead to a final value for the building. Even if this method is really interesting and could be a powerful tool for designers, it is outdated (1998) because of the development in construction techniques and the strengthening of requirements [85]. Such worksheets are easy to use, but infiltration phenomenon is the airflow through components and is not linked to general building characteristics. These worksheets do not deals with the physical phenomenon of infiltration, which could be problematic for future necessary updates or future requirements strengthening.

4.4. Single Component Model

Single component models aim to describe the airtightness of building parts instead of the whole building (e.g. a window or a wall-roof junction). The contributions of all the different component leakages can be summed in order to obtain the whole building leakage. This sum was already suggested in section 3.4 through the choice of parameters (equation 5). These models are really promising since they give the designer direct information on the impact of construction and technical choices and to the contractor direct information about effective retrofit actions.

The first type of single component models is the databases found in literature. The AIVC database based on the work of Orme [85] (in 1998) and ASHRAE database based on the work of Dickerhoff and Harrje [24, 86] (in 1982) were widely used in previous years. Table 5 shows an example of a typical table found in the work of Orme.

Unfortunately such databases are nowadays outdated in Europe: they were developed a long time before European energy regulations which have been a watershed in the evolution of building performances throughout Europe. Moreover the component choice is often made based on construction technology or on thermal bridges. Although linked, heat and air transfer are not the same phenomenon and a specific classification should be used.

Component	Lower quartile	Median	Upper quartile	Sample size
Windows weatherstripped				
Hinged	0.086	0.13	0.41	29
Sliding	0.079	0.15	0.21	19
Windows non-weatherstripped				
Hinged	0.38	0.74	01.1	42
Sliding	0.18	0.23	0.37	36

Table 5: Example of windows flow coefficient (C) values taken from the work of Orme in 1998 [85]

Another model is the sound reduction method developed by Hassan. The calculation of the component infiltration rate is based on the sound reduction index [87]. This model is based on acoustic measurements but can be considered as a predictive model because one can deduce the reduction index from the theory of sound insulation. It always depends on geometry and boundary conditions, but one can often use the theory of infinite plates to determine this reduction index [88]. Equation 6 gives an example of reduction index formula for plane wave incidence [89]. Unfortunately the theory of sound insulation in the context of airtightness has not been developed in practice.

$$R = 10.log\left[1+\left(\frac{\pi f M cos(\theta)}{\rho_0 c}\right)^2\right] dB \tag{6}$$

R is the sound reduction index, f is the wave frequency (Hz), M is the specific mass (kg/m^2), θ is the angle of wave incidence (degrees), ρ_0 is is the air density (kg/m^3) and c is the sound velocity in air (m/s)

If cracks or openings can be identified and dimensioned in a given component, theoretical models presented in section 4.1 (either fundamental equations or CFD models) can also be used to predict single component leakages.

4.5. Discussion

In previous sections, the lack of standardization at different levels and the impact of workmanship and supervision partially explain why reliable and suitable models are difficult to develop. This section shows that numerous airtightness models already exist. However the lack of predictive tools in the construction field nowadays is still important.

Different factors can explain this issue. Firstly, the need of accurate predictive tools has only came out recently with the strengthening of requirements. Second, explanation related to the model can be highlighted. All models are not intended to be used as predictive tools. Some are used to make statistical analysis of existing buildings as regression analysis. Nevertheless regression analysis can be used as predictive tools in conditions close to the one used to determine the empirical relation. Moreover, all of the predictive models have small drawbacks making them unsuitable for practical use as predictive tools. For governing equations, the need of literature leads to high inaccuracy. For CFD simulations, the calculation time, the powerful computation tools needed and the crack distribution, which is sometimes difficult to obtain, make these models difficult to use in practice. Empirical models, both regression analysis and neural network, do not deal with the infiltration phenomenon and require huge sets of data. Building characteristic models are really simple but completely outdated. An update of these models would probably be useful, but the lack of physical considerations could become a limitation if requirements strengthen further. Regarding component models, the sound reduction model is still not fully developed and single component databases are outdated. Third, some models do not deal with all the influencing factors. For CFD, it depends on the hypothesis and geometry and for governing equations it depends on the coefficients and on the hypothesis. Empirical models deal with influencing factors chosen in the original analysis. Current versions of building characteristic models deal with the main influencing factors. An update should add "supervision and workmanship" as a model parameter. Influencing factors taken into account in single component models are different from other models because of the scale difference. As for building characteristic models, an update should include the "supervision and workmanship" factor as a model parameter.

The three points presented in the previous paragraph are summarized in table 6 for each model. The capability to deal with main influencing factors (Building Geometry (BG), Technology & Materials (TM) and Guidance & Supervision (GS)), the main drawback and the intended use of each model are mentioned. Today none of these models seem suitable for designer practical use.

Models	BG	TM	GS	Drawbacks	Intended use
Thoretical Models					
Governing equations	Y	Y	Y	Inaccurate	Predictive
CFD simulations	Y	Y	Y	Time consuming	Predictive
Empirical Models					
Regression analysis	Y	Y	Y	Reduced set of buildings	Statistics
Neural Network	Y	Y	Y	Reduced set of buildings	Statistics
Building Characteristics					
Formula	Y	Y	Y	Outdated	Predictive
Worksheets	Y	Y	N	Outdated	Predictive
Component Models					
Databases	*	*	N	Outdated	Predictive
Sound reduction	*	*	N	Not enough developed	Predictive

*Non-sense due to scale

Table 6: Summary table - type of models, their influencing factors and practicability

In our view, single component models are the most promising predictive tools. These models deal with infiltration and the main influencing factors since they are based on the air flowing through building components. An update of these models could lead to a suitable tool for designers, similar to the thermal bridges catalog [90]. This update is very challenging in two aspects: the measurement method and the integration of supervision and workmanship. First, blowerdoor tests measure only whole building performances. One way to measure the leakage of an individual component would be to compare successive blowerdoor tests: one made before and one after sealing the component. The difference between both values is then defined as the component leakage. Dickerhoff [86] or more recently Pereira et al. [91] use this methodology. In this method the uncertainty analysis is crucial and has to consider the measurement method, the regression to obtain n and C, the average made between pressurization and depressurization results and the derived quantities (ACH_{50}, q_{50}, w_{50},...) [32]. Second, the impact of supervision and workmanship quality is most of the time unknown or undefinable. It can be considered as a parameter or as an uncertainty on the measurement. With such an uncertainty, results are not a leakage value anymore but a range or even a probability distribution when enough data is collected. Different quartiles would correspond to different construction quality as Orme et al. did in their work [85].

5. Conclusion

Enhanced requirements reveal a need for predictive tools for designers and contractors. This paper discusses the development of new predictive tools and the existing airtightness predictive models. To explain why predictive tools are still missing, the paper develops two questions: "why has no new appropriate model been developed today" and "why are existing predictive model not used"? The first question is assessed in both the first and second chapters, highlighting the lack of standardization and the difficulties encountered in modeling. The first chapter deals with airtightness and infiltration key concepts and highlights the problem of metric standardization. The second chapter deals with influencing factors and highlights two other standardization problems: factors classification and impact quantification. In addition to standardization problems, this second chapter points out the significant impact of supervision and workmanship, a parameter difficult to integrate in predictive models. The second question is addressed in the third chapter. This chapter describes numerous existing predictive models, their drawbacks, how they deal with identified influencing factors and whether they are intended to be used as predictive or descriptive tools.

Conclusions are unanimous: none of the existing predictive models can be used, in their present form, as a design tool and the development of a new predictive model is hindered by the lack of standardization and the necessity for the integration of "supervision and workmanship." However, such conclusions logically lead to possible future works to develop an effective model suitable for practical use.

5.1. Further Work

The first and most important point is the lack of standardization. A significant piece of work has to be done, focusing on metric, parameter definition and impact quantification. In our point of view, none of the metrics used nowadays are appropriate and new metrics must be established and tested. These new metrics would be useful for designers and contractors and would give information about main building leakage types. The choice of new metrics is discussed in section 2.5, but suggestions by themselves are not enough and future reflections should be nourished by test results. Regarding the definition of parameters, the list suggested in section 3.4 is not exhaustive and should be developed in future researches too. Finally, a statistical tool to quantify significance should be assigned to each parameter in the list.

Besides standardization issues, a predictive tool should be developed to meet the needs of designers and contractors. The use of such a tool should be easy and it should take into account the physics underlying airtightness and infiltration. Interesting step in this direction would be the classification of "air leakage paths" based on the way air flows around them. This classification would provide a better understanding of the phenomenon and would logically lead to appropriate design tools based on components air leakages, similar to thermal bridge catalogs.

Some interesting points are presented in literature and could be further investigated. For example, research on parameters such as the length of frames and the number of significant penetration areas/points is rather limited while, intuitively, it seems intuitively highly correlated to airtightness. Some criticized results should also be more investigated as well as the difference between different ventilation systems.

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