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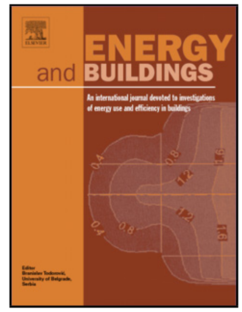

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Authors: Thor-Oskar Relander, Sverre Holøs, Jan Vincent Thue

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Airtightness estimation – a state of the art review and an en route upper limit evaluation principle to increase the chances that wood-frame houses with a vapour- and wind-barrier comply with the airtightness requirements

Thor-Oskar Relander[1],, Sverre Holøs[2] and Jan Vincent Thue[1]*

[1]Norwegian University of Science and Technology, Department of Civil and Transport Engineering

[2]SINTEF Building and Infrastructure

**Corresponding author. Tel.: +47 735 94 558; fax: +47 735 97 021*

E-mail address: thor.oskar.relander@ntnu.no (Thor-Oskar Relander)

Abstract:

High airtightness is particularly important in order to achieve energy efficient buildings. Of this reason airtightness estimation is of interest. Over the past 30 years researchers have worked on airtightness estimation. This article is divided into two parts. The 1st part deals with earlier work on airtightness estimation. It is seen that there are relatively few references in the literature that deal with estimation of airtightness. None of the reviewed references argue that airtightness measurements can be replaced by estimates. The only reference that deals with airtightness estimation of wood-frame houses with high airtightness did not manage to find a correlation between the estimated and the measured airtightness.

For a contractor what really matters is not an estimate of the airtightness of the finished building, but a reliable means to be sure of reaching the airtightness requirement. It is therefore customary to perform blower-door tests stepwise during the construction process. First the airtightness of the building with the wind-barrier is measured, n_{50w}. Then the airtightness of the finished building that also has a vapour barrier is measured, n_{50f}. The airtightness requirement is set for n_{50f}. Of various reasons it is not given that $n_{50f} < n_{50w}$ for a given building, and consequently one should have an idea of what an upper limit of n_{50w} should be in order to be confident to reach

the n_{50f} requirement. In the 2nd part of the article it will be shown how this upper limit of n_{50w} can be found by statistical analysis based on systematic measurements of n_{50w} and n_{50f} as part of a quality assurance system.

1. Introduction

1.1 General

There are many reasons to construct buildings with low infiltration. One of them is that infiltration causes energy losses. In short the infiltration depends on the airtightness and the shielding of the building, the climate and the ventilation system. The infiltration, and thus the energy loss by infiltration can for instance be calculated according to NS 3031 [1] or the LBL model [2].

The airtightness of a building expresses the number of and the severity of the holes and cracks on the building envelope. Consequently, the airtightness is independent of the climate. Of this reason, the most feasible and economical way of controlling the infiltration is by instead controlling the airtightness. Limiting airtightness requirements are often to be found in building regulations. An overview of different airtightness requirements in European countries can be found in e.g. Kluttig et al. [3]. In recent years the Norwegian airtightness requirements have become stricter. This has led to an increased interest for airtight constructions and methods.

When measuring the airtightness of buildings, a blower-door is used to find the relation between the pressure difference over the building envelope, ΔP [Pa], and the airflow rate through the building envelope, Q [m^3/h]. This is usually expressed by the power-law, Eq. (1). The constants C and n are obtained when curve fitting Q vs. ΔP. There exist various traditions in different countries for normalizing the airtightness. In Norway the volume normalization is used and the airtightness is reported at 50 Pa pressure difference, n_{50} [h^{-1}].

$$Q = C\Delta P^n \tag{1}$$

Instead of measuring the airtightness, there have been attempts in the literature to estimate the airtightness. If the airtightness could be estimated with acceptable accuracy, one could save measuring costs, and easier find solutions that would result in buildings with high airtightness, low infiltration and consequently – being energy efficient.

1.2 Objective of the article

The first objective of this article is to review what has previously been done on airtightness estimation. It is seen that some of the reviewed references in the literature have an optimistic view on the possibilities of being able to predict the airtightness, whereas others do not. In general it is seen that airtightness estimation has received little attention and much is left without further development.

The second objective of the article is to motivate for, and describe an en route upper limit principle for increasing the chances of complying with the airtightness requirements. This principle will be introduced and it will be shown how it can be used to give quantitative recommendations on how to reach the airtightness requirement of wood-frame houses.

The overall motivation of the article is to give practical advice to the building industry so that the energy losses through air leakages can be reduced.

2. Earlier work on airtightness estimation

The reviewed references have been grouped into three categories: 1) estimation based on multiple regression, 2) estimation based on rough characteristics of the building and 3) estimation based on component leakage and geometry of the building. In the following, emphasis is put on the component leakage methods.

2.1 Estimation based on regression analysis

These estimation models are derived from regression analysis where the air leakage of a given collection of buildings is regressed against some rough predictors or variables. The model is therefore valid for that specific dataset only. Of this reason these models are only briefly mentioned.

Bassett [4] used multiple regression to investigate the airtightness of houses in New Zealand. The measured air leakage [m^3/s] was regressed against the joint length [m] and the envelope surface area [m^2].

Chan et al. [5] developed a regression model for the airtightness of US houses. The airtightness was expressed as effective leakage area, ELA, normalized by the floor area and a correction factor for building height, normalized leakage, NL. The most important factors were floor area and year built.

Montoya et al. [6] used multiple regression to arrive on a model for estimating the airtightness of Catalan dwellings. The factors included in the model were the floor area, the age of the dwelling, the structure type and the number of storeys.

Pan [7] developed a regression model for the airtightness of post-2006 dwellings in the UK. The factors included in the model were dwelling type, management context and building method.

2.2 Estimation based on rough characteristics of the building

2.2.1 AIVC prediction method – Whole Building leakage

This prediction method is described in Orme et al. [8] and is to be used for approximate guidance. The estimation is based on 5 different calculation sheets: Timber Frame Insulated Construction – Low Rise, Brick and Block Construction - Low Rise, Concrete/Curtain Wall construction – High Rise, Concrete Panel – Industrial and Metal Panel - Industrial. Each of these sheets has a so-called basic leakage or default leakage (for the wood-frame house sheet, the basic leakage, n_{50}, equals 3 h^{-1}).

Based on the geometry and sealing methods used, the user adds and subtracts $\triangle n_{50}$ values to adjust the basic leakage to obtain the estimated leakage. For the wood-frame sheet there are in total 7 additions and 3 subtractions which lead to the final airtightness. For instance unsealed service penetrations in a wood-frame house make the basic leakage (3 h^{-1}) increase by 1 h^{-1}, and if the windows and doors have been gasketed the leakage is reduced by 1 h^{-1}. The different sheets can be found in Orme et al. [8]. It is emphasized that all windows, vents, flues and purpose provided openings must be closed.

2.2.2 Stichting Bouwresearch (2001), SBR Method 1

This estimation method is described in SBR [9]. The air leakage at 10 Pa pressure difference, q_{v10} is estimated by Eq. (2). C_1 assumes different values depending on three different types of construction alternatives: masonry (assumes 2.0), prefabricated concrete or timber frame (last mentioned assumes 0.5). The value of C_2 relates to the type of roof; pitched roof ("kapconstructie" in Dutch, assumes 1.7) or flat roof (assumes 1.0). C_3 is a factor taking the workmanship into account. 3 alternatives are given: poor construction (assumes 2.0), normal building construction (assumes 1.0) or good construction. A_{loss} is the area of the building envelope.

$$q_{v10} = 0.5 \cdot C_1 \cdot C_2 \cdot C_3 \cdot A_{loss} \ \left[L/s \right] \quad (2)$$

2.2.3 De Gids et al. (2010)

De Gids et al. [10] present an empirical method for estimating the airtightness of Dutch residential houses. The method represents a further development of the SBR 1 method [11]. The air leakage at 10 Pa pressure difference is estimated by Eq. (3) C_1 relates to the type of building (wood-frame assumes 1.3), C_2 relates to the type of roof (1.7 for pitched roof of wood elements, “kap”), C_3 depends on the façade (1.0 for standard façade), C_4 relates to the building quality (1.5 for poor) and finally C_5 depends on the building form (volume per area). The method was developed by adjusting the factors C_1 to C_6 using measurements of buildings. The method is not validated on new sets of buildings.

$$q_{v10} = 0.25 \cdot C_1 \cdot C_2 \cdot C_3 \cdot C_4 \cdot C_5 \cdot C_6 \qquad [L/s] \tag{3}$$

2.3 Estimation based on component leakages and geometry of the building

Component leakage models are based on summing up individual air leakages over the building envelope, and multiplying the quantities [m], [m^2] or [each] with their respective specific air leakage, [m^3/h] per m, m^2 or each. This concept is quite analogous to energy calculations using thermal bridges, U-values and geometry as input. The component models rely on the assumption that the specific leakage is uniform over the construction detail.

2.3.1 Reinhold and Sonderegger (1983)

Reinhold and Sonderegger [12] developed an estimation model to be used either for early stage design when blower-door tests were not possible to perform, or when the importance of the various air leakages of the building envelope was of interest. The method required basic knowledge of the geometry and of basic factors influencing the airtightness, e.g. sealing around windows and doors. The geometry information (length of joints, areas etc.) was obtained from building drawings. Relevant component leakages to use as input for the model were obtained by a review of existing literature. Because there can be many small leakage paths on the building envelope, Reinhold and Sonderegger only considered air leakages that were known to be of importance. The leakages included in the model were those listed in Table 1. The estimation model was found by an iterative procedure using the airtightness measurements of 36 houses, i.e. the model was made from the data [13].

Table 1 represents an example of how the air leakage was estimated. The air leakages were tabulated to fit with the LBL model (leakage area at 4 Pa pressure difference). The two furthermost columns to the right in the table were not provided in Reinhold and Sonderegger [12]. L_i [m^3/h] at 50 Pa shows the magnitude of the component leakage at 50 Pa assuming that the exponent n in Eq. (1) equals 0.65. D_i denotes the quantity [m], [m^2] or [each] and L_i denotes the component leakage [cm^2] at 4 Pa.

Table 1 Estimation example from Reinhold and Sonderegger [12]. D_i denotes the quantity [m], [m^2] or [each]. Li is the magnitude of the component leakage given both as [cm^2] at 4 Pa and in [m^3/h] at 50 Pa. Modified from Ref. [12] with kind permission of the AIVC.

Fig. 1 is a reprint of the scatter plot given by Reinhold and Sonderegger [12]. The figure shows the calculated air leakage [cm^2 at 4 Pa] versus the measured air leakage [cm^2 at 4 Pa] for the 36 US single-family residential houses. The stapled lines represent 10 % deviation from ideal relationship between the predicted and the measured value. Assuming that n in Eq. (1) equals 0.65, and a typical volume of 400 m^3, a rough estimate of n_{50} of the houses is from about 1.3 h^{-1} to 18 h^{-1}.

In Reinhold and Sonderegger [12] it is stated that the airtightness can be estimated based on drawings, information on whether there are dampers in the ventilation system and in the fireplace and basic knowledge of sealing methods. It is also said that one should continue to estimate airtightness if blower-door equipment is not available. However, it is emphasized that the method had uncertainties associated with it no matter how adequate information that is given about a building. Therefore it is stressed that the estimation method should *not* be regarded as an invitation not to perform blower-door tests.

*Fig. 1 Scatter plot with regression from Ref. [12]. The regression curve was Calculated = 0.84*Measured + 111.5 with R^2 = 0.84. Reprinted with kind permission of the AIVC.*

2.3.2 AIVC prediction method (1994)

The numerical database of AIVC is found in Orme et al. [8]. It contains component leakage data from various countries. The database is mainly based on field measurements, but component leakages from laboratory measurements are also present. The following construction details are present: windows, doors, interfaces of window and door frames with walls, walls, ceilings, floors, ceiling/wall/floor interfaces, wall/wall, penetrations, roofing, fireplaces and flues, trickle ventilators and vents. According to Orme et al. [8] the component leakages are to be regarded as default values unless more specific information is available. It is stated that preferably the component leakages are to be verified with measurements. The component leakages are divided into 25, 50 and 75 percentiles to take thoroughness of workmanship into consideration.

In Orme [14] an example of how the airtightness can be calculated is shown. With specified assumptions, the airtightness of a brick house is calculated for three different cases: based on the 25, 50 and 75 percentile of the component leakages. It is stated that the component leakages should be used with caution because they are rather vaguely described, and originate from various countries with various building traditions.

2.3.3 Perera et al. (1997)

Perera et al. [15] made a spreadsheet tool for predicting the airtightness of large commercial buildings before construction or refurbishment. Data input was restricted to the building size, glazed area, construction type and whether or not various airtightness measures were incorporated. Median values of component leakages were taken from the AIVC component leakage database. Because the tool was designed to be simple, input data was restricted to that available at the design stage. The tool was developed so that the contribution of each individual airtightness measure to the overall airtightness was provided. The spreadsheet [16] shows (not attached in Ref. [15]) that the method is re-examinable and that a set of leakages are chosen to be the important ones – i.e. not all kinds of leakages are included. The leakages used were found by development work and were walls, windows, doors, wall to window joints, wall to door joints, wall to floor joints and wall to ceiling joints.

In Perera et al. [15] a table is presented to show how the model fits with existing measurements given in a BRE database. The 10 offices were built in the period 1963-1991. It is stated that the model is evaluated against these 10 buildings. By assuming that n in Eq. (1) equals 0.65, n_{50} of the 10 office buildings varied from 2.2 h^{-1} to 10.0 h^{-1}, median 5.6 h^{-1} and a 75 percentile of 9.6 h^{-1}. As apparent from the table in Perera et al. [15] there is quite a good fit between the estimated and the measured airtightness. It is stated that the airtightness cannot be calculated if airtightness has not been an issue/outset in the building process, or if large gaps are left in the building envelope. Also Perera et al. state that the tool cannot substitute blower-door measurements.

2.3.4 SENVIVV (1997)

In SENVIVV [17] the airtightness of houses in Belgium was calculated based on visual house inspections and component leakage data. The air leakage categories included were based on experience from field measurements. Based on house geometry and component leakage data, mainly obtained from the AIVC database, the airtightness was calculated. The air leakage categories used in the estimation were: walls, floors and ceiling, connections between wall and floor/ceiling, joints in windows and doors, joints between walls and woodwork, vents and other leaks. As commented in Ref. [17] the method usually gave an underestimation of the air leakage. The method was therefore argued to have a value as lower limit for the airtightness.

2.3.5 Stichting Bouwresearch (2001), SBR method 3

This method can be found in SBR [9]. The method clearly describes which component leakages that should be included in the calculation and which should not. The included component leakages are junctions between building elements, and penetrations. Leakages in surfaces are thus excluded. The appropriate component leakages are listed in SBR [9] for two cases: class 1 and class 2. Class 1 is intended for buildings having natural ventilation system, or mechanical exhaust, and class 2 is for buildings having mechanical supply with natural exhaust or for mechanical balanced ventilation. The component leakages for class 2 are for almost all cases the half of that for class 1. The component leakages are based on the numerical database of AIVC.

2.3.6 Relander and Holøs (2010)

In Norway it is customary to measure the airtightness of wood-frame houses stepwise during the construction process to increase the chances of complying with the airtightness requirements. Relander and Holøs [16] made a model to predict the airtightness of the wood-frame houses when wind-tightened only, n_{50w}. In all 26 component leakages that should correspond to “all” the leakages that could be thought of when measuring n_{50w} were used. No leakages were therefore consciously omitted or excluded. The n_{50w} of 17 wood-frame houses was measured and varied from 0.4 h^{-1} to 2.6 h^{-1}, median 1.0 h^{-1} and 75 percentile 1.27 h^{-1}. Detailed information of sealing techniques and materials of all the construction details for the houses was collected.

Component leakage data relevant for Norwegian wood-frame houses was collected, i.a. Refs. [19-22]. Because as-built sealing methods did not always match with what was found in the literature, an acceptance range was established so that discrepancies between as-built (e.g. PU foam around a window) and what was available in the literature (closest match e.g. backer rod) was established in a reproducible manner. After the model and after the compiled database with the assumptions were established, the suggested model was *tested* to estimate n_{50w} of the 17 wood-frame houses. Consequently the measurements were not used to adjust a model. The estimated n_{50w} did not correlate with the measured n_{50w}.

2.4 Estimation based on references in the literature –Van Den Bossche (2005)

Van Den Bossche [23] estimated the airtightness of 10 houses in Belgium with varying building form and construction type. Some of the presented references on airtightness estimation as well as some databases containing component leakages were used. The estimated airtightness of the 10 houses is shown in Fig 2. In the figure AIVC low, mean and high are based 25, 50 and 75 percentiles respectively as described in Orme et al. [8] in Section 2.3.2. The AIVC WBL, is based on Orme et al. [8] as described in Section 2.2.1. SBR mean 1 and 2 are based on class 1 and class 2 for the SBR method 3. SBR WBL was based SBR method 1, in SBR [9].

In ASHRAE Fundamentals [24], a list of component leakages are found. The component data is given for min, mean and max – analogously to that in Orme et al. [8]. In Zeller at al. [25] also a list of component leakages is given. Neither Ref. [24] nor [25] gives information on how the airtightness can be estimated using the component leakages. In Fig. 2 the estimates based on Refs. [24] and [25] (IWU in the figure) are given. For the interested reader it can also be mentioned that Sandberg et al. [26] also provides a component leakage database. The estimates based on SENVIVV [17] as described in Section 2.3.4 are shown in Fig 2.

Fig. 2 Measured and estimated airtightness for the 10 houses reported in Van Den Bossche [23]. The figure is identical to that found in Van Den Bossche [23], except for the translation. Reproduced with kind permission of Ghent University.

2.5 Discussion and comparison of the references on airtightness estimation

There is a difference in the success of the estimation methods previously presented. This section will discuss what the main differences are and how this can influence on the success of the estimation.

2.5.1 Differences in model development – a posteriori or a priori model

There is a difference between Reinhold and Sonderegger [12] on one hand and Perera et al. [15], Relander and Holøs [18] and Van Den Bossche [23] on the other hand. In Ref. [12] (and also SBR 1 and de Gids [10]) a model is developed *from* the measurement data, whereas in Refs. [15], [18] and [23] a priori models are tested on independent cases. It should also be mentioned that Orme [14] does not compare the predicted airtightness with measurements – although it is stated that the airtightness can be estimated.

2.5.2 Differences in included air leakages

The different references vary on which air leakages that are included and which are not. Relander and Holøs [18] differ from the others in the way that more component leakages are included in the estimation model than in the other references. The other references are more limiting in which leakages that should be included. For instance Reinhold and Sonderegger [12] found that a limited set of leakages were found to be the dominating ones, see Table 1. It should also be mentioned that in Table 1 the chimney stands for 40 % of the leakage, which increases the correspondence between measured and estimated airtightness. An overall trend is also that the AIVC database is the dominating for component leakages.

2.5.3 Differences in the reproducibility

In Orme [14] it is stated that "*the airtightness of a building can be approximately derived from the database, either by dealing with the structure as a single room, or as a combination of openings".* Ref [14] does not give guidance on what to do when as-built does not match with what is available of component leakages. This is a rather general tendency in the references. Accordingly Van Den Bossche [23] had to do many assumptions when using the different references to estimate the airtightness of the Belgian houses in Fig. 2.

How the leakages were matched with the actual building is also unclear in e.g. SENVIVV [17]. This is seen generally in the references, except for the rough methods in Section 2.2. In this context it could be relevant to reflect on how the AIVC component leakage database was assembled and how the leakages were named.

2.5.4 Differences in the airtightness of the houses

One always will have uncertainties and statistical variations when it comes to airtightness both at house level and at component leakage level. Many examples of this exist. Holøs and Relander [27] found that for similar row houses built by the same craftsmen the average n_{50w} was 1.08 h^{-1}, and the SD 0.20 h^{-1}. Further, the average n_{50f} was 0.96 h^{-1} and the standard deviation, SD 0.18 h^{-1}. At laboratory level the same tendency is seen. In Relander et al. [21] the influence of various coating techniques on the airtightness of air open light weight aggregate concrete (LWAC) elements were measured. 5 LWAC elements all coated with a brush in a normal tempo and with one layer of coating had an average airtightness of 1.91 m^3/h with a SD of 1.24 m^3/h.

The airtightness of the houses in Relander and Holøs [18] was much higher than those in Reinhold and Sonderegger [12] and in Perera et al. [15]. Consequently the level of airtightness of the component leakage data was different. Component models rely on the assumption of homogeneity of the specific air leakage along the construction detail. This assumption becomes more critical when the airtightness increases because an absolute uncertainty in craftsmanship has a much higher relative effect on a low specific air leakage than a higher specific air leakage. For instance a deviation in craftsmanship of e.g. 0.5 m^3/hm in the specific air leakage is almost unnoticeable for a leaky component such as that for sills in Table 1, whereas for a more airtight it is not.

3. An en route upper limit evaluation principle for complying with the airtightness requirements

3.1 Motivation

The previous section revealed that it is not straightforward to estimate the airtightness of wood-frame houses with high airtightness prior to construction. This is supported by Sherman and Chan [28] stating that the quality of the workmanship and the design are often the determining factors in achieving desirable airtightness. Zeller and Werner [29] also states that the airtightness mainly does not depend on the type of construction, but on the planning and workmanship – the last mentioned to be controlled by airtightness measurements.

3.2 Stepwise measurement tradition

In Norway wood-frame houses are built both with an exterior vapour open wind-barrier and an interior vapour barrier. The purpose of the wind-barrier is to avoid energy-demanding wind-washing of the air open mineral wool, protect the building envelope against precipitation, provide for static rigidity and to avoid infiltration. The vapour barrier's purpose is to avoid moisture convection, moisture diffusion and infiltration. Wood-frame houses in Norway are typically constructed in the following way: first the wood-frame structure is built. Then the wind-barrier is mounted. The next stage is to insulate with an air open mineral wool, and finally the vapour barrier and the inner lining are mounted.

The industry has found that the chances of reaching the airtightness requirement for the finished building can be increased if the airtightness is measured stepwise during the construction process. The airtightness is often first measured when the wind-barrier only is mounted, n_{50w}. At this stage corrections for increasing the airtightness can more easily be done than on the finished building. In some cases the airtightness is also measured when the vapour barrier is mounted – so that corrections can be done on the vapour barrier.

In Norway the stepwise measurement is often considered to be a part of the quality assurance system, and is therefore integrated into the total building cost of the house, i.e. not reducing the profit for the contractor. The building costs of a typical Norwegian wood-frame house of around 175 m^2 are in the order of 250.000 Euro. A measurement of n_{50w} (or n_{50f}) of a house of this size is around 1250 Euro, i.e. around 0.5 % of the total building cost.

Before n_{50w} is measured, many penetrations have often been taken – and are sealed. However, of practical and logistics reasons, it is customary that additional penetrations are taken after the vapour barrier is mounted – weakening the wind- and vapour barrier if not sealed properly. This is for instance often the case with light weight aggregate concrete, LWAC element chimneys, or with unplanned penetrations. Consequently, it is not given that the airtightness must increase from n_{50w} to n_{50f}, although one could expect that at first.

To cope with this uncertainty, there are different opinions between contractors on which upper limit that should be used on n_{50w} to be confident to reach the n_{50f} requirement – taking the uncertainties in possible increased air leakage after n_{50w} is measured into consideration. It has for instance been said that n_{50w} should be equal to or less than the n_{50f} requirement before one can continue the building process and mount the vapour barrier.

This chapter will investigate measurement data of n_{50w} and n_{50f} and use this to find an upper-limit value so that one can be confident to reach the n_{50f} requirement – taking the uncertainties statistically into consideration. Before this principle is explained, the statistical concept, the terminology and the data collection will be described.

3.3 Statistical concept

In order to find this upper-limit value, the idea is to collect measurements of both n_{50w} and n_{50f} for the *same* house to investigate the relation between n_{50w} and n_{50f}. This will be repeated for many wood-frame houses, and the data will be analysed using simple linear regression where n_{50f} will be plotted against n_{50w}. The question to answer is whether n_{50f} can be predicted from n_{50w}. Because many houses will be investigated, statistical uncertainties inherent in craftsmanship and different building geometries will be implicitly included. In the following the term "measurement pair" will be used for n_{50w} *and* n_{50f} for the *same* house.

Because statistical inference was to be done on the n_{50f} vs. n_{50w} plot, it was important to make sure that the statistical assumptions were not violated. Therefore a Goodness of Fit Test was run to investigate whether any transformations were needed. It was found appropriate to use a log transformation of all the measurement pairs. A Goodness of Fit Test also revealed that a log transformation was appropriate for the data in Holøs and Relander [27] and Brunsell and Uvsløkk [30]. For normalized leakage, Chan et al. [5] also argues for a log transformation. Consequently the log transformation was used.

3.4 The difference between n_{50w} and n_{50f}

In this article n_{50w} will be used as the airtightness measured when the wind-barrier was mounted (*no* vapour barrier mounted), and windows and doors were installed and sealed. The definition of n_{50w} is not too exact because this measurement is actually meant as a "help" for the craftsmen. When measuring the finished building, n_{50f}, the vapour barrier had to be installed also. A finished building was regarded as one of the three alternatives: the vapour barrier was mounted, the vapour barrier and an inner lining were mounted or a turn-key house.

The concept when measuring both n_{50w} and n_{50f} was that unfinished penetrations were closed or taped in the orifices if these later would be closed. This was done to prevent disproportionate and "non-relevant" airflows that would be absent when measuring n_{50f}. Nothing was done with the circumference sealing of the penetrations. For instance if mastic was used as sealing around a penetration, this was left un-taped.

3.5 Acquiring airtightness measurements

3.5.1 Blower-door measurements

To obtain measurement pairs, different wood-frame "catalogue house" contractors in the area around Trondheim were contacted. The contractors were questioned whether they were interested in a free of charge n_{50w} measurements of houses built by the company. The prerequisite presented for the contractors was that the craftsmen should be accommodating when questioned about the current house built. It was also communicated that it was of great interest also to measure n_{50f}. Of practical reasons not all of the 17 n_{50w} measurements were possible to measure when finished, n_{50f}. Totally 10 measurement pairs were obtained in the survey and are labelled "NTNU" in Fig. 3. The houses were measured according to NS-EN 13829 method B [31].

3.5.2 Finding blower-door measurements in the literature

To expand the number of measurements, the literature was investigated. Refs. [32-35] contained measurement pairs of wood-frame houses. Aurlien and Rosenthal [32] had totally three measurement pairs of wood-frame houses. Syversen and Ulimoen [33] contained totally 8 measurement pairs of wood-frame houses. 6 of these were excluded either because different volumes were used for n_{50w} and n_{50f}, or because the definition of n_{50w} or n_{50f} were not in agreement with that described in Section 3.4. Jacobsen et al. [34] had totally 5 measurement pairs of wood-frame houses and Myhre and Aurlien [35] contained measurement pairs of one wood-frame house.

Additionally two measurement pairs were obtained from two different companies doing blower-door tests (labelled "Ext". in Fig. 3). The requirement was also for these that the measurements were done according to NS-EN 13829 method B. Some uncertainty must be ascribed to the volume calculation and the definition of n_{50w} and n_{50f} in the two measurement pairs from the industry and those from Ref. [33] – because it was not done by NTNU or SINTEF Building Infrastructure. Although these measurement pairs cannot be said to form a statistical representative picture of Norway, it is reason to believe that this to some degree should reflect the broadness regarding different techniques and sealing methods used in Norwegian wood-frame houses in the period 2005-2010.

3.5.3 Characteristics of the wood-frame houses

All the wood-frame houses were single-family houses and had both an external vapour open wind-barrier and an internal vapour barrier. They must be said to represent typical Norwegian building traditions. The documentation of the measurements from the literature and that from the two companies varied. However, for the houses that had documentation, the following general tendencies were observed: slab on ground was dominating over basement and saddle roof was used for about half of the houses. The others had lean-to, flat and hip roofs.

Double wind-barrier on the walls (board wind-barrier and rolled wind-barrier in combination) was dominating over the use of a single wind-barrier, on the roof double wind-barrier was observed in roughly half the cases, and a single wind-barrier in the other. On the walls the pulled-in vapour barrier, giving an installation layer of typically 50 mm was dominating, whereas in the ceiling installation layers were mounted in about half of the cases. The wind-barrier was for most cases mounted continuously from the wall to the roof giving a practically unbroken wind-barrier layer at the eaves. This could be done by either drawing the wind-barrier around the eaves, or using loose eaves that were mounted after the wind-barrier at the roof and on the wall were mounted.

3.6 Results

Fig. 3 shows a scatterplot of n_{50f} vs. n_{50w} for the 23 houses with log scale on both axes. The origin of each of the measurement pairs is shown. The coloured area below the diagonal division line shows the area for which $n_{50f} < n_{50w}$ – i.e. where the airtightness is improved from n_{50w} to n_{50f}. The n_{50f} requirements for passive houses, low energy houses and TEK 2010 houses are also shown by horizontal lines in the figure. TEK 2010 refers to houses built according to the technical regulations of Norway [36].

The thick black line shows the regression line. The short-stapled curved line and the long-stapled curved line show the confidence interval, CI, and the prediction interval, PI, respectively. The 95 % CI shows where one can be 95 % confident that the average value falls within – for a given n_{50w}. The 95 % PI shows where one can be 95 % confident that the *next* observation will fall within – for a given n_{50w}.

For the regression equation in Fig. 3 the P-value for the constant was 0.61 and for the slope, log(n_{50w}) it was 0.000. Consequently there is a significant relation between n_{50f} and n_{50w}, but the position of the interception is not significant.

Fig. 3 Measurement pairs of n_{50f} and. n_{50w} for the 23 wood-frame houses.

3.7 Discussion

3.7.1 Changes in the airtightness from n_{50w} to n_{50f}

The plot in Fig. 3 is rather scattered. The spread of the data is also visualised in the rather wide CI and PI. The regression line lies just barely within the yellow area – i.e. suggests an on average improvement from n_{50w} to n_{50f}. This is *very* marginal, and taking into consideration that both the CI and PI are on both sides of the diagonal division line, one should rather interpret this that it is practically equally likely that the airtightness improves from n_{50w} to n_{50f} that it does not.

Both the CI and the PI have their practical interpretations. If many houses are built and reach the same n_{50w} – the average n_{50f} value of these houses is likely to fall within the confidence interval. Correspondingly – the PI shows in which range n_{50f} is likely to fall within for the next house built with a given n_{50w}. For instance, if n_{50w} for a given house is measured to 1.0 h^{-1}, one can be 95 % confident that n_{50f} for *this* house is likely to fall within 0.35 h^{-1} and 2.6 h^{-1}. Of this reason one *cannot* stop measuring n_{50f} and rely on n_{50w} only.

The idea that the upper limit of n_{50w} should be equal to the n_{50f} requirement therefore does not seem appropriate for these measurements. Before continuing with how to find an alternative upper limit value of n_{50w}, it is relevant to look at how the airtightness can decrease from n_{50w} to n_{50f}. Measurements outside the yellow area in Fig. 3 could at first seem unexpected because a house with a wind- *and* a vapour barrier should be more airtight than one with a wind-barrier only. There are various reasons why the airtightness can decrease from n_{50w} to n_{50f}:

Often additional penetrations are taken in the vapour and wind-barrier after n_{50w} is measured. If these penetrations are not properly sealed, additional air leakages not included in n_{50w} are likely to occur. For instance in the house with (n_{50w}, n_{50f}) equal to (0.52 h^{-1}, 1.48 h^{-1}) in Fig. 3 additional vents were mounted after n_{50w} was measured. It is customary that light weight aggregate concrete element chimneys do not penetrate the roof before after n_{50w} has been measured. In the house with (n_{50w}, n_{50f}) equal to (1.55 h^{-1}, 2.68 h^{-1}) in Fig. 3 the chimney was not sealed in the ceiling nor at the outer side, nor was the stove itself sealed well when measuring n_{50f}. According to Jacobsen et al. [34] the reason why the airtightness of the house with (n_{50w}, n_{50f}) equal to (0.62 h^{-1}, 0.73 h^{-1}) in Fig. 3 decreased was air leakages in a fuse terminal installed after the n_{50w} measurement.

Air leakages are observed both in the fabric, in the joints and around penetrations. With rather airtight wind-barriers, the leakage through the fabric is limited given non-faulty workmanship. For instance a very commonly used rolled wind-barrier often used in Norway has an air leakage of 0.15 m^3/hm^2 at 50 Pa pressure difference, with a normal amount of joints. For the wood-frame houses investigated here a typical ratio of wall surface per volume is around 0.36 m^2/m^3. This gives a contribution to n_{50w} of 0.05 h^{-1} only. A vapour barrier therefore does not necessarily reduce the surface leakages in practice because the wind-barrier is rather airtight in the first place.

When it comes to air leakages in the joints, it is rather varying whether the effect of a vapour barrier will reduce the air leakage if the wind-barrier is properly mounted. For instance in a structural floor it is seen that the effect of a vapour barrier can be very limited if not properly mounted [20].

3.7.2 Determination of upper limits of n_{50w} to comply with the airtightness requirements

The results from the preceding section showed that there are many reasons why it is reasonable to set the upper limit of n_{50w} lower than the n_{50f} requirement. The R^2 in Fig. 3 is not that high, but an upper limit value of n_{50w} can be found by looking at the PI. For instance, when building a TEK 2010 house, the upper PI shows that the contractor can continue mounting the vapour barrier when n_{50w} < 0.95 h^{-1} to be 95 % confident to fall within the airtightness requirement of 2.5 h^{-1}. If n_{50w} is above this limit, the contractors should continue with the wind-tightening, i.e. adjust n_{50w} by adjusting the labour achievement (the materials are decided already at this stage). Similar reasoning can also be used for houses that are to comply with the low energy requirement of n_{50f} ≤ 1.0 h^{-1} [37]: The measurements suggest that one can continue mounting the vapour barrier when n_{50w} < 0.36

h^{-1}. For passive houses, that have an airtightness requirement of $n_{50f} \leq 0.6$ h^{-1} [37] it is seen that the upper PI does not intersect with the horizontal requirement line on the y-axis. This is because there are not enough measurement data in this lower range and also because the data is rather scattered.

Fig. 3 can also be used if the airtightness requirement for some practical reason should be regulated by contract to be less than a certain average value for a collection of houses – e.g. a housing development. As can be seen by the upper CI, the requirement can be stretched from 0.95 h^{-1} (for *one* TEK 2010 house) to 1.95 h^{-1} if the n_{50f} requirement is set for the *average* of a collection of houses – e.g. a housing development aiming for TEK 2010 standard. Similar reasoning can also be used for houses that are to comply with the low-energy or passive house requirement.

This simple upper-limit-principle takes workmanship into consideration, but cannot be used prior to construction. Of this reason it must be regarded as an en route principle to increase the chances of complying with the airtightness requirements. Unlike the component leakage models, this principle does not require running updates of component leakage data and model assumptions. This would have been needed in a component model to take into consideration that craftsmen continuously improve their building style – and information quickly gets out of date.

3.7.3 Delimitation of included data

In Holøs and Relander [27] 62 measurement pairs of wood-frame *row* houses are given. The houses were highly identical and were built in order to reach the low energy requirement of $n_{50f} < 1.0$ h^{-1} (not all houses managed that, but on average the project did). The spread of n_{50w} was from 0.7 h^{-1} to 1.4 h^{-1}. In Ref. [27] it is seen that there is practically no correlation between n_{50w} and n_{50f}. In Fig. 3 there *is* a correlation between n_{50w} and n_{50f}. The spread in n_{50w} in Fig. 3 is from 0.25 h^{-1} to 2.6 h^{-1} – i.e. > 1:10. It is therefore reason to believe that the lacking correlation between n_{50w} and n_{50f} in Ref. [27] is due to a limited spread in the measurements, and also the fact that the houses were so similar – that the measurements are practically only replicates of each other. To detail this further, merging the measurements from Ref. [27] into Fig. 3, makes R^2 decrease to 54.6 %, but both the CI and the PI become narrower. The merging of the data from Ref. [27] into Fig. 3 also gives a correlation between n_{50w} and n_{50f} which was practically non-existing in Ref. [27]. Because the aim of Fig. 3 is to describe a variety of Norwegian wood-frame houses – and give a recommendation on upper limits of n_{50w}, the measurement pairs of the *row* houses from Ref. [27] were excluded.

3.7.4 Utilizing the upper limit evaluation principle at company level

Some contractors might find the upper limits way too conservative, based on their own experience. It is therefore important to emphasize that Fig. 3 is statistically derived, is based on a given set of Norwegian wood-frame houses built from 2005-2010, and that the main intention of Fig. 3 is to illustrate a *concept*. The recommendations derived from Fig. 3 are therefore not to be regarded as "the set answer" for Norwegian wood-frame houses.

It is at company level, when own sealing techniques and solutions are used, that a figure such as Fig. 3 comes into its own. Contractors therefore could start collecting measurement pairs of their own houses and plot them in a similar diagram and derive the PI and the CI to find the upper limits. This could be done for different work teams and over time to increase the benefit. If this is done systematically, and airtightness is a focus in a company, the intervals can be slackened considerably from that in Fig. 3.

3.7.5 Energy considerations

From the previous sections it is clear that uncertainty is associated with reaching a given level of airtightness. What matters for the contractor is to comply with the airtightness requirement. If it does turn out that the contractor unintentionally actually reaches a n_{50f} lower than the requirement, this results in free energy savings for the house buyer. To form a conception of the infiltration heat losses depending on how many facades that are exposed, the shielding, and n_{50f} [h^{-1}] one can use a standard Norwegian detached wood-frame house of 175 m^2 with a volume of 430 m^3 and a perfectly balanced ventilation system as an example. (With a perfectly balanced ventilation system, the calculated infiltration n_{inf} [h^{-1}] reduces to n_{50f} multiplied by the shielding e [-] according to NS 3031.) Table 2 shows the calculated infiltration heat losses depending on n_{50f} [h^{-1}], the shielding e [-] and in which city the house is located, based on a simple year average temperature calculation using an indoor temperature of 21 °C.

Table 2 Calculated infiltration heat losses [kWh/m²yr] depending on n_{50f} [h^{-1}] and the shielding e [-] of a house of 175 m^2 and a volume of 430 m^3 situated in two different cities in Norway. The house has a perfectly balanced ventilation system. The year average temperature of Oslo and Tromsø are 6.1 °C and 2.7 °C respectively [38].

As apparent from Table 2, there is a considerable energy saving potential in high airtightness. It is also seen that the colder the climate and the more exposed the building is, the more noticeable it is on the energy losses for the house buyer if the contractor constructs a house with a lower n_{50f}.

4. Conclusions

The authors suggest that the estimation methods can be categorized into three different types: rough methods, regression methods and component leakage methods. None of the reviewed references on airtightness estimation show that one can substitute airtightness measurements by estimates. The reproducibility of the earlier estimation work is very varying. Not all the references show validation of the results with new measurements. The references based on component leakages are largely based on the AIVC component leakage database which is rather old. For all the reviewed methods the level of thoroughness of workmanship is a challenge. Relander and Holøs [18] is the only reference found that deals with estimation of wood-frame houses with high airtightness. This reference did not succeed to estimate the airtightness prior to construction.

For a contractor what really matters is not an estimate of n_{50f}, but a reliable means to be sure of reaching the n_{50f} requirement. It is therefore customary, as part of a quality assurance system, to perform blower-door tests stepwise during the construction process, for instance when the wind-barrier is mounted, n_{50w}. It has for instance been said that a safe upper limit of n_{50w} should be the n_{50f} requirement because when measuring n_{50f} the vapour barrier has been installed also. Measurements of n_{50w} and n_{50f} of 23 wood-frame houses are investigated to analyse this further. The correlation that is found between n_{50w} and n_{50f} shows that it is good reason to keep measuring n_{50w} because it gives an indication of n_{50f}. However, the large scatter shows that an appropriate n_{50w} is no guarantee for a low n_{50f}. The upper limit value of n_{50w} therefore should be set more conservative than the n_{50f} requirement because n_{50f} not necessarily has to be lower than n_{50w}. The analysis shows that when building e.g. a house according to the Norwegian building regulations, TEK 2010, it can be recommended that $n_{50w} < 0.95$ h^{-1} in order to be 95 % confident to reach the n_{50f} requirement of 2.5 h^{-1}.

The intention of the upper limits is not to give a “set answer” for Norwegian wood-frame houses, but rather to illustrate a concept that can be further utilized at company level. Companies therefore could implement the upper limit principle on their own measurements for increased applicability. The suggested upper-limit principle cannot be used prior to construction and is not to be regarded as an estimation method. However, it seems to be a safe way to reach the airtightness requirements.

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Table 1 Estimation example from Reinhold and Sonderegger [10]. D_i denotes the quantity [m], [m^2] or [each]. Li is the magnitude of the component leakage given both as [cm^2] at 4 Pa and in [m^3/h] at 50 Pa. Modified from Ref. [12] with kind permission of the AIVC.

Component	**Description**	**Di**	**Li [cm^2] at 4 Pa**	**DiLi**	**Relative share**	**Li [m^3/h] at 50 Pa**
Sills	Uncaulked	43.2	4	173	20 %	19.20
Electrical outlets		20	0.5	10	1 %	2.40
Windows	Sliding	13.1	4	75	9 %	19.20
Framing			1.7		0 %	8.16
Exterior doors	Single	5.7	7.7	54	6 %	36.96
Framing			1.7		0 %	8.16
Fireplace	Without damper	1	350	350	41 %	1680.03
Penetrations	Pipes	7	6	42	5 %	28.80
Heating ducts	Ducts untaped, in basement	1	144	144	17 %	691.21
					0 %	
Calculated Building Leakage Area, Lc (cm^2)				847		
Measured Building Leakage Area Lm(cm^2)				770		

Table 2 Calculated infiltration heat losses [kWh/m^{2}yr] depending on n_{50f} [h^{-1}] and the shielding e [-] of a house of 175 m^2 and a volume of 430 m^3 situated in two different cities in Norway. The house has a perfectly balanced ventilation system. The year average temperature of Oslo and Tromsø are 6.1 °C and 2.7 °C respectively [38].

			Calculated infiltration heat loss [kWh/m^{2}yr]	
n_{50f} [h^{-1}]	e [-]	Description of exposure and shielding	Oslo	Tromsø
2.5	0.07	More than one facade exposed, moderately shielded building	18.52	22.75
2.5	0.1	More than one facade exposed, exposed building	26.46	32.50
2.5	0.01	One facade exposed, shielded building	2.65	3.25
1	0.07	More than one facade exposed, moderately shielded building	7.41	9.10
1	0.1	More than one facade exposed, exposed building	10.58	13.00
1	0.01	One facade exposed, shielded building	1.06	1.30
0.6	0.07	More than one facade exposed, moderately shielded building	4.45	5.46
0.6	0.1	More than one facade exposed, exposed building	6.35	7.80
0.6	0.01	One facade exposed, shielded building	0.64	0.78

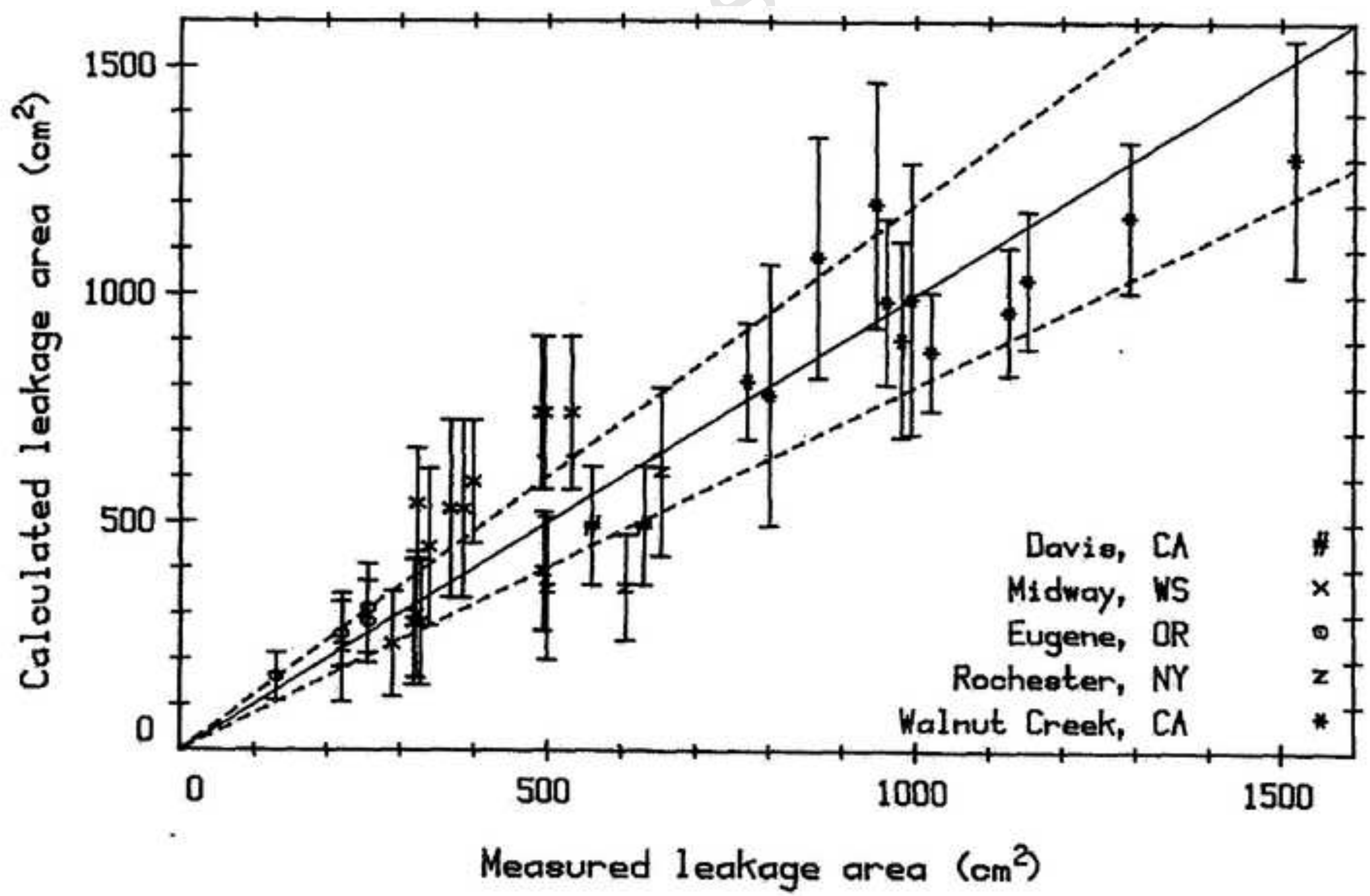
List of Figures

*Fig. 1 Scatter plot with regression from Ref. [12]. The regression curve was Calculated = 0.84*Measured + 111.5 with* R^2 *= 0.84. Reprinted with kind permission of the AIVC.*

Fig. 2 Measured and estimated airtightness for the 10 houses reported in Van Den Bossche [23]. The figure is identical to that found in Ref.[23], except for the translation. Reproduced with kind permission of Ghent University.

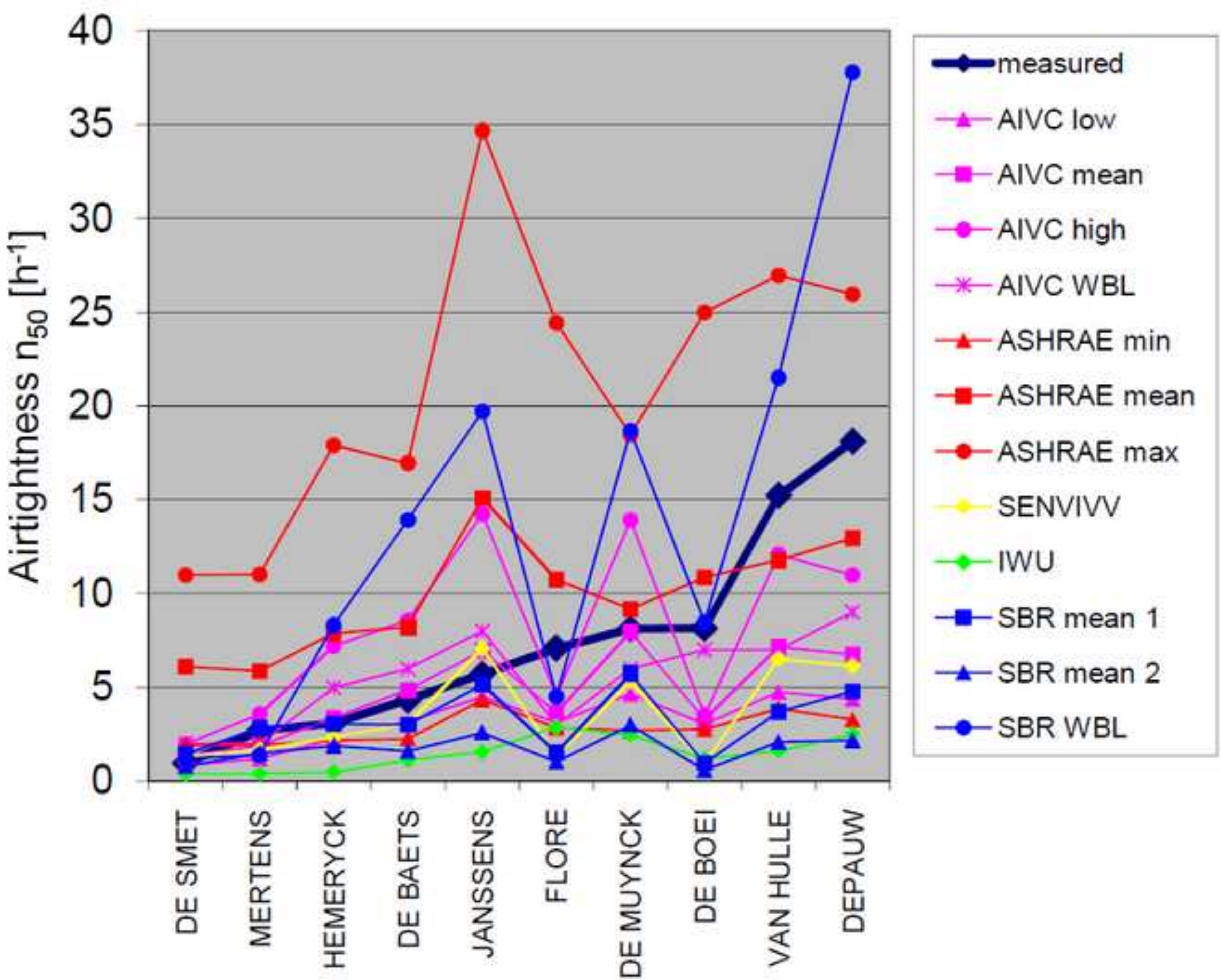
Fig. 3 Measurement pairs of n_{50f} *and.* n_{50w} *for the 23 wood-frame houses.*

Figure 1



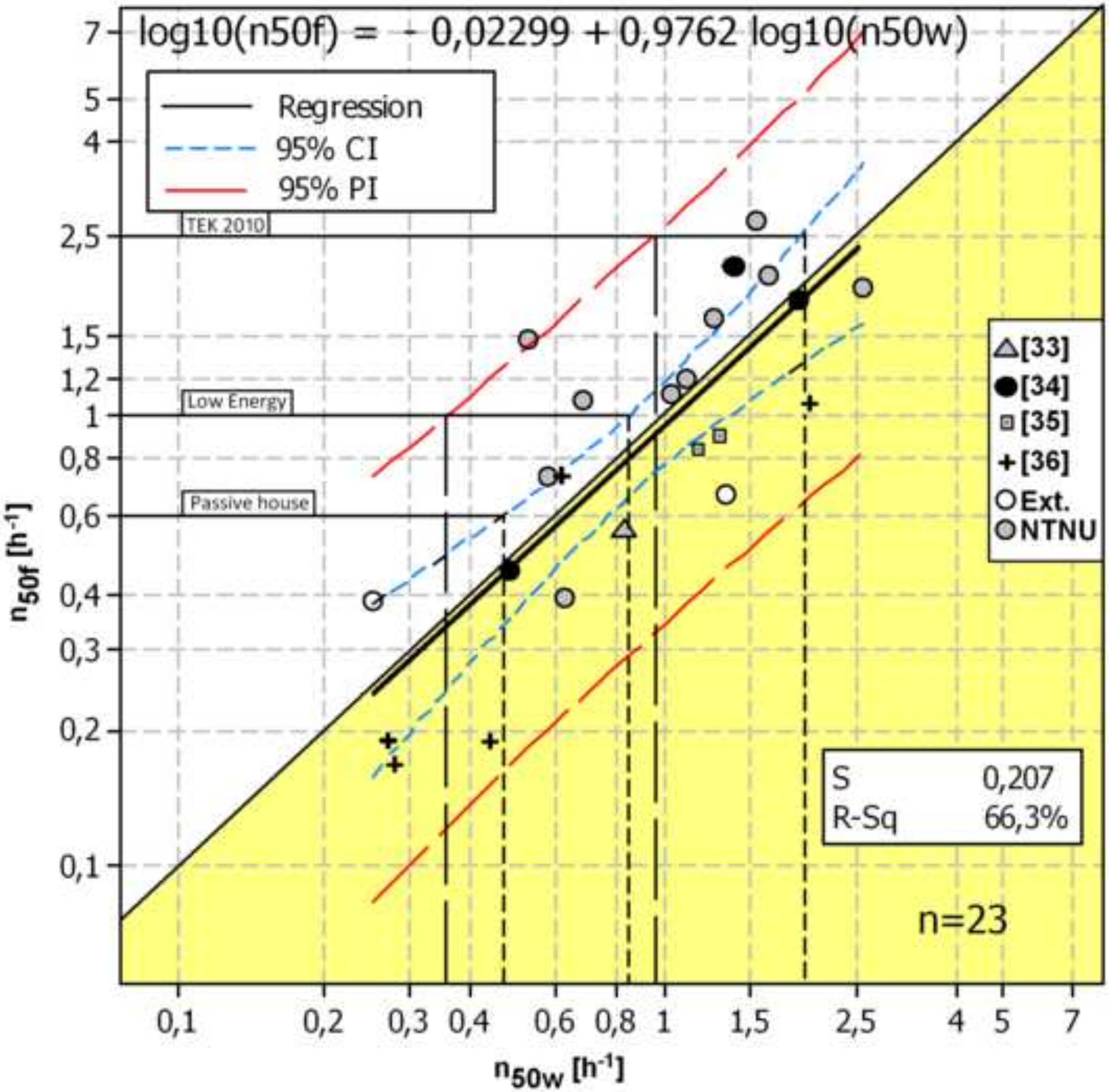
Calculated leakage area (cm²)
Measured leakage area (cm²)
1500
1000
500
0
0
500
1000
1500
Davis, CA #
Midway, WS x
Eugene, OR o
Rochester, NY z
Walnut Creek, CA *

Figure 2



40
35
30
25
20
15
10
5
0
Airtightness n_{50} [h^{-1}]
DE SMET
MERTENS
HEMERYCK
DE BAETS
JANSSENS
FLORE
DE MUYNCK
DE BOEI
VAN HULLE
DEPAUW
measured
AIVC low
AIVC mean
AIVC high
AIVC WBL
ASHRAE min
ASHRAE mean
ASHRAE max
SENVIVV
IWU
SBR mean 1
SBR mean 2
SBR WBL

Figure 3



log10(n50f) = - 0,02299 + 0,9762 log10(n50w)
Regression
95% CI
95% PI
TEK 2010
Low Energy
Passive house
[33]
[34]
[35]
[36]
Ext.
NTNU
S 0,207
R-Sq 66,3%
n=23
7
5
4
2,5
1,5
1,2
1
0,8
0,6
0,4
0,3
0,2
0,1
0,1 0,2 0,3 0,4 0,6 0,8 1 1,5 2,5 4 5 7
n_{50f} [h^{-1}]
n_{50w} [h^{-1}]

Highlights:

- No references claim that one can substitute airtightness measurements with estimates.
- The reproducibility of the reviewed estimation methods is varying, and not all show validation of estimates with measurements
- The airtightness of houses measured first when the wind-barrier only is mounted, n_{50w} is found to give an indication of the airtightness of the finished building, n_{50f}.
- Consequently, recommendations can be given on what n_{50w} should be so that one can be confident to reach the n_{50f} requirement.