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EPBD **I**mpact
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REPORT

Stimulation of good building and ductwork airtightness through EPBD

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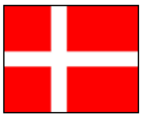

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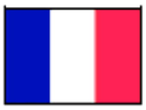

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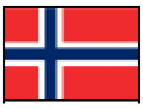

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TABLE OF CONTENT

1 SUMMARY

Building and ductwork leakage are detrimental to energy conservation, comfort, and hygiene. They can cause building damage and it can prevent proper control of the ventilation airflow rates. Through the ASIEPI project, we have identified that while some key elements for a market transformation on envelope airtightness are under development in many countries, status quo seems to prevail for the duct market. With the objective of all new constructions being "nearly zero energy buildings" in 2020, policy makers need to know how better airtightness can be stimulated. Within ASIEPI, we have come to the following recommendations :

To the question "How promote a market transformation of envelope airtightness ?" the following 3 main recommendations can be formulated:

- to include airtightness with fair reward in the EP calculation methods of the member states, combined with compulsory measurements and/or quality management approaches for claiming such reward in the EP-calculation, in labels and in subsidies;
- to promote cooperation with building professionals through development of practical tools and through pilot and research projects;
- to promote a global dissemination strategy depending on the target which is potentially wide as it includes owners, builders, designers, craftsmen, measurement technicians.

To the question "How support a market transformation of ductwork airtightness ?" Based on the Scandinavian success stories the following 3 main recommendations can be formulated:

- to develop dissemination on the benefits connected to good ductwork airtightness aimed at the building professional community and at industries to convince them that airtight round duct systems have many additional benefits (low costs, space efficiency) over both rectangular duct systems and round ducts without pre-fitted seals;
- to support industrial development of efficient products because a technology push was clearly observed in Scandinavia where 90-95% of ductwork installed are spiral-seam steel circular ducts with factory-fitted sealing gaskets;
- to include requirements in national regulation, with penalties for non compliance, and to develop technical guidelines and/or standards.

Major contributions of ASIEPI on the "building and ductwork airtightness" issue are described in the summary report [25] . They include :

- A review of regulations requirements, partly based on a questionnaire submitted to experts with the 13 countries represented in the consortium, and summarized in one conference paper;
- A focus on 5 countries where a market transformation is underway, with 2- to 4-page reports that analyse the market transformation mechanisms;
- A focus on technical issues, with a series of information and conference papers on very-low energy buildings, calculation and measurement methods;
- Awareness raising, namely through several national and international workshops, internet sessions, and presentations in conferences.

2 INTRODUCTION AND BIRD'S EYE VIEW OF THE PROJECT RESULTS

One objective of the EU SAVE funded project ASIEPI (Assessment and Improvement of the EPBD Impact, October 2008 until March 2010) is to study building and ductwork airtightness. The issue entitled 'Stimulation of good building and ductwork airtightness through EPBD', aims to give a clear picture to policy makers regarding the way better envelope and ductwork airtightness is stimulated in the member states, including indications on the impact of the measures taken to transform the market.

The purpose of this report is to present the work done on this issue and the acknowledgments dressed through the different deliverables and productions, which are more described in the part B of the summary report [25] :

- ✓ **The report** "Report on the building airtightness measurement method in European countries" [6] ;
- ✓ **The document** " Brainstorming document on the envisaged ISO 9972 revision"[5] ;
- ✓ **The report** " An overview of the market transformation on envelope and ductwork airtightness in 5 European countries", a compilation of 5 internal short country reports (Germany, Belgium, Norway, Finland, France) [24] ;
- ✓ **The report** (in french) « Synthesis of ASIEPI's questionnaire : Status regarding envelope and ductwork airtightness in Europe » [22] ;
- ✓ **The report** " Methods in the national EPB-calculation procedures to determine the ventilation heat transfer coefficient" [41] ;
- ✓ **Information Paper P072** "Implementation of energy performance regulations: opportunities and challenges related to building airtightness" [39] ;
- ✓ **Information Paper P147** " International comparison of envelope airtightness requirements & success stories that could inspire the EC and other MS" [2] ;
- ✓ **Information Paper P157** " Airtightness requirements for high performance building envelopes" [13] ;
- ✓ **Information Paper P165** " Airtightness testing of large and multi-family buildings in an Energy Performance regulation context" [40] ;
- ✓ **Information Paper P187** "Duct System Air Leakage - How Scandinavia tackled the problem" [33] ;
- ✓ **Information Paper AIVC VIP29** " An overview of national trends in envelope and ductwork airtightness" [11] ;
- ✓ **The ASIEPI web event 1** " Ways to stimulate a market transformation of envelope airtightness - Analysis of on-going developments and success stories in 4 European countries", held in December 2008 [8] ;

- ✓ **The ASIEPI web event 7** " How to improve ductwork airtightness -Ongoing developments and success stories in Europe ", held in December 2009 [34] ;
- ✓ **ASIEPI presentation-on-demand 2** " Envelope airtightness: How to stimulate a market transformation? " [23] ;
- ✓ **ASIEPI presentation-on-demand 6** "Main lessons learned and recommendations from the IEE SAVE ASIEPI project", published in 2010 in several different languages, focuses on guidelines for Member States;
- ✓ **Paper n°1** "International comparison of envelope airtightness measurements", was presented at 3rd European BlowerDoor Symposium. Held in Kassel, Germany, in May 2008 [31] ;
- ✓ **Paper n°2** " Testing the airtightness of large or mutliple-storey-buildings in an EU-regulation context", was presented at 3rd European BlowerDoor Symposium. Held in Kassel, Germany, in May 2008 [38] ;
- ✓ **Paper n°3** "Stimulating better envelope and ductwork airtightness with the Energy Performance of Buildings Directive", was presented at 2008 AIVC Conference, held in Kyoto, Japan, in October 2008 [7] ;
- ✓ **Paper n°4** "Airtightness requirements for high performance buildings", was presented at 2008 AIVC Conference, held in Kyoto, Japan, in October 2008 [14] ;
- ✓ **Paper n°5** " Measurement of building airtightness in the EPB Context : specific procedure and sources of uncertainties", was presented at BPS symposium, held in Leuven, Belgium, in October 2008 [4] ;
- ✓ **Paper n°6** " Treatment of envelope airtightness in the EPB-regulations: some results of surveys of the IEE-ASIEPI project ", was presented at Buildair conference, held in Berlin, Germany, in October 2009 [40] ;
- ✓ **Abstract n°7** " Envelope and ductwork airtightness in the revision of the french energy regulation: calculation principles and potential impacts", was submitted at the end of the project at the 2010 AIVC Conference, in Seoul, South Korea [10] ;
- ✓ **Paper n°8** " Airtightness requirements for high-performance buildings ", was presented at the AIVC conference, held in Berlin, Germany, in October 2009[15] .
- ✓ **Internal questionnaire** in the EU project ASIEPI, December 2008 [9] ;
- ✓ **Internal report :** G. Voisin, M. Fleury, F.R Carrié, An overview of the market transformation on envelope and ductwork airtightness in France, Internal short country report in the EU project ASIEPI [37] ;
- ✓ **Internal report :** T. Aurlien & P.G. Schild, An overview of the market transformation on envelope and ductwork airtightness in Norway, Internal short country report in the EU project ASIEPI [3] ;
- ✓ **Internal report :** N. Heijmans, Paul Van den Bossche, An overview of the market transformation on envelope and ductwork airtightness in Belgium, Internal short country report in the EU project ASIEPI [26] ;

- ✓ **Internal report :** J. Shemeikka, An overview of the market transformation on envelope and ductwork airtightness in Finland, Internal short country report in the EU project ASIEPI [35] ;

- ✓ **Internal report :** B. Rosenthal, W. Walther, An overview of the market transformation on envelope and ductwork airtightness in Germany, Internal short country report in the EU project ASIEPI [32]

3 WHAT ARE THE CHALLENGES CONNECTED TO AIRTIGHTNESS ?

3.1 Envelope airtightness

Building airtightness is not a new subject. Much research has already been done on building airtightness in the Nordic countries since the 1970s. In August 1980, an article in the Air Infiltration Review (AIR) (Figure 1) entitled '*Build tight – ventilate right*' already very well described the challenges connected to airtightness.

Figure 1 : Illustration used in the Air Infiltration Review of August 1980 0

DEFINITION AND INDICATORS

Envelope airtightness can be defined as the resistance to inward or outward air leakage through unintentional leakage points in the building envelope, i.e. not through leaks in the ventilation system. This air leakage (also called 'infiltration') is driven by differential pressures across the building envelope due to the combined effects of stack, external wind and mechanical ventilation systems.

The airtightness of a building is often expressed in terms of airflow rate (Equation 1) through the building's envelope at a given conventional pressure weighted either by the heated building volume V (Equation 2) or by an area A (Equation 3). The area genreally used is the envelope area defined in Standard EN 13829[16] .

The lower the 'airtightness' value is, the more airtight the building's envelope is.

$$Q = C \cdot \Delta p^{n} \qquad [m^3/h]$$

Equation 1. Power law used to calculate airflow rate through envelope leaks

where:
Q volume airflow rate through the leakage site [m³/h]
Δp pressure difference across the envelope building [Pa]
n flow exponent (0.5 < n < 1). Typical value is 0.66
C airflow coefficient [$m^3\,h^{-1}\,Pa^{-n}$]

$$n_{\Delta p} = \frac{Q(\Delta p)}{V_{building}} \qquad [h^{-1}]$$

Equation 2 . First sort of commonly used indicator: Airflow rate through building envelope at conventional pressure ΔP weighted by the heated building volume. n_{50} is used in a lot of countries[31] .

$$Q''_{\Delta p} = \frac{Q(\Delta p)}{A_{envelope}} \quad [(m^3/h)/m^2]$$

Equation 3 . Second sort of commonly used indicator : Airflow rate through building envelope at conventional pressure ΔP weighted by an area

IMPACTS ON ENERGY LOSSES AND INTEREST IN VERY LOW ENERGY BUILDINGS

Infiltration losses account for a significant share to the energy performance. In Belgium and in Germany, it is estimated that envelope airtightness accounts for about 10% of the energy performance level. In these countries, the benefit of envelope airtightness is similar to the installation of solar collectors[14] [8] . In France, the impact of envelope airtightness is estimated at 2 to 5 kWh/m²/year per unit change of leakage-number (n_{50}) for the heating needs. In Scandinavia, the impact might be around 10 kWh/m²y per unit change of n_{50}[24] . In Norway, comparisons to insulation thickness show that envelope airtightness can be more effective regarding the reduction of the energy consumption (Figure 2).

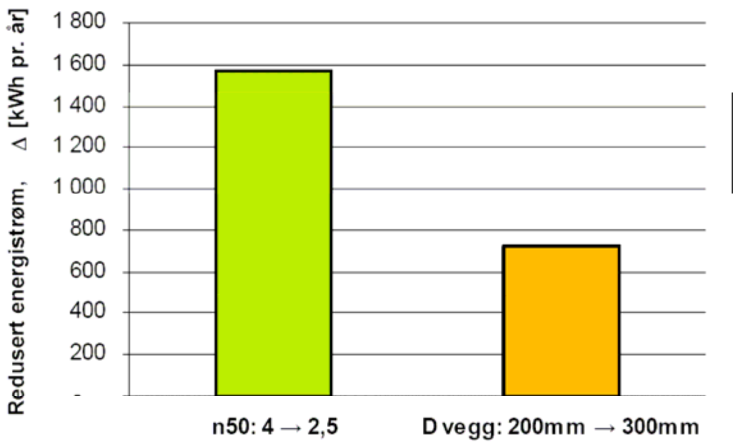


Figure 2 : the relative energy saving from building more airtight (green) compared with the energy savings from building according to the new standard for wall insulation in Norway (also regarded as being dramatic), for a normal single family dwelling. Source : [24]

An information paper[13] summarises the used terms and definitions of “high performance building” and shows that most of them imply a building airtightness that is better than for regular buildings. In the case of low energy buildings, comparisons have been made between envelope airtightness and insulation thickness [13] [14] . As a result, infiltration is recognized as a significant factor especially for such buildings. Moreover, airtightness measurements show that very strict requirements can be met in practice with simple cost-efficient measures [14] .

Airtightness is not only an issue in cold climates. In warm climates, while an airtight envelope may have a smaller impact on heating energy, it can reduce the cooling energy in buildings with air conditioning.

However, energy simulations show that the dependence between building leakage, usage, systems, inertia, and energy use is quite complex in warm climates. For instance, an airtight envelope might be detrimental to thermal comfort in summer, but this depends on the temperature during the night, window opening scenarios, ventilation systems, and thermal mass. Therefore, it is wise to be specific about climates a well as building characteristics and usage when stating energy impacts of envelope leakage in warm climates.

The simplest approach for a policy maker is to enforce minimum airtightness requirements for all buildings that use energy for heating or cooling, irrespective of climate and usage. However, given the complex dependence between building leakage, usage, climate and energy use, we recommend a careful evaluation of these impacts at national level to help define the appropriate schemes to enforce airtightness in that country.

OTHERS IMPACTS ON VENTILATION, INDOOR AIR QUALITY AND BUILDING HEALTH

There are other challenges connected to envelope airtightness:

- ✓ Poor envelope airtightness may have consequences on ventilation system efficiency[7] . For extract ventilation systems, because infiltration is uncontrolled, a poor airtightness can short-circuit some rooms. With heat recovery systems, due to a poor airtightness, there are additional energy losses which short-circuit the heat recovery unit. As a result, energy consumption increases and indoor air quality is affected.

- ✓ Poor airtightness can lead to moisture condensation in the walls. Any resulting mould growth can cause health problems and eventually damage the structural integrity of the envelope. The thermal conductivity of insulation can also be affected. This is why airtightness is taken into account more often in wood constructions.

3.2 Ductwork Airtightness

DEFINITION AND INDICATORS

Duct airtightness classes A to D (see Figure 3) are defined in European Standard EN 12237 [53] for circular ducts and EN 1507 [48] for rectangular ducts. Class A is the leakiest class. A new standard for airtightness of ductwork components is in preparation: prEN 15727 [58] . The leakage test method for system commissioning is described in EN 12599 [54] . Airtightness classes for air handling units (L1 to L3) are defined in EN 1886 [50] . System standards, in particular EN 13779 [55] , give further recommendations for airtightness class selection for different purposes.

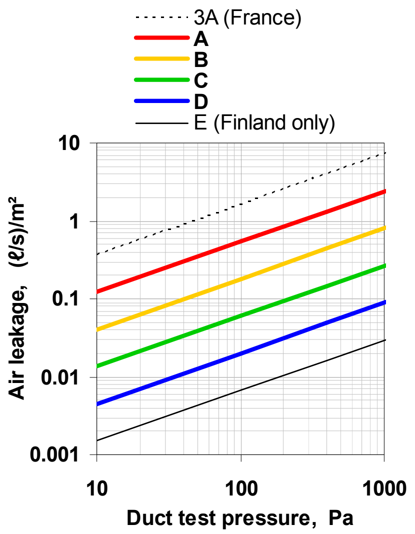


Figure 3 Illustration of duct leakage classes listed in Table 2 (with exponent 0.65) Special classes in France (3A) and Finland (E) are also shown

Table 1 Duct airtightness classes, measured at a test pressure of 400 Pa. Area is calculated according to EN 14239

Airtightness class	Limiting leakage (ℓ/s)/m²
A – worst	< 1.32
B	< 0.44
C	< 0.15
D – best	< 0.05

IMPACTS ON ENERGY LOSSES

Apart from Scandinavia, many countries in Europe have generally very leaky ventilation systems [61] . Leakage rates can be typically 3 times leakier than Class A, which is up to 30 times higher than is observed in Scandinavia.

To ensure that each room in a building is properly ventilated, the total air flow rate through the central air handling unit should to be high enough to compensate for any leakages in the ducts between the unit and the rooms. This in turn affects the electrical power consumed by the fans [8] . Class C round ductwork has typically 30% less fan power than traditional Class A ductwork.

Moreover, airtight systems facilitate exploitation of the full benefit of other energy efficiency measures, including demand-control, and heat recovery. This affects the energy use for both heating & cooling. French calculations show that air leaking out of the ducts can reduce the global efficiency of a heat recovery system from 85% (nominal value) to less than 60% (ducts 3 times leakier than Class A ducts). This equates to approximately 0 to 5 kWh/m²/year of space heating.

It should be noted that the energy consequences of leaky ducts heavily depend on the type of ventilation system and the way ducting is planned. In recent years there has been a trend of moving all ducts, fans, etc. down from the cold attic to within the thermally insulated envelope of our modern houses. This reduces the number of penetrations of outer constructions, in itself a major goal. It also makes tending filters etc. easier, and the energy impact of leaks is less significant.

OTHERS IMPACTS ON COMFORT, VENTILATION, INDOOR AIR QUALITY, FIRE SECURITY, ETC…

Duct leakage is not only detrimental to energy efficiency, but also indoor air quality (in terms of lower air change rates and ventilation efficiency in rooms), comfort, and fire protection. It is often accompanied by other problems, such as inferior commissioning and cleaning. In Scandinavia good ductwork airtightness has largely been promoted together with indoor air quality benefits. Note that the Swedish VVS AMA guideline not only deals with energy issues related to duct airtightness but also with safety and indoor environment. This point will be more discussed in part 5.7 of this report.

3.3 Airtightness and the EPBD : Be ready for the “nearly zero energy building” !

The EPBD does not explicitly require taking building airtightness into account, but clearly gives a signal for a shift. According to article 3 of the directive, the national methodology of calculation of energy performance of buildings shall include thermal characteristics of the building (shell and internal partitions, etc.). It is also specified that these characteristics may include airtightness. The deadline for implementation of the requirements was January 4, 2006.

We have seen that envelope and ductwork airtightness generally have a strong impact on energy consumption (see part 3.1 and part 3.2). This impact is generally incompatible with very low energy use, which explains why “high performance buildings” require that attention be paid to envelope and ductwork airtightness.

Therefore, with the objective of all new constructions being “nearly zero energy buildings” in 2020, it is key for policy makers to take that issue into account and to take measures where appropriate to stimulate the market for better airtightness.

4 ENVELOPE AIRTIGHTNESS IN EUROPE

4.1 European standards

The European Committee for Standardization (www.cen.eu), has published different documents that could promote a harmonised consideration of building airtightness in the framework of the EPBD. The information paper P72 [39] gives an overview of these important standards.
A first important standard is EN 13829:2001[16] . Very similarly to standard ISO 9972[21] , it describes the measurement method of envelope airtightness through fan pressurization. Within Asiepi, we have written a draft position paper[5] for the revision of standard ISO 9972 based on existing technical documents from Belgium, France, and Germany, which was presented at the 2009 AIVC/BUIDAIR conference.
Other (draft) standards describe the method to calculate the ventilation air flow rates in buildings (including infiltration) to be used for applications such as energy calculations, heat and cooling load calculation, summer comfort and indoor air quality evaluation. The documents cover dwellings (EN 13465:2004[17]), buildings in general (prEN 15242[20]) and commercial buildings (prEN 15241[19]).
Finally, other documents like EN 13779:2004[18] or TR 14788:2006[36] give guidance on the maximum envelope leakage value for buildings.

4.2 Overview of airtightness in national regulations

In the ASIEPI project, a questionnaire [8] was submitted to 13 experts in the 13 countries (BE, CZ, DE, DK, ES, FI, FR, GR, IT, NL, NO, PL, PT) represented within the ASIEPI consortium in November 2007. The survey included 22 questions dealing with the way envelope and ductwork airtightness is taken into account in the regulation; the market uptake of better envelope and ductwork airtightness and reasons behind; and the major barriers towards better airtightness. The results of this questionnaire are summarized in one conference paper [7] and in a report[22] , only available in French.

Most (10/13) (BE, CZ, DE, DK, ES, FI, FR, NL, NO, PL) countries take into account envelope airtightness in their energy performance calculation procedures (Figure 4). Six countries have minimum requirements on envelope airtightness, among which Spain has partial requirements focusing on windows (Figure 5).

At least 7 out of these 10 countries give the possibility to reward good envelope airtightness as it results in lower “regulatory” energy consumption. In general, there is no requirement for existing buildings except in case of major renovation (CZ, DE).

The regulations’ compliance scheme obviously depends on the nature of the requirements. Most of the time, a pressurisation test has to be performed to be able to claim for a reward for good envelope or ductwork airtightness. In theory, the compliance to a minimum requirement should be systematically tested. However, to our knowledge, this is done only in the UK, where envelope pressurisation tests are compulsory since 2006 in all new buildings [13] . This requirement extends the previous one in force since 2002 for large buildings (over 1000 m²). Note that although compulsory testing does not apply in Denmark and Germany, these countries test respectively 5% and 15-20% of their new buildings. Also, ductwork testing is very widespread in Denmark.

There exist alternative routes to pressurisation tests. Quality management approaches are rewarded in Finland and in France. In other words, if a builder proves that he has implemented a quality management approach to obtain good envelope airtightness, he can use a value different from the default value in his energy performance calculation. In Finland, this route is targeted primarily at pre-fabricated houses. In France, the alternative route is applicable by all builders of individual houses. The approach has to be approved by the ministry based on a dossier filled by the builder that includes airtightness measurements on a sample of buildings. A few dossiers are being processed in 2008.

In the questionnaire the experts feel that envelope airtightness tests are frequent in none of the 13 countries investigated. They are rarely (4/13) (DE, DK, NL, NO) or very rarely (9/13). The experts feel that few or very few companies can perform pressurisation tests except in Germany, Denmark and the Netherlands. Since the questionnaire, the situation has changed considerably in France: Now (2010) there are a significant number of companies offering pressurization tests as well.

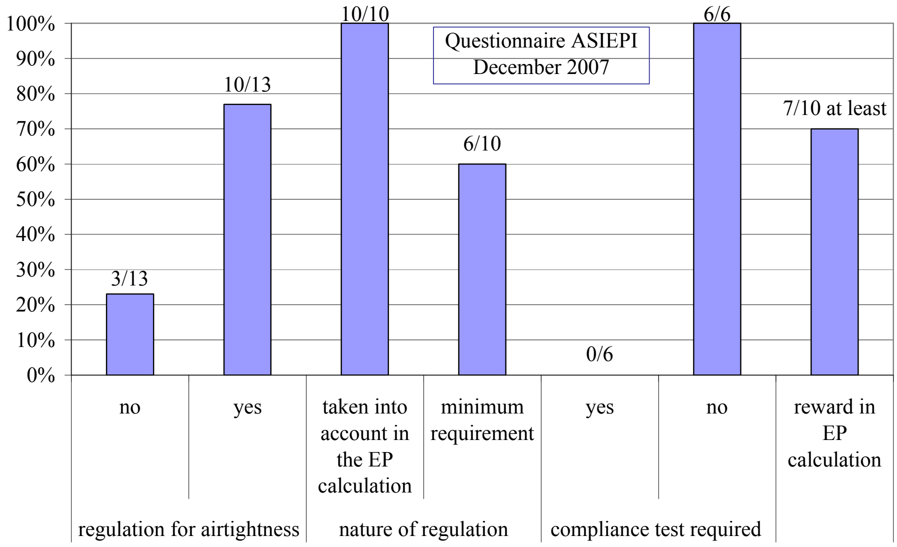


Figure 4. Overview of envelope airtightness in national regulations. Source : [7]

EU Member State	Air tightness requirements at 50 Pa pressure	
	Natural ventilation	Mechanical ventilation
Czech Republic	4.5 1/h	w/o recuperation: 1.5 1/h with recuperation.: 1.0 1/h
Germany	3.0 1/h or 7.8 m³/h per m² floor area	1.5 1/h or 3.9 m³/h per m² floor area
	Leakage rate per façade area: 3.0 m³/m²h	
Denmark	1.5 l/s per m² floor area	
Norway	3.0 1/h	
The Netherlands	Dwellings: 200 dm³/s (at 10 Pa) Non-residential buildings: 200 dm³/s per 500 m³ (at 10 Pa)	
United Kingdom of Great Britain	New dwellings and new commercial and public buildings over 500 m²: 10 m³/m²h (stated as reasonable limit for the design air permeability in building regulations 2000 L1A and L2A)	

Figure 5 : Airtightness requirements in European Union Member States. Source : [12]

A FOCUS ON AIRTIGHTNESS IN NATIONAL EP CALCULATION

One other topic studied in the ASIEPI project was the intercomparison[1] of requirement levels in Member States. As part of the task to develop a comparison methodology, a sample dwelling was calculated according to the EPB-calculation methods of different countries. In order to gain better insight in the way envelope airtightness is taken into account in the methods, the national calculators were asked to perform an additional calculation, namely to vary their national airtightness input variable and to report the impact on the ventilation heat transfer coefficient (for space heating calculations). A paper[40] presents and discusses the results of this quantitative exercise, with no intention to discuss which model best represents the real behaviour of the building and its users but with the purpose to highlight the consequences of some calculation details.

On Figure 6, it can be seen that generally calculation gives a reward all the way to the limit value of perfect airtightness (n50=0). Several impacts can be observed:

- the total ventilation heat transfer coefficient does not diminish any more below a certain value of the airtightness, (DE and NL for this particular dwelling case). In this case, there is no incentive/reward in the calculation method for further improving the airtightness below this point ;
- the total ventilation heat transfer coefficient flattens out nearly horizontally (NO and PO for this particular dwelling case). In this case there remains little stimulus in the EPB-calculation method to strive for very good airtightness levels.

However, there may be other explicit requirements that impose a certain degree of airtightness (e.g. the maximum n50-value in Norway).

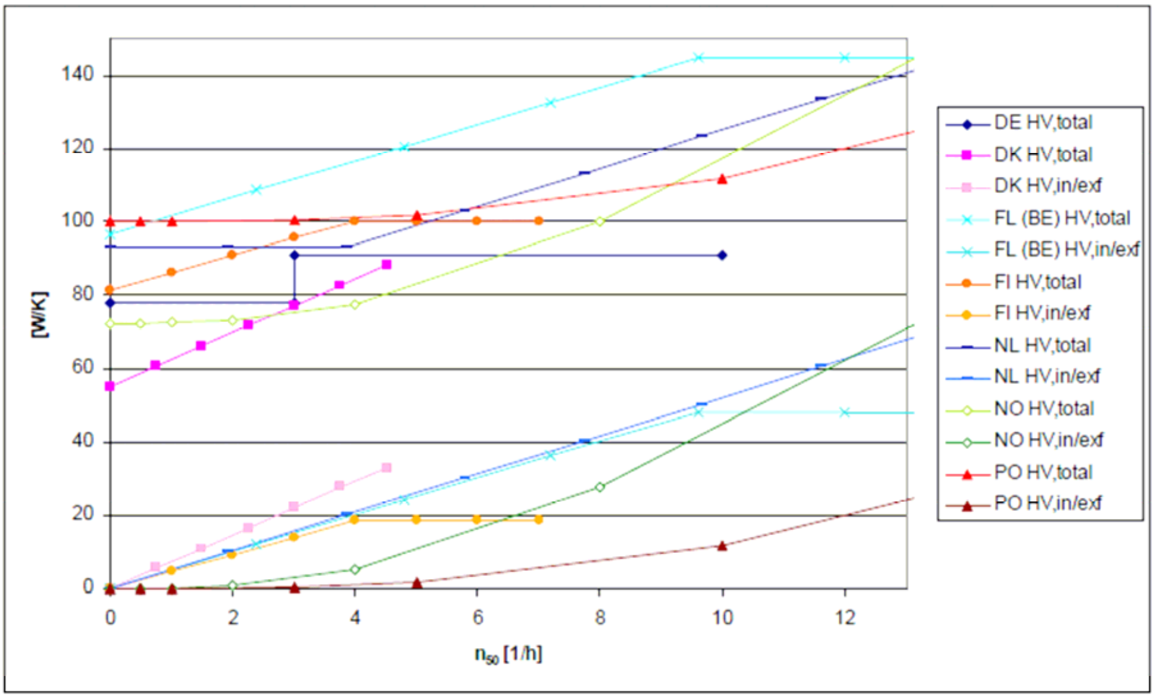


Figure 6 . The total ventilation heat transfer coefficient and (if possible) the part of in/exfiltration in it as a function of the national airtightness indicator for 8 countries. Source : [40]

The report [41] "Methods in the national EPB-calculation procedures to determine the ventilation heat transfer coefficient" gives more information on this issue, with an english translation of excerpts of the national EPB-regulations to determine the ventilation heat transfer coefficient, sometimes also some background information.

[1] See : http://www.asiepi.eu/wp2-benchmarking.html

4.3 Envelope airtightness measurements data

A recent study [31] aimed to collect recent measurement results of whole building airtightness from different European member States to present a comparable analysis among them. In this study 1094 n_{50} values from 7 European countries were brought together: Belgium (excerpt from BBRI measurement database, 2007), Greece (Sfakianaki et al, 2008), The Netherlands (Cornelissen et al, 1994 and 1996), France (except from CETE de Lyon measurement dataset, 2007), Norway (except from Norwegian low energy dwelling project - SINTEF), Finland (Korpi et al, 2007) and Germany (except from BlowerDoor GmbH dataset, Dorschky et al, n.d.).

First step of the study was to choose the right airtightness indicator to do the comparison. In this study all measurement results at the pressure difference of 50 Pa weighted by heated building volume were considered which is commonly used for measurements (Equation 2). Some of the n_{50} values have been provided as such while others must have been calculated.

Conclusions were limited to comparison data for specific building categories or for specific countries but no reliable conclusions could be drawn for the overall building stocks in Europe. Moreover, for one country, the available database is not always representative of the national building stock. For instance, the 17 houses considered for Norway were rather considered as “low energy houses”. This leakage-level does also not reflect the general level in Norwegian housing. To arrive at more precise level of details of intercomparison of airtightness, an expansion of the available sample is strictly necessary concerning the number of measurements per building category and the level of available details per measurement: type and quality of construction, year of construction, specific habits, etc.

Significant differences that vary from 1.09 for Norway (followed by Germany and The Netherlands) to 6.38 for Greece (with Belgium being close at 5.51) were found between the mean n_{50} values for the category of “houses”. Mode n_{50} values are found to be again the highest for Greece (4.5), while being 2.5 for France and Finland and 1.5 for all other countries.

Country	Source	Number of available n50 values	Types of buildings tested	mean n50	min n50	max n50	stdev	stdev/ mean	median
Belgium	Belgium Building Research Institute (BBRI)	21	18 houses, 1 industrial, 2 offices	4,99	0,50	22,50	5,10	1,02	3,70
Greece	National and Kapodistiran University of Athens, Group Building Environmental Research (NKUA)	39	39 houses	6,38	1,87	13,10	3,15	0,49	2,64
The Netherlands	Netherlands Organisation for Applied Scientific Research (TNO)	218	110 houses, 108 appartments	1,48	0,06	6,20	1,03	0,70	1,26
France	Centre d' Etudes Techniques de l' Equipement de Lyon (CETE de Lyon)	644	317 houses, 242 appartments, 10 industrial, 5 offices, 4 hotels, 5 information, 7 multiple use halls, 4 sports, 4 whole appartment buildings, 46 others	3,38	0,04	60,96	4,42	1,31	2,55
Norway	Stiftelsen SINTEF (SINTEF)	17	17 houses	1,09	0,17	2,79	0,86	0,79	0,74
Finland	Tampere University of Technology, Department of Civil Engineering Helsinki University of Technology, HVAC laboratory	128	70 houses, 58 appartments	2,54	0,30	16,20	2,33	0,92	2,05
Germany	BlowerDoor GmbH, Energie- und Umweltzentrum (EUZ)	27	13 houses, 3 industrial, 2 offices, 2 homes for eldrly people, 2 shops, 1 hospital, 1 school, 1 library, 2 other	1,21	0,01	4,70	1,07	0,88	1,00

Figure 7 : Summary of n_{50} field measurements for the 7 countries of the study. Source: [31]

The study underlined the fact that measured airtightness data are not always fully comparable. Depending on the country, the standard used and the local uses, the conventional pressure difference used may be either 1, 4, 10 or 50 Pa and different surface and volume calculations are used. A general agreement on these calculations would give a more international status to the measurement data and would ease the comparison between the member states.

4.4 Market trends, warnings & barriers

Many years ago, in the 1970s, envelope airtightness had already been identified as a major problem to efficiently ventilate buildings. In the Air Infiltration Review (AIR) of August 1980, an article entitled ‘Build tight – ventilate right’ already very well described the challenges. Since then and until 3-5 years ago, little had been done in most countries.

In there answers to the questionnaire presented above most experts (11/13) underline however a change in practice as regards envelope leakage; this is not felt only in Finland and in Spain.

In the project ASIEPI, five short country reports were written by France, Belgium, Germany, Finland and Norway [3] ,[26] ,[32] ,[35] ,[37] . They were compiled together in a public avalaible report [24] . The aim of these reports was to give an overview of the mechanisms that have lead to a market transformation on envelope and ductwork airtightness in some countries, and to emphasize the key elements that could inspire other member states.

We have analysed the market trends with a similar approach as that adopted by Rennings (2005), who identified three major components of the market transformation: a) regulatory push; b) technology push; c) market pull. Concerning envelope airtightness following market trends can be identified in these three components which interact with each other as described in Figure 1.

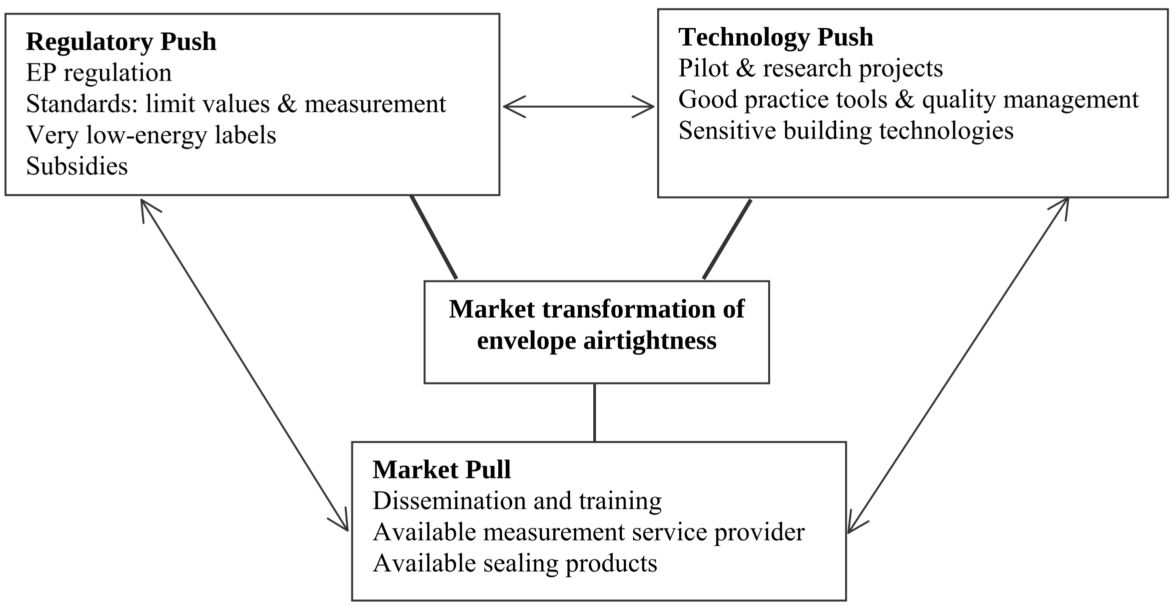


Figure 8. Different components of a market transformation of envelope airtightness.

REGULATORY PUSH : EP REGULATION, STANDARDS, LOW ENERGY LABELS AND SUBSIDIES

In Germany, success stories regarding airtightness market can be mostly explained by over two decades of regulatory push including: taking into account airtightness in EP regulation, developing standards, developing low energy-label with requirement on envelope airtightness and subsidies.

The “era” of airtight buildings started in 1974 with additional regulations to the standard DIN 4108 for the limitation of the joint permeability of windows. Since 1999, German Energy Saving Regulation (EnEV) gives the possibility to reward a measured airtightness value in EP calculation.

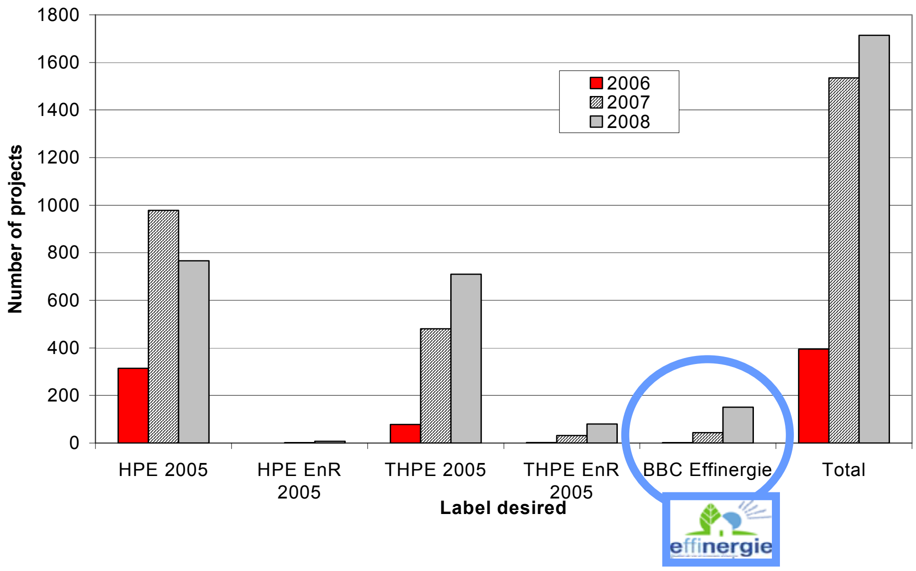
Role of standards was especially shown in Germany where EP regulations refers currently to standards with two types of standards developed: standards with limit values and measuring standards.
The limit values of the DIN V 4108-7 were first published in the Federal Bulletin in 1998 and thus became law with a maximum n_{50} value ($\leq$ 3,5 h^{-1} naturally ventilated; $\leq$ 1,5 h^{-1} mechanically ventilated). In 2001 the revised standard DIN 4108-7 gives maximum n_{50} values ($\leq$ 3 h^{-1} all other buildings; $\leq$ 1 h^{-1} with ventilation system).
In 1991 a draft standard for the measuring of air tightness (ISO/DIS 9972) was published. It was replaced in 2001 by the standard EN 13829.

The development of the KfW 40 ou KfW 60 houses and passive houses [13] with minimum requirements on airtightness has played a big role on market.

In 1991 Germany started requiring airtightness of n_{50} < 3 h^{-1} for buildings to be eligible for financial support. Today the Reconstruction Loan Corporation (Kreditanstalt für Wiederaufbau KfW) demands that air tightness shall be measured for funded buildings.

In France, airtightness has been taken into account in EP calculations since 2000, but the reward has become really significant only since 2005. The BBC-Effinergie label introduced in 2007 minimum requirements on airtightness [13] : I_4[2] < 0.6 (m³/h)/m² for detached houses and I_4 < 1 (m³/h)/m² for multi-family buildings. Moreover only authorized technicians are allowed to perform tests to prove the compliance with these requirements [12] . The “Grenelle” gives the objective to generalize BBC label for all new buildings in 2012. As a result we observe a growing interest for envelope airtightness and the number of companies offering measurement services increased in 2006 due to significant reward in the EP calculation. It increased very much in the last two years due to this low-energy label BBC -Effinergie.

[2] I_4 =Q(4Pa) / A_{Tbat} unit : (m³/h)/m² . A_{Tbat} is envelope area without floor area.



HPE : high energy performance

THPE : very high energy performance

EnR : Renewable energy

Figure 9 : Number of applications for regulatory-based energy performance labels in France. Note the significant increase in 2008 for the BBC-Effinergie label that includes a minimum requirement for envelope airtightness

TECHNOLOGY PUSH

Pilot & research projects

In the member states we observed a multiplication of pilot projects (low energy buildings) arousing the attention of actors on envelope airtightness issues. These have significantly driven the market, supported by regional and national bodies. Among those are Passivhaus pilot projects in Germany, Belgium, France, Czech republic, and Poland.

Some pilot projects were coupled with measurement campaigns, such as Norway (1980) where 14 low energy houses were tested with n_{50} ranging from 0.6 to 1.5 h^{-1}.
In Germany in 1990's 30 low energy housed were tested through a federal state support program with $n_{50} < 3$ h^{-1}. Very recently, a low energy project with 73 semi-detached houses in Norway was tested twice, with wind-barrier only, and then when the houses were finished. The required airtightness for this project was $n_{50} \leq 1$ h^{-1}, and a median of $n_{50}=0.88$ h^{-1} was achieved [75] .

Sometimes measurement campaigns are also performed to characterize the quality of the building stock.
In Norway in 1981, the air-tightness of a relatively large number of Norwegian ordinary dwelling houses were measured. This resulted in the only statistically representative study of this property ever. Average value showed just slightly more leakiness than prescribed by regulations ($n_{50} > 4$ h^{-1}). Later attempts to update this knowledge have not succeeded, resulting in guesswork, when calculating energy saving potential etc.
In Belgium in 1995-1997, a large study was carried out to analyse the actual insulation level, the airtightness of the envelope, the installed ventilation provisions and heating plants of recently built residential buildings (both single-family houses and apartments). The study has shown that the building airtightness of new dwellings was quite poor. Measurements were carried out in 50 dwellings; only 4 presented a rather good airtightness ($n_{50} \leq 3$ h^{-1}), and 10

presented a very poor airtightness (≥ 10 h^{-1}). The average n_{50}-value[3] was 7.8 h^{-1}. This study can be considered as a very important step to what became the EPB regulation in Belgium. Indeed, the lessons learned in this study (which was quite extensive for the size of Belgium[4]) were intensively used to prepare the EPB regulations.
The air tightness of Finnish single-family houses and apartments has been studied during the past five years in two large research projects to get state-of-the-art analysis of the current business-as-usual construction [35] . The results by construction type (Figure 10) show that current business-as-usual constructions do not meet the recommended air tightness value (n_{50} = 1 h^{-1}) of the national building code. The most important result was that good air tightness was achievable for all house types and with all kinds of structures and methods of construction.

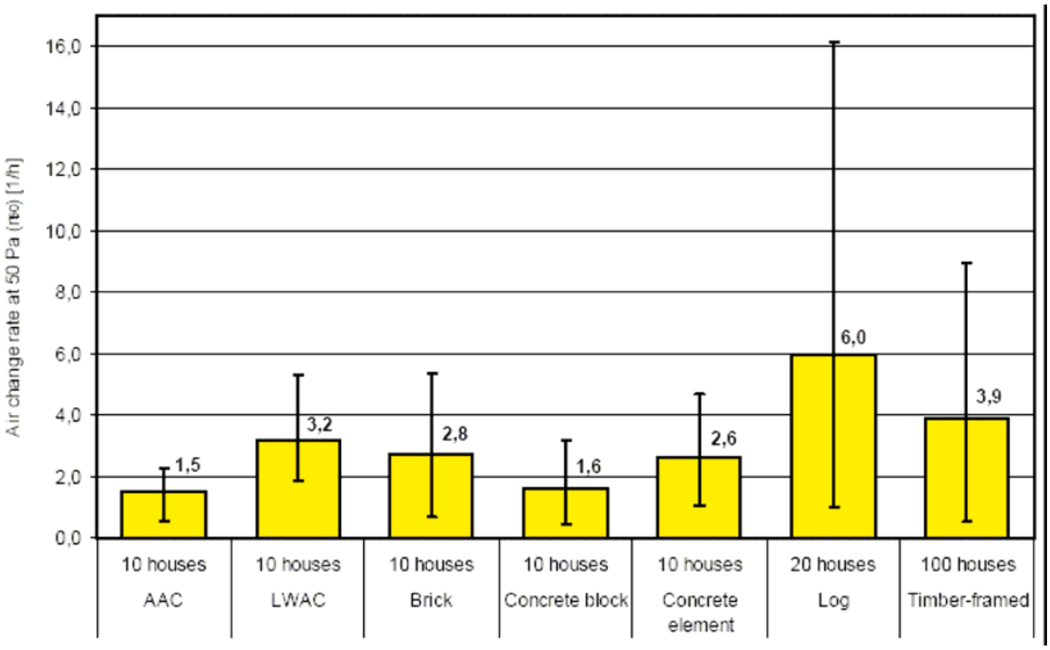


Figure 10 : Measured air tightness values of Finnish single-family houses by construction type (Korpi 2008). With minimum and maximal values. Abbreviations: AAC = blocks of autoclaved aerated concrete, LWAC = lightweight aggregate concrete. Source : [35]

Good practices tools & quality management

Generally only 4 countries among the 13 investigated[8] have documentation for professionals about airtightness: through workshops (CZ) or technical guides (DE, NL, NO). They are several type of documentation, including documentation about the measurement and about design.

In fact, there exists two very similar standards covering envelope airtightness measurement with fan pressurisation (EN 13829 and ISO 9972). However, there remain many unanswered questions regarding the way a test should be performed[6] [4] . Some questions which are relevant include: which method must be used: A or B? How do you measure the volume? What should be the highest pressure difference? Is it needed to perform test under pressurisation and/or depressurisation? Which intentional openings must be sealed during

[3] Note that at that time the n_{50}-values were calculated on basis of the external volume, so comparable values are even higher.
[4] Belgium is a Federal Stated composed of 3 Regions. The SENVIVV study was carried out in the Flemish Region.

the test depending on the calculation method, or in case of large or multi-family buildings ?. The "measurement of large or multi-family buildings" issue was especially underlined in the questionnaire answers[8] . These types of buildings are extremely rarely tested. Besides, the tests are performed on a building zone (e.g., an apartment) rather than on the whole building envelope as required by EN 13829. In the Netherlands, Norway, and Poland, the test is always performed on a sample of apartments or on a building zone (for NL and PL). As explained in a recent paper [38] , current discussion and studies in Germany are concerned with this topic. The aim is to deal with methodology for the measurement, including the choice of the sample, the use of more than two and up to ten fans, the use of the guarded zone measurement, the way to calculate the energy efficiency of the building when only apartments have been tested, etc.

In control and compliance schemes we must be sure that everyone uses the same procedure and that the uncertainties are limited, otherwise this could distort competition between measurement technicians, designers and builders. To this end, additional recommendations concerning measurement are used in some Member states among them: Germany (flib.eu), in France (www.effinergie.org, [30]), in Belgium (www.epbd.be).

Within Asiepi, we have written a draft position paper[5] for the revision of standard ISO 9972 based on existing technical documents from Belgium, France, and Germany, which was presented at the 2009 AIVC/BUIDAIR conference.

Concerning design there is also a strong need for practical tools. However in the questionnaire all experts mentioned a lack of such practical local tools, except for Germany where an association for airtightness has published practical recommendations (FliB, 2001), for Finland where a guidebook of airtight constructions and joints for building professionals must be published[24] , and for France, where one on-going national PREBAT project called "Mininfil"[29] is financed by French national Energy Agency (ADEME) and the French Ministry of Energy and Ecology. There is also a guide[27] from the United Kingdom identifying the common air leakage paths in typical constructions and providing practical advice on how these can be addressed.

Sensitive building technologies

In some Nordic European countries traditional constructions have specific characteristics or systems that are very sensitive to airtightness. In such a case envelope must also be or become airtight.

In this way, in Finland airtightness has improved during the 30 past years because of the transition from natural ventilation to mechanical ventilation with heat recovery systems, which concerns today about 100% of the buildings. A guideline value recommended for well functioning mechanical ventilation and heat recovery is : $n_{50} = 1\ h^{-1}$.

In Norway and in Finland, they are a lot of wood constructions for which the airtightness is known to be sensitive to the quality of design and workmanship, i.e., the airtightness of these constructions can be very poor or very good depending on the attention paid to small details. This may be an important reason why the envelope airtightness has been considered for a long time in these countries.

MARKET PULL

In Germany, through dissemination, training and thanks to available measurement service provider and sealing products, nearly everybody who is working in the building sector has heard about air tightness measurement, has seen a measuring procedure, has also a basic knowledge about the fault-prone building details like joints of construction elements.

Dissemination & training

Dissemination and training play an important role to pull the market about envelope airtightness.

In Germany the Blower Door Symposium started in 1993, was held between 1995 and 1999 every two years. It became a yearly meeting in 2000 and became a European conference in 2006. There are also training and certification of measurers, planners and craftsmen.

In France dissemination has intensified in the last few years. In 15 months, 5000 persons have attended to the 66 national campaign events on the new energy performance regulation (RT 2005) ; over 1000 persons have participated to miscellaneous events specific to airtightness organized in various regions by local and national authorities and construction professionals. Demand about such events is still growing, and with it the demand for trainings for measurers, designers and craftsmen.

Available measurement service provider & sealing products

Germany gives a good example about how availability of measurement service providers and sealing products pull the market.

As mention by E.U.Z [32] appropriate measuring devices are a precondition for air tightness measurement and they exist in Germany since 1989 with the Minneapolis Blower Door. There are six major providers in the market with different measuring devices. Actors buying measuring devices are also changing: If in earlier times manufacturers of prefabricated houses were the main clients, at the moment dry wallers mostly buy them. It also is a big market for chimney sweeps and a growing market for energy consultants, who use it in building reconstruction. About 2000 to 2500 devices of all providers are today estimated to be in the market.

Building sealing has existed in Germany since the middle of the 80s, with first airtight systems. In the middle of the 90's new products and suppliers appeared: Manufacturers of electrical goods started selling airtight pattress or junction boxes and later air tightness sleeves for cables and tubes and airtight recessed luminaire boxes. Today in Germany there are a fistful of suppliers and about 100 different products in this field in 4 product groups. We estimate to have about 50 brands of adhesive tapes and about 50 different sealing glues in the market. The market is on the move and business volume is increasing. In the beginning the material was used only in new buildings; since then, it has been more and more used in renovation. As a result buildings are considered as more airtight today thanks to correct installation of the airtight layer and better bonding materials: in earlier times butyl rubber was used while today acrylates are used in most cases.

4.5 How promote a market transformation of envelope airtightness ? Three main practical recommendations to keep

A preliminary work should consist in defining more precisely the strategy proper to every country: should we promote a market transformation of envelope airtightness everywhere in the country and for every building? The simplest approach for a policy maker is to enforce minimum airtightness requirements for all buildings that use energy for heating or cooling, irrespective of climate and usage. However, given the complex dependence between building leakage, usage, climate and energy use, we recommend a careful evaluation of these impacts at national level to help define the appropriate schemes to enforce airtightness in that country.

Once this crucial point has been clarified and the opportunity to change the market has been confirmed, we have selected 3 main practical recommendations to promote better envelope airtightness in Europe, through all the measures identified above as pushing and pulling the market, which are summarized below:

Figure 11 . Three components for a market transformation of envelope airtightness, according to Rennings approach (2005)

1 Fair reward in EP- regulation and measurement or quality management approach as a precondition for claiming rewards, labels or subisidies

Compulsory airtightness measurements are identified as a major push for an airtightness market transformation. Moreover envelope airtightness measurement represents mostly both a key element to achieve low-energy buildings, a cost-effective measure to reduce energy use and a relevant indicator of the quality of a construction.

A side-effect of the pre-requisites for claiming benefits is that some craftsmen in Germany, Norway, or France for instance, have bought their own device to control airtightness during construction. For example, two Norwegian manufacturers of ventilation equipment have started to manufacture low-cost portable automated fans for measuring airtightness of dwellings (Figure 12a&b). Small building firms can afford and master these simple products.

For larger buildings, modern air handling units (Figure 12c) can now be used to both pressurize the building and measure the leakage flow rate. These air handling units have centrifugal plug fans (both supply and exhaust fans) each with a venturi inlet cone with pressure tappings and a manometer to constantly monitor the air flow rate.

(a) A simple 'builder's own fan for airtightness testing of dwellings [foto © Flexit]

(b) Another new fan for 'one-button' airtightness testing of dwellings [foto © Bygg & Bolig]

(c) Modern air handling units can be used for airtightness testing of large buildings

Figure 12: Examples of products for simple testing of airtightness

There are three main efficient ways to make these measurements compulsory: in national regulations as a precondition for claiming a good reward in EP calculation ; in low-energy labels which should include a minimum requirement on envelope airtightness[13] ; and/or as a precondition for claiming local or national subsidies for a construction project. These aspects are developed below.

In national EP regulations compulsory measurements at commissioning coupled with good reward in EP regulation for better airtightness can be a major driver for change if the reward is well-adjusted.
Airtightness has been included and can be rewarded in the EP calculation method of the majority of the states investigated (Figure 4).
Recent experience (France, Finland) with the implementation of quality management approaches as proof of compliance including measurement of random samples is also promising. Such alternative route had been explored in the UK some years ago [39] , based on the adoption by builders of "robust" construction details for residences, defined in a reference document. However, we heard that the evaluation of the scheme, based on leakage measurements of buildings that went through this process, did not give satisfactory results: apparently, about half of the buildings tested failed. The UK experience calls into question the relevance of the more recent French and Finnish approaches, although it is clear that the success of such schemes depends heavily of fine tuning. In fact, these approaches appear similar in principle, but they include important differences in their implementations. Since then, the UK introduced minimum requirement on envelope airtightness and compulsory compliance documentation by measuring airtightness.

This also applies to low energy building labels or subsidies.

In low energy building labels a minimum requirement on envelope airtightness coupled with compulsory test have significantly pushed the market in Germany with the PassivHaus label, and more recently in France with the BBC-Effinergie label. In France since the BBC-Effinergie label introduced such requirements (2008) the number of companies offering measurement services grew from about 10 in 2007 to over 100 in 2009. These are interesting examples that illustrate this recommendation. The number of companies offering measurement services in France grew from about 10 in 2007 to over 100 in 2009 (the BBC-Effinergie label came up in 2008). In Germany, practical experience in achieving extremely airtight envelopes has been demonstrated. Estimates on the number of passive houses around the world range from 15,000 to 20,000[24] .

For claiming subsidies envelope airtightness test should be considered as a “proof” of the good quality of the construction. In Norway the governmental House Bank gives economic incentives to low energy buildings with a condition for payments: energy relevant characteristics must be documented. Airtightness measurement is also regarded as a way of documenting this property[24] . Those measures are recognized as a major reason behind the trend back towards more measurements taking place.

2 Promote cooperation with building professionnals and industry trough pilot and research projects and practical tools

In the member states we observed a multiplication of low energy buildings pilot projects arousing the attention of actors on envelope airtightness issues. Often supported by regional and national bodies, they significantly droved the market. Among those, there are passive houses pilot projects in Germany, Belgium, France, Czech Republic, Poland, etc… Nine experts (of the 13 questioned[8]) consider that those pilot and research projects are significant drivers for a market transformation. Those projects, showing very concrete and practical experience, are of interest to a large scope of building professionals, including designers, builders, craftsmen, and industries.

There is also a common concern regarding the help building professionals need for an effective market transformation and the lack of practical local tools (e.g., catalogues of construction details) with relevant recommendations to build airtight starting at the design stage.

However in the questionnaire all experts mentioned a lack of such practical local tools, except for Germany where an association for airtightness has published practical recommendations (FliB, 2001), for Finland where a guidebook of airtight constructions and joints for building professionals must be published[24] , and for France, where one on-going national PREBAT project called “Mininfil”[29] is financed by French national Energy Agency (ADEME) and the French Ministry of Energy and Ecology. In this project, in order to give an adequate answer to the practical needs, building professionals (designers, builders and craftsmen national federations) and industry participants are associated in the development of recommendations concerning building details, airtight materials and coordination of craftsmen (Figure 13). Those draft recommendations experience a great success among professionals (more than 450 downloads in few months).

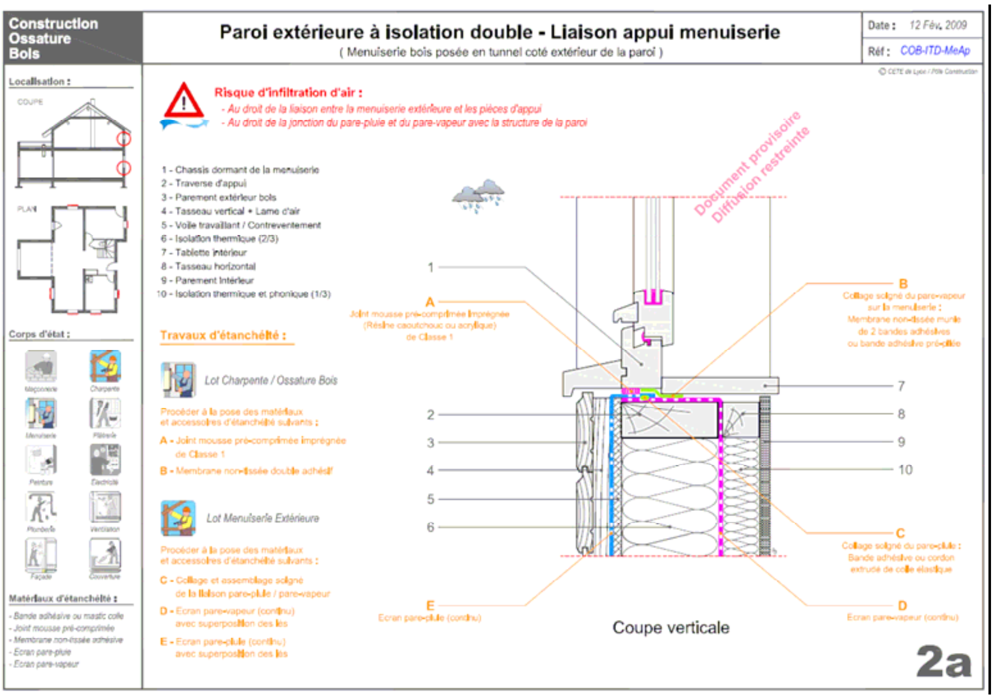


Figure 13 : Buildings details, airtight materials and coordination of craftsmen. Source: CETE de Lyon, PREBAT Project MININFIL, « MINimiser les INFILtrations » , Draft version, January 2009, source : [29]

3 PROMOTE A GLOBAL DISSEMINATION STRATEGY

A last key driver for a market transformation of airtightness we identified in the project is the dissemination strategy.

The dissemination strategy can include trainings, communication and events regarding pilot and research projects, practical tools, very-low energy labels, or the EP regulations depending on the target which is potentially wide as it includes owners, builders, designers, crafts, measurement technicians.

In Germany, through dissemination and training (and thanks to available measurement service provider and sealing products), nearly everybody who is working in the building sector has heard about air tightness measurement, has seen a measuring procedure, has also a basic knowledge about the fault-prone building details like joints of construction elements. In this member state, the Blower Door Symposium, organized since 1993, and the well-organized trainings and certification process for planners, craftsmen and measurers show that beyond such actions, to go with the market transformation and all the topics connected to airtightness, there remains an important demand.

In France the recent numerous miscellaneous events and increasing demands for trainings show that dissemination is asked and needed by the building professionals as soon as a market transformation is beginning.

AVOID PIT FALLS

Thanks to our focus on 5 countries - Norway, Finland, Germany, Belgium and France (14) – some pitfalls were underlined as barriers to a good development of envelope airtightness market.

The main pitfall to avoid is to underestimate the challenge. Standardizing good envelope and ductwork airtightness for every construction is a tremendous challenge that calls into question traditions in the design and erection of buildings. It requires to revisit trainings of architects, engineers and craftsmen, quality assurance processes, regulation (calculation methods and requirements), and to develop specific regulation or certification frameworks for example, for rewarding quality management approaches, or for performing reliable measurements.
Most countries are just starting to realize the challenge they have to overcome.

The second pitfall lies in the barriers to a social and economic acceptance of airtight envelopes.
In Norway[24] , it was observed that some builders would like to avoid measurement due to costly repairs needed when a measurement shows that airtightness does not meet the initial requirements. There is also a great deal of uncertainty involved if a certain airtightness requirement needs to be strictly satisfied. The building team (builder, designers, contractors, etc.) is confronted with an obligation that it cannot guarantee on the basis of the drawings and specifications alone. This is different from nearly all other aspects of the energy performance calculations (thermal insulation, efficiency of the heating system, etc.) where precise, well-evaluated design decisions provide in principle definitive certainty in advance. With respect to airtightness, the building team faces much more uncertainty. It may be confronted with unexpected surprises during construction and when testing. Will it then still be possible to correct any deficiencies? And at what cost? Because of such doubts, the building team may be reluctant to engage in airtightness; it may prefer not to commit itself to a result. Airtightness thus raises new challenges. How can the uncertainties be managed? How can the building team gain control over the entire design and construction process so as to arrive with confidence and at reasonable cost at the intended result? This may call for new ways of handling the entire course of the building process, new ways with which many practitioners may as yet be unfamiliar. In most countries, the vast majority of the construction professionals still need to gain its very first experience with the issue of quantified airtightness. As familiarity grows, professionals may gain more confidence with the issue, and become more willing to accept contractual, result oriented obligations.

On the other hand, erroneous or misleading statements such as “who would live in a plastic bag ?” by influential persons have great potential for slowing down, stalling, or even reversing a market transformation. This problem has been clearly identified in Finland and Norway.

While airtightness is favourable to the overall building quality, bad designs or workmanship (for example, absence of natural or mechanical ventilation system, inadequate strategy with combustion devices, absence of capillary breaks, or water leaks) can worsen damage.

Clear information must also be given at every stage (decisions makers, owners, builders, designers, craftsmen, measurement technicians) to avoid mistrust or misunderstandings of these kinds. That is why our third recommendation “Promote a global dissemination strategy” should be considered as a very important point.

A third pitfall concerns technical difficulties associated with the measurement protocol.

There exists two very similar standards covering envelope airtightness measurement with fan pressurisation (EN 13829 and ISO 9972). However, there remain many unanswered questions regarding the way a test should be performed[6] . For example, the intentional openings to be sealed during the test depending on the calculation method, or in case of large or multi-family buildings.
As a result, this could distort competition between measurement technicians, designers and builders. Within Asiepi, we have written a draft position paper[5] for the revision of standard ISO 9972 based on existing technical documents from Belgium, France, and Germany, which was presented at the 2009 AIVC/BUIDAIR conference.

5 DUCTWORK AIRTIGHTNESS: SUCCESS STORIES AND BARRIERS

5.1 Introduction

Apart from Scandinavia, many countries in Europe have generally very leaky ventilation systems [61] . Most people are unaware of this ‘out-of-sight’ problem. Inferior rectangular ductwork is widely used and poorly installed, yielding leakage rates up to 30 times higher than is observed in Scandinavia. Duct leakage is detrimental to indoor air quality (IAQ), comfort, and energy efficiency. It is often accompanied by other problems, such as inferior commissioning and cleaning. Airtight circular (round) ductwork is known to have many other benefits over rectangular ductwork, including cost. But why do designers, installers, and building owners forego airtight duct systems? It is due to:

- **(i)** lack of awareness of the benefits,
- **(ii)** lack of performance requirements and penalties for noncompliance, and
- **(iii)** no one is found accountable, as there are no commissioning measurements.

Conversely, in Scandinavia (DK, SE, NO, FI), high-quality airtight systems are the norm. 90~95% of ductwork in Scandinavia is now circular steel ductwork with factory-fitted airtight gasket joints (Class C or better). Sweden has spearheaded this development. This impressive result has come about after the problem of leakage (in terms of IAQ and energy) was first identified in the 1950s, leading to the first contractual requirements on ductwork airtightness in the 1960s (e.g. Swedish VVS AMA). Since then, the requirements have been tightened concurrently with advances in duct technology. There is strict control in Sweden, Finland and Denmark, so most installations comply with these stringent requirements after commissioning. Due to this success, pressure testing is no longer commonly required in Norway.

This chapter is in part based on the following work done in the ASIEPI project:

- A questionnaire [8] was submitted to experts in the 13 countries (BE, CZ, DE, DK, ES, FI, FR, GR, IT, NL, NO, PL, PT) in 2007. It had 22 questions dealing with envelope and ductwork airtightness.
- Five short country reports which give information about success stories in Finland [35] and Norway [3] , and barriers in France [37] , Belgium [26] and Germany [32] , concerning the market of ductwork airtightness.

The Scandinavian approach is described in detail, giving recommendations on how it can be adopted in other countries.

5.2 Overview of airtightness requirements for duct systems

Only 7 of the 13 countries in the questionnaire survey (BE, DK, ES, FI, FR, PL, PT) have specific regulations dealing with ductwork airtightness (Figure 14). Five of these (DK, ES, FI, PL, PT) have a minimum requirement, three of which (ES, FI, PT) have compulsory testing at commissioning. Testing is required also in Sweden (which was not included in the questionnaire survey). Two others (BE, FR) take ductwork leakage into account in their energy-performance calculation procedure, although it is limited to some building types in Belgium. No country surveyed has requirements for already existing ventilation systems.

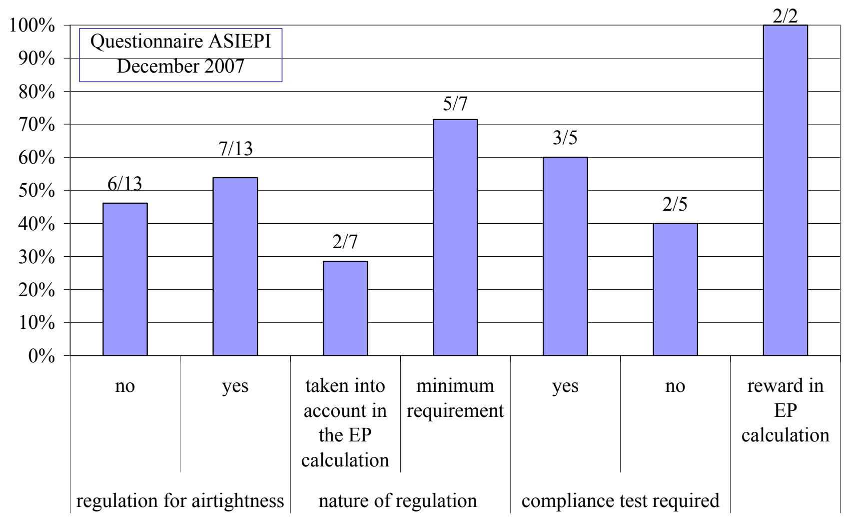


Figure 14. Overview of ductwork airtightness in national regulations. Source : [7]

The regulations' compliance scheme obviously depends on the nature of the requirements. Most of the time, a pressurisation test has to be performed to be able to claim for a reward for good envelope or ductwork airtightness. In general, compliance with minimum requirements should be systematically tested. This is why ductwork testing is common throughout Scandinavia, except Norway.

Despite the above measures, the questionnaire survey (Figure 15) indicates that, contrary to envelope airtightness, there is mostly no market transformation of ductwork airtightness in most MS. Only 3 countries (DE, FI, NL) consider that there is a growing interest in the issue, and duct leakage is probably already better addressed in these countries than in the rest of Europe (besides Scandinavia). Ductwork pressurisation tests are very rarely performed outside Scandinavia, except in the Netherlands (rarely). In other countries, these tests are performed mostly by research laboratories (FR, PL).

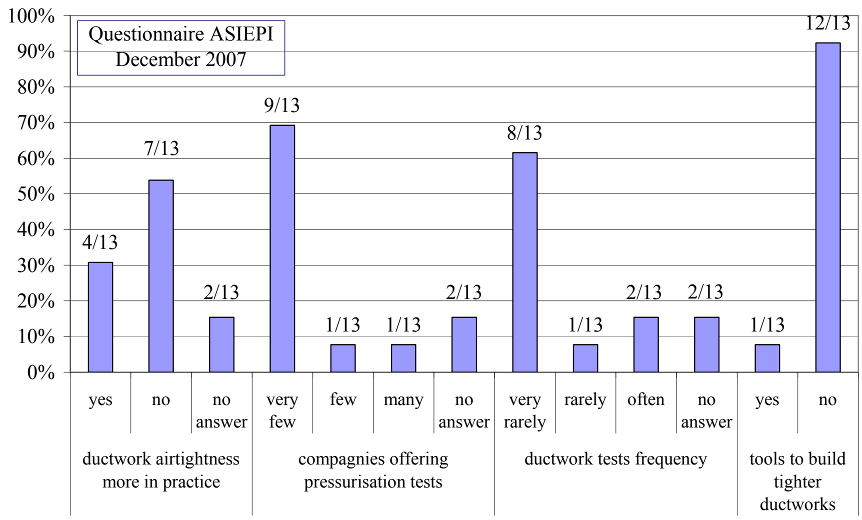


Figure 15. Market status, trends and barriers on ductwork airtightness. Source : [7]

5.3 European Standards on ductwork airtightness

Duct airtightness classes A to D (see Figure 16) are defined in European Standard EN 12237 [53] for circular ducts and EN 1507 [48] for rectangular ducts. A new standard for airtightness of ductwork components is in preparation: prEN 15727 [58] . The leakage test method for system commissioning is described in EN 12599 [54] . Airtightness classes for air handling units (L1 to L3) are defined in EN 1886 [50] . System standards, in particular EN 13779 [55] , give further recommendations for airtightness class selection for different purposes. ASHRAE's classes differ from the EN classes.

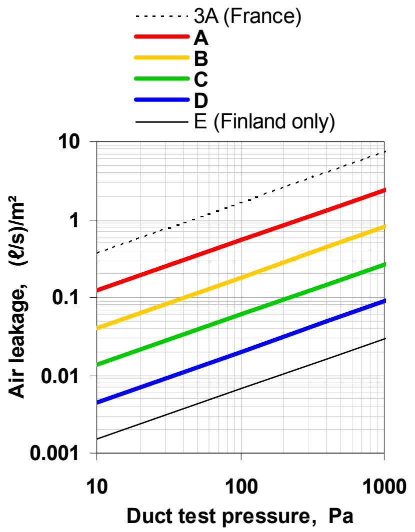


Figure 16 Illustration of duct leakage classes listed in Table 2 (with exponent 0.65) Special classes in France (3A) and Finland (E) are also shown

Table 2 Duct airtightness classes, measured at a test pressure of 400 Pa. Area is calculated according to EN 14239

Airtightness class	Limiting leakage (ℓ/s)/m²
A – worst	< 1.32
B	< 0.44
C	< 0.15
D – best	< 0.05

5.4 Today's situation

DUCT SYSTEMS USED IN SCANDINAVIA

The Scandinavian countries have similar climates and architecture. Requirements on IAQ and building services are therefore largely harmonized. The Nordic Committee on Building Regulations (NKB, now disbanded) published Nordic guidelines on 'Indoor climate – Air quality' [46] which give recommendations for duct systems and its commissioning. This consolidated a common stance on ductwork airtightness in Scandinavia.

Regarding ductwork leakage, the major reason behind the success stories observed in Sweden, Denmark, Finland, and Norway lies in the fact that 90~95% of ductwork installed in Scandinavia is spiral-seam steel circular ducts (Figure 17) with factory-fitted sealing gaskets (Figure 18), with airtightness Class C or better. This product is gaining popularity in other countries, including The Netherlands and Germany. The gasket system enables easy joining and dismantling. To prevent the joints from sliding apart, they are fixed in position using special screws or rivets [52] . One manufacturer has recently introduced a clickable system that makes screws/rivets obsolete, and thus can speed up installation (not dismantling). Duct products are generally type-tested in 3rd party laboratories.

Figure 17 Circular ducts in a compact Norwegian plant room [foto: SINTEF]

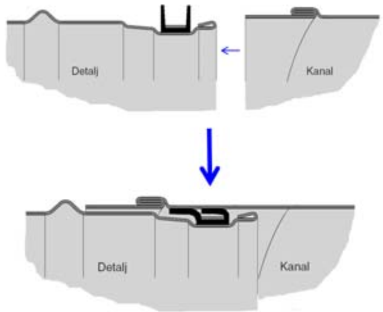


Figure 18 Cross section of circular duct joint with double gasket, giving airtightness Class D. Single gaskets generally achieve Class C, but there are other factors that affect airtightness, such as roundness and flatness of seams at the joints. [Lindab]

A contributory factor is the careful design of ventilation systems and ductwork in these countries compared to most other countries investigated. In fact, it is proven that pre-fitted components are very efficient solutions; however, this is not the case when they need to be customized on site, for non-standard plenum connections or for example a water pipe is in the way. Therefore, the challenge is precisely to minimize on-site customisation, which means that extra care should be given at design stage. In sum, careful design coupled with widespread use of pre-fitted seals is certainly one way to explore to drive the market towards tighter duct systems.

Scandinavia is also aware of the need for hygiene in ventilation systems. Ductwork is delivered to building sites with end caps. Numerous inspection hatches should be installed, before leakage testing, to provide access to the ductwork interior (in accordance with EN 12097[52]). Cleaning is undertaken as needed after inspections. The recommended inspection interval is 2~9 years depending on building & system type. A European Standard is in preparation with guidance on system cleanliness (prEN 15780 [59]). Nordic best practice is described in REHVA Guidebook 8 [66] .

SWEDEN

Nearly all Swedish buildings and their installations fulfil the voluntary AMA specification guidelines (‘General Requirements for Material and Workmanship’). AMA is referenced in building contracts between the owner and contractors. One section of the guidelines concerns HVAC (VVS AMA). The current version of VVS AMA is from 1998[45] . AMA refers to national and European standards. AMA’s ductwork airtightness classes are the same as those defined in European standards. VVS AMA specifies which airtightness class shall be used in different situations, and commissioning rules/protocols. Installations that do not fulfil the requirements when installed are eventually corrected, due to the strict commissioning regime.

VVS AMA requirements for duct system airtightness

- **Class A** (the lowest level allowed) applies to visibly installed ducts in the space being served. A leakage here will not have any real significance, as the leakage airflow is beneficial to the space.
- **Class B** (3 times tighter than A) applies to all rectangular duct systems, and any duct systems with surface area ≤ 20 m². Surface area is according to EN 14239 [56] . This generally applies to small houses.

- **Class C** (3 times tighter than B) applies to round duct systems with surface areas > 20 m². This applies to the vast majority of buildings.
- **Class D** (3 times tighter than C) is not a standard requirement, but can optionally be specified for systems in which airtightness is essential. This normally calls for round duct systems with double gaskets (Figure 18).

VVS AMA requirements on commissioning of duct systems

- This is done by HVAC contractors as part of the contract. AMA requires the contractor to include the cost of testing in their contract price
- The contractor can conduct the measurements themselves if they have the necessary competence and equipment. More often, they engage specialised subcontractors to do the testing
- The owner's consultant, is normally also present during the test
- The parts to be measured are chosen by the owner's consultant
- For round duct systems, 10 % of the duct surface area is tested; For rectangular duct systems, 20 % of the duct surface area
- A one-pressure leakage measurement is taken, normally at 400 Pa (a flow exponent of 0.65 is assumed).

It is expensive for contractors to install inferior duct systems, because they have to pay for both remedial work and additional tests. This is motivates contractors to ensure that the work is done properly in the first place.

Figure 19 Example of Swedish duct leakage testing equipment [Swema]

Figure 20 Another example of Swedish duct leakage testing equipment [Lindab]

Other Commissioning and Maintenance Issues

VVS AMA is much broader than just covering duct airtightness. Commissioning includes criteria related to safety (e.g. fire protection installations), energy performance and indoor environment (e.g. cleanliness, airflow). All extracted and supplied airflows in the building shall be measurement and adjusted if needed; the result should be within ±15 % of design (including uncertainty). For this, measurement points shall be provided in the main ducts for measuring total airflow, both for commissioning and for future monitoring. VVS AMA also requires that all commissioning details shall be included in the building's Operation and Maintenance manuals, to ease maintenance and retrofit. This shall include detailed drawings of ductwork installations, specifications for the materials and devices, and a maintenance schedule.

Regular Inspections

In 1992 a Swedish regulation came into force requiring performance checks of ventilation installations. The scheme is called OVK (Obligatorisk Ventilasjonskontroll, 'Obligatory Ventilation Control') [43] . This scheme has since been harmonized with EPBD inspections in EN 15239 [57] . The inspection frequency depends on how critical the building is, and how complicated the ventilation system is. The intervals range from 2 years for day-care and health care centres, schools, etc., up to 9 years for houses with balanced ventilation. The performance checks are conducted by about 2000 authorised inspectors. The required qualifications depend on the types of building and system, and whether the authorisation is local or national.

The inspection scheme does not include ductwork leakage measurements. On average, 6 faults are found in each system, 2 of which are serious. The most common fault is insufficient airflow rate; other faults are summarised in Figure 21.

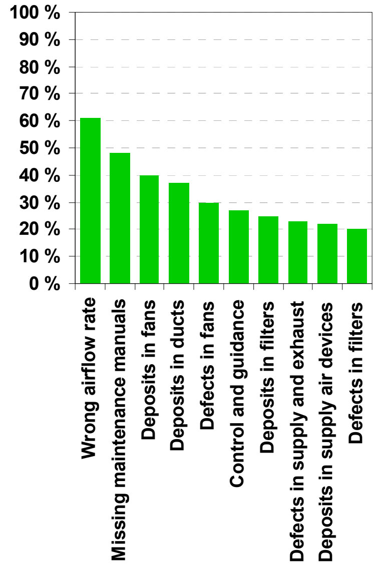


Figure 21 Most common defaults found during inspection of Swedish ventilation systems (duct leakage is excluded)

NORWAY

The Norwegian building regulations state merely that "Ducts and air-handling units shall be satisfactorily airtight". Norway includes duct airtightness in its national standard for building specs, NS 3420 [51] . It defines leakage classes, and leakage testing is specified a cost item (an optional one). As neither NS 3420, nor the building regulations, give quantitative requirements for airtightness; it is up to the building owner to specify in each case. In practice, the specified minimum requirement for duct systems is normally Class B [67] . Despite this, over 90% of installed ductwork is round with Class C. This is because most ductwork suppliers deliver Class C (with gaskets) to the Scandinavian market; it is cost effective and simple to fit.

Leakage tests were very common practice until the mid 1990s. Norway has exactly the same approach as AMA. Ten percent of the duct system area was tested, just as for AMA. Since then, testing has become uncommon because it is now rarely a contractual obligation, and is now never required for small buildings. Nevertheless, major ventilation contractors still recommend their own employees to perform pressure tests on their own systems as part of QA. They do this to discover installation faults at an early stage of construction, not just before the system is commissioned and handed over. This is especially true for critical ductwork (i.e. with high operating pressures, and main duct risers before they are built-in), not small ducts near air terminals (operating pressure < 100 Pa). If such a leakage test is done, then the results are handed over as part of the handover documentation. Only few systems are tested this way, maybe < 10% of large buildings.

Why is testing no longer required? It may simply be because duct leakage is no longer regarded as an issue, now that Class C has become the de-facto standard product. However, this is a false premise. Measurements have shown that there can be a significant difference between leakage in a real building and that documented in laboratory conditions [71] . Air leakage can amount to 5~7 % of the total ventilation flow rate in a commercial Norwegian building [68] . The reason for this is that in a real installation, many components are connected without gaskets, which creates numerous opportunities for leakage, particularly on branch ducts as opposed to main ducts [72] . Examples are flexible ducts, plenum collars, VAV-box collars, and pressed saddle taps (Figure 22)[69] [71] . The latter are a popular alternative to tee pieces (Figure 23, which are both more airtight and aerodynamic) because they simplify fitting, but poor workmanship can leave gaps between the collar and the duct.

Figure 22 Collar saddle for in-situ tees [source: L.A.Matsson]

Figure 23 Factory made tee with low flow resistance and airtightness Class D [©Lindab]

In the 1980s, a voluntary inspection scheme called Norsk ventilasjons¬kontroll (‘Norwegian Ventilation Control’) was started. It was funded by an insurance scheme, whereby HVAC consultants registered new buildings, and paid an insurance premium. The concept was to check at random 10% of new buildings covered by the scheme, so it was very cost-effective. The checks were similar to Sweden’s OVK, focusing on IAQ, ventilation flow rates and controls, but not leakage. At its height, approximately 10% of new buildings were being registered, which means that about 1% of all new buildings were checked. There was initially great enthusiasm for the scheme, but building owners eventually became weary of the fact that their buildings were not being picked out for checks. Interest in the scheme petered out after a few years, so it was terminated. If all consultants had joined the scheme, then 30 controllers would have been needed to check 10% of all registered new buildings nationally. Norway has now re-established an inspection scheme for ventilation and air-conditioning systems with capacity over 12 kW, in fulfilment of EPBD. The scheme includes all ventilation systems, also those without cooling. The inspection frequency is 4 years.

FINLAND

The Finnish situation [35] is similar to that in Sweden. The building regulations (Part D2 ‘Indoor climate and ventilation’) require minimum Class B for the whole system and gives experience-based recommendations to generally use ducts and components of Class C (minimum default) or better, and air handling units of Class L3 or better. However, the EP-number (energy performance) calculation does not take ductwork tightness into account.

The Finnish D2 regulations also have requirements for air handling units (Class L3 or better), and requires Class E (i.e. ⅓ of the leakage of Class D) for ducts & components for certain very special applications.

Compliance with the regulations is tested during the building process in all buildings except in single family dwellings, for which also use of Class C products is strongly recommended. Many companies offer testing services.

For commissioning, Finland has adopted the Swedish principle of random tests but modified the contents saying: "Where the ductwork system consists of ducts and ductwork components with air-tightness class C or better, and are tested and checked for quality, airtightness can be measured by random tests. The extent of such random tests shall cover 20% of the ductwork surface area. In case the air-tightness class of the ducts and ductwork components is better than C, the extent of such random tests is 10% of the surface area of the ductwork". In case of failure in the random test, or if inferior or non-tested components have been used, then the whole system shall be measured.

Most of the Finnish ventilation systems are made of prefabricated system components, in which the airtightness is typically easier to handle than in on site manufactured ventilation systems. Manufacturers have improved their components. The type approval and quality control for commercial ducts and components is common nowadays. Nationally VTT provides product certification for ductwork systems including ducts and components and testing of a typical duct configuration according to EN 12237.

Figure 24 relates the different aspects that have been implemented to the three market transformation components mentioned earlier in the report.

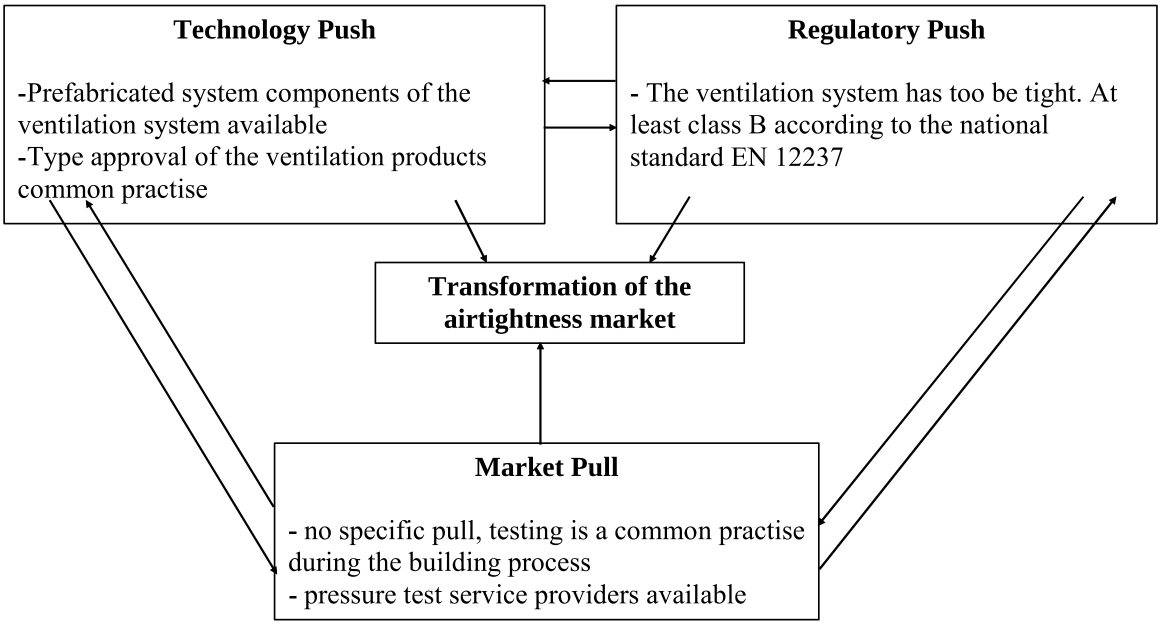


Figure 24. Key elements that have driven the ductwork airtightness market in Finland. Source : [35]

In conclusion, just like Sweden, quality control procedures for ductwork are an important tool to achieve better airtightness in Finland. As a result, the quality of the ductwork seems to be adequate at the moment, and the business environment is stable. Dramatic changes cannot be foreseen in the future.

DENMARK

The Danish code of practice for mechanical ventilation installations is DS 447 [47] . It has the same status as AMA in Sweden, in that it is not statutory, but ensures compliance with the building regulations. DS 447 states that airtightness of ductwork and air handling units shall be documented and satisfy the requirements in the building contract. The majority of systems are tested, even though other means of documenting airtightness are allowed besides leakage tests, such as referring to product documentation. Typically, the contractor bears the responsibility for documentation, which is presented after commissioning. Systems normally fulfil at least Class B and often Class C, just as in Norway and Finland.

Denmark has a ventilation inspection scheme, VENT (www.vent.dk). In 2008 it became mandatory for ventilation systems with fan power > 5 kW.

OTHER COUNTRIES

In other European countries, rectangular ducts are more common than in Scandinavia. Flange systems (Figure 25 & Figure 26) are often used with rectangular metallic ducts and with other components that need to be dismantled regularly for maintenance purposes. Round ducts are still generally sealed in-situ using duct tape (Figure 30) in combination with screws or mastic (screws/mastic are sometimes omitted). Next to metal ducts, an important part of the market is site-assembled duct-boards, which are made of rigid insulation (mineral wool or foams) covered with aluminium foil (Figure 27). These are mainly used in warmer climates (South Europe and USA) where air-conditioned buildings need thermally insulated ducts. Mastic and fastening clamps are rarely used in practice even though they are recommended, and the clamps (if installed at all) and taped seals (Figure 28 & Figure 29) can fail or loosen with age [69] . In conclusion, ductwork airtightness in these countries depends a lot on workmanship and materials.

Moreover, cleaning access is generally fairly poor and duct systems are rarely inspected. Furthermore, when being installed or being repaired, installations are rarely cleaned.

Figure 25 Rectangular duct with standard length [foto: Lindab]

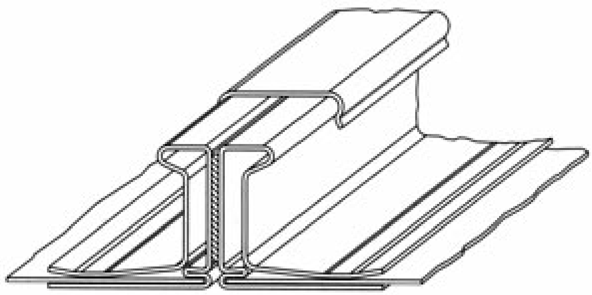


Figure 26 Close up cross-section of a flange for connecting two rectangular ducts. Cleat slides on the top to hold the two flanges together.

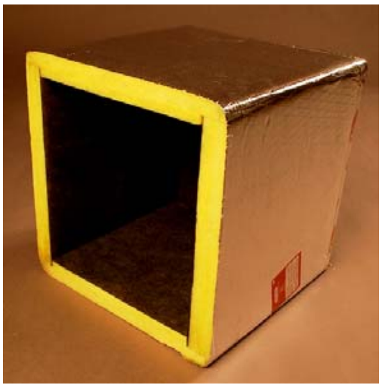


Figure 27 Example of duct-board

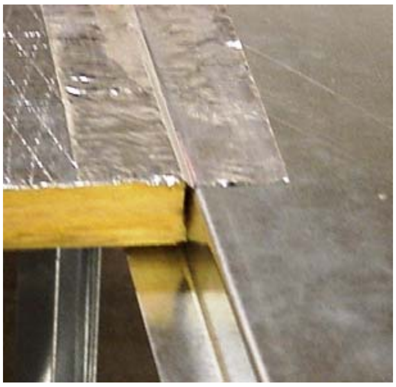


Figure 28 Duct-board tape seal

Figure 29 System with failed tape, and omitted fasteners, in USA [© Weldin Engineering]

Figure 30 Conventional duct tape (i.e., fabric-backed tape with natural rubber adhesive) fails more rapidly than all other duct sealants [69]. It has also been shown that the trade standard for advanced tapes (UL 181) does not guarantee durability [69].

Tests are very seldom performed in standard buildings, as there are no incentives to do so. This has led to poor ductwork installations in much of the building stock. Knowledge about the ductwork airtightness mainly relies on a few studies [61] [63]. Field studies suggest that duct systems in Belgium and in France are typically 3 times leakier than Class A (Figure 31). Studies in USA show a similar or worse pattern. Analysis of specific cases indicates that leakage drastically affects overall system performance. Duct leakage therefore probably has a large energy impact outside of Scandinavia.

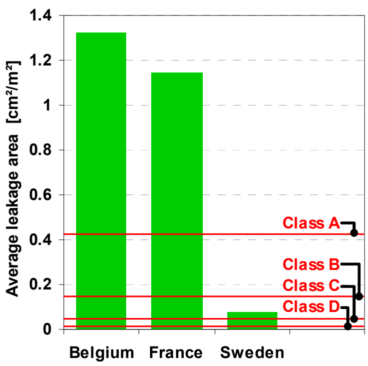


Figure 31 Comparison of average measured duct leakage in Belgium, France & Sweden [61]

In France [37], despite some pilot projects and the fact that ductwork airtightness is now explicitly taken into account in the EP-regulation, little has changed with regard to the interest paid by professionals on this issue. The reasons behind this status quo might be:

- poor reward given to ductwork airtightness for extract-only systems which are very commonly used in France;
- lack of pilot projects and dissemination on this issue over the past 5 years, as opposed to envelope airtightness;
- little use of round steel components pre-fitted with seals which may be encouraged by the lack of attention given to ductwork and ventilation system design (pre-fitted components should not be customized on site, which means that extra care must be given for designing the system).

Half of the ventilation ducts assembled in Germany are not being installed according to the current standards. There is also a lack of permanent information and good training. Some reasons behind this status seem similar to those identified in France (poor reward in EP regulation, little use of round steel components with pre-fitted seals, little care for ductwork and ventilation system design). The coming revised EnEV 2011-12 may help to change things slowly. While ducts for the best airtightness class are available, information for designers, craftsmen and owners is still lacking.

5.5 Other duct materials

Besides metal ducts, other available duct types include:

- **Rigid insulation ducts**: These can be rectangular (made of 'duct-board', Figure 27) or round (Figure 32). Besides having providing thermal insulation, they are light to transport and have good acoustic properties (partly due to higher break-out noise than round metal ducts). Typical sealing methods include tapes or mastics applied around the joints in the system. Field examinations have shown that taped seals tend to fail over extended periods of time [69] [72] . In addition, the clamps required by the trade standard (UL 181[73]) can fail and their durability has been questioned [69] . Good airtightness can potentially be achieved with durable mastics applied with by good workmanship. The ducts in Figure 32 achieved airtightness Class C in the laboratory when new, but data for aged systems is not available. Apart from the fact that they are site-fitted, and have seals with questionable durability, round insulated foam ducts share many of the benefits of round metal ductwork, such as space- and material efficiency.
- **Flexible ducts** (Figure 33): These are generally composite ducts made of plastic, metal, and possibly insulation fibre. They come in wide range of qualities, from flimsy ducts with thin plastic foil walls to semi-rigid ducts with walls of aluminium sheet with a concertina form. These ducts a convenient means of connecting components such as ducts to air terminals, and also act as duct silencers. However, they are known to be difficult to clean and the less rigid varieties can easily become compressed. Their use should therefore generally be kept to a bare minimum. Just as for duct-board flexible ducts pose a challenge with respect to achieving airtight connections (see [69]).

Figure 32 Round foam duct

Figure 33 Flexible duct

- **Plastic ducts** (e.g. Figure 34): Round plastic ducts exhibit the same benefits as round metal ducts. Because of their flammability, they should not be used in systems spanning multiple fire cells. They are therefore mainly limited to residential ventilation, except connections to kitchen hoods. One particular Finnish product is made of low-emitting antistatic polypropylene, with many components (bends, tees etc., Figure 35) available with the same self-sealing joint that achieves Class C airtightness [74] . Other types of plastic ducts are used for underground ductwork, with watertight joints, because of their corrosion resistance.

Figure 34 Round plastic duct [74]

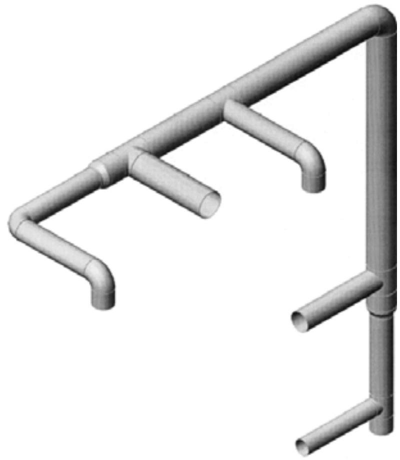


Figure 35 Round plastic duct system with Class C [74]

5.6 How Did We Get To Where We Are? The evolution of duct airtightness in the last 50 years

Here we present the chain of events that led to the solution of the ductwork airtightness problem in Scandinavia [60] [61] .

1950s

- Ducts were mainly rectangular, prepared on site, and little attention was given to airtightness, balancing, cleanliness, or energy performance
- The problem of leakage was first identified in the 1950s.
- Launch of the world's first SpiroTubeformer (Figure 36), the machine for the manufacture of spiral tubes that revolutionised the ventilation industry

Figure 36 Example of a machine for manufacturing spiral ducts [Spiro Tubeformer]

1960s

- Awareness of the problem of leakage grows
- Machines were developed to manufacture cylindrical, spiral-seam ducts in standard sizes. This was seminal to further developments, as round ducts had hardly been used before
- AMA version 1966: Two airtightness ‘norms’ A and B, to be spot-checked by the contractor; minimum tested surface area is 10 m²

1970s

- There is growing use of round ductwork, but the majority is still rectangular
- AMA version 1972: Requirements renamed airtightness 'classes' A and B. Class A was required for the complete system, i.e. ducts, dampers, filters, humidifiers and heat exchangers. Class B was recommended if the air was treated (cooling, humidification, high class filters etc.) or the system operated for more than 8 hours/day
- First EUROVENT 2/2 [44] trade norm on airtightness classification (Classes A & B), and is introduced in VVS AMA
- Growing attention for cleaning and inspection of ductwork
- Development of rectangular ducts that were fitted with different types of rubber seals at the joints, replacing putty and tape that had been used before.
- Further breakthroughs in the mass production of round ducts and components in standard sizes
- First use of rubber gaskets on round ducts

1980s

- AMA version 1983: Airtightness Class C was introduced. Also requirements for commissioning and maintenance were added. The airtightness requirements were: Class A for visible ducts within the ventilated room; Class B for all rectangular ductwork, and round duct systems with area < 50 m²; Class C for round duct systems with a surface are > 50 m². This met resistance from contractors, who considered that it was too demanding. However, the opposition died down after a year, when it was found that the requirements were easier to fulfil than first assumed.
- Class C was adopted in a revision of the trade norm EUROVENT 2/2 [44] .
- Norwegian voluntary inspection scheme 'Norsk ventilasjonskontroll' started. Was initially very successful, but died out after a few years.
- Increasing use of seam-welded duct components. More prefabrication of rectangular ducts with better seals.
- National Building Code of Finland, Part D2, version 1987, adopted the AMA Classes and extended the classification to the whole system, including air handling units (AHU). Also requirements for hygiene, commissioning and maintenance of ventilation systems
- Increasing use of round ducts, especially in Scandinavia:
- Scandinavia: 90% round ducts, 100% of which with rubber gaskets
- Middle Europe: 30% round ducts, 20% of which with rubber gaskets
- Southern Europe: < 30% round ducts, none with gaskets

1990s

- Concern about growing prevalence of SBS, allergy and asthma, due to inadequate dilution of indoor emissions by inferior ventilation systems
- As a result of the above concern, in 1992 the obligatory ventilation inspection scheme (OVK) was established. See page 2.
- Increasing use of round ductwork in Middle Europe: 50 % round with 60 % rubber gaskets
- Clean ducts and fittings at delivery, supplied with covers at the ends.
- Draft CEN standards on airtightness, based largely on Nordic experiences, are adopted in practice in several EU states. Prestandard ENV 12097 on cleanliness published.

- AMA version 1998: In this version of AMA, Airtightness Class D was added as an optional requirement for larger round duct systems. See page 2

2000s

- Publishing and first revisions of the CEN standards [48] [50] [52] [53] [54] [55] [56]
- More attention to airtightness, cleaning solutions, noise, pressure drops, and environmental impacts
- Large studies on duct performance; SAVE-DUCT [61] [63] , AIRWAYS [62]
- Finnish regulations revised 2003: Classes D and E were introduced. The recommendation tightened to min. Class C for ducts and L3 for AHUs.

5.7 Recommendations : The 3 ingredients for success

The Scandinavian experience has shown that there are 3 basic steps in a market transformation to more airtight duct systems: (i) awareness, (ii) requirements, and (iii) industrial development. Obviously, if quality is not demanded, there are no penalties or incentives, and no checks made, quality will not be provided [60] .

Figure 37. Three forces for a market transformation of ductwork airtightness, according to Rennings approach (2005)

1 Market Pull: Increased awareness of the benefits quality round ductwork

The first step along the path of a market transformation is to increase awareness of the consequences [61] of air leakage, and that commercially-available airtight round duct systems have many additional benefits over both rectangular duct systems and round ducts without gaskets.

An important decision that must be taken early in the design of an HVAC system, is whether to use round, rectangular, or flat-oval ductwork, or maybe even ductless solutions. Often, a combination of these is used. In Scandinavia, HVAC designers take it for granted that round ducts are used throughout the whole system, using rectangular ductwork only where it is unavoidable, such as connection plenums at the air handling unit. This maxim is echoed in ASHRAE Fundamentals, which simply says '*Use round ducts wherever feasible*'.

Below are some moments that illuminate the benefits of round ducts:

Space efficiency

It is commonly believed that rectangular ducts have the advantage that they make maximal use of limited rectilinear spaces. However, this belief needs moderation. Here are three examples:

- A common practice is to use rectangular ducts near the fans, where the airflow is large, and large ducts are needed in a cramped space. Further away, the smaller branch ducts can be round. However, one problem with this is that ductwork near fans experiences a higher operating pressure than smaller ductwork near air terminals, so its airtightness is more critical. Rectangular ducts are known to be leakier.
- To the inexperienced designer, rectangular ducts seem a logical choice in rectangular service spaces (risers, shafts). However, in practice, one must provide access space to slide cleats onto all the flanges (Figure 38). This access space must be as wide as the widest rectangular duct. Round ducts often need less installation space than rectangular ducts with the same pressure drop (Figure 39 & Figure 40) [62] .

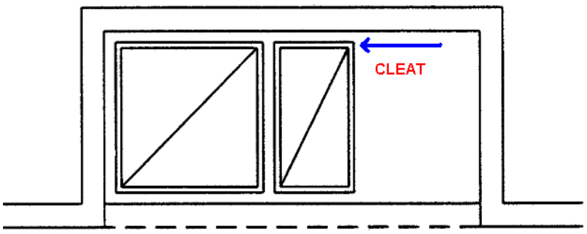


Figure 38 ◄ The need for access space to install cleats makes it difficult to use the whole shaft area with rectangular ducts [61]

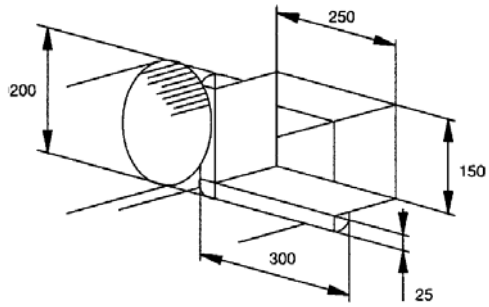


Figure 39 ▲ Rectangular duct (with flanges) and circular duct with same height requirement and same free duct area [61]

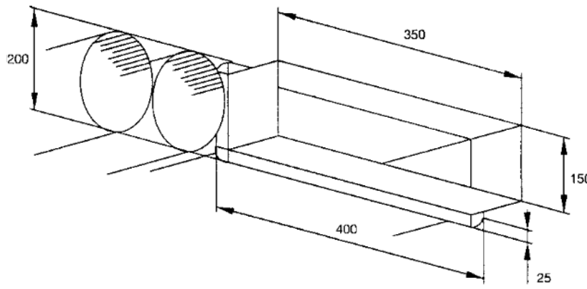


Figure 40 ▲ A flat rectangular duct can often be replaced by several parallel round ducts. The example here shows equal height and free duct area [61]

- One advantage of rectangular ductwork is that it can have virtually any aspect ratio. For example, flat-&-wide ducts can be used in ceiling voids above rooms with crossing beams or in corridors with little head-room. However, the flanges around rectangular ducts protrude 20-40 mm, so round ducts do not necessarily occupy more space. The alternative is to use multiple parallel round ducts. Incidentally, this can simplify balancing and enable zoning (See Chapter 8 in [62]). If considered early in the design phase, it is possible to influence the architectural planning to ensure sufficient space for round ductwork.

Leakage

- Figure 41 compares average leakage from on-site measurements of round and rectangular duct systems in Sweden and Belgium. The Swedish data shows little difference between round and rectangular systems, simply because the round and rectangular systems in this particular data set had approximately the same airtightness requirement (Class B). In Belgium, which has neither strict tightness requirements nor any testing, rectangular ducts are very leaky, while round duct systems perform only slightly worse than in Sweden (Class A). This shows us that huge reductions in duct leakage can be achieved simply by adopting round ducts as an industry standard, even if testing is not practiced as part of commissioning.

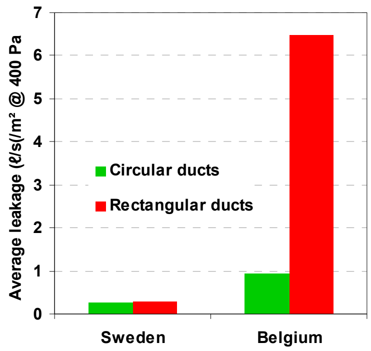


Figure 41 Rectangular versus circular ductwork in Sweden and Belgium [61]

- Round ducts are tighter. Larger duct systems (≥ 50 m² duct surface area) are, according to VVS AMA 83 (1984), required to be three times tighter than a rectangular duct system;
- Connecting two round spiral wound ducts only requires one fitting, whereas rectangular ducts are connected by use of a completely separate flanging system (Figure 42 & Figure 43). Round ducts can have any length between the connections, a duct length of 3 m is standard but 6 m is also frequently used. The length of a rectangular duct is limited by the size of the steel sheet, which is usually less than 2 m, which requires more connections.

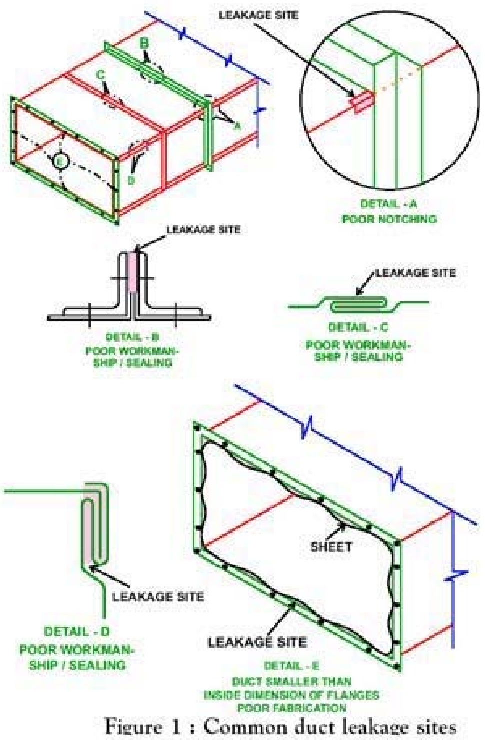


Figure 42 Illustration of typical leakage points for rectangular ductwork [source: AC&R J.]

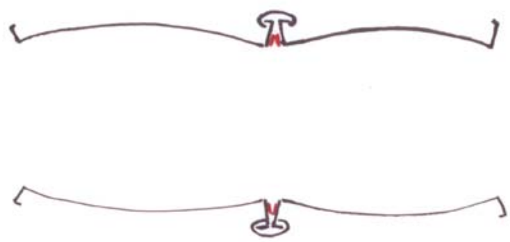


Figure 43 Cross section of a rectangular duct under pressure – causing the flange gasket seal to open [source: L.A.Matsson]

Indoor environment, health & safely

- Reduced leakage means that the air needed to maintain the indoor environment flows exactly where it is intended to go. Hence the whole system can be dimensioned and balanced exactly as it should, providing good indoor environment.
- Round ducts are easy to clean, as there are no sharp corners.
- The noise generated in straight ducts is normally insignificant compared to the noise generated in e.g. elbows. Standardized round duct components have well known acoustic properties, whilst the properties of ‘tailor-made’ parts in rectangular ducts is often unknown.
- It is easier to measure the airflow in round ducts, which can make for simpler and more accurate balancing.
- The round duct wall is stiffer than the rectangular one and thus will allow less sound transmission through the duct wall. Whether this is an advantage or not depends on the application.
- Fire insulation of a duct to a specified fire safety class might be achieved with thinner insulation on round ductwork. Rectangular ductwork may need thicker insulation as it is compressed at corners.

Energy efficiency & environmental impact

- The pressure drop in round duct systems is often lower than in a rectangular duct at the same air velocity due to industrially manufactured and aerodynamically designed duct components such as elbows and branches. This leads to lower fan power.
- The total airflow rate can be lower due to less leakage, which further reduces fan power. Class C round ductwork has typically 30% less fan power than traditional Class A ductwork. Similarly, airtight systems facilitate exploitation of the full benefit of other energy efficiency measures, including demand-control, and heat recovery, and energy for heating & cooling is reduced by approx. 15%.
- Less material (steel & insulation) is used. On a large scale, this has environmental benefits.

Costs

- The installation time for a round duct system is normally shorter, approximately half that for a similar rectangular system [65] . Delivery times can also be shorter due to the standardized sizes & components.
- Using round ductwork with standard sizes (the diameters of the ducts increase by 25 % upwards: 80, 100, 125, 250, mm, etc.) decreases the waste during installation. Short pieces of round duct, or surplus components, need not be scrapped, but can be used elsewhere. The investment cost for suspensions and insulation are also reduced. Thus total material costs can be 12~25% less than rectangular systems [65] .
- The overall cost (sum of material and assembly costs) is normally lower, approximately by 25% [65] , at least in countries where round ducts have been in use for a longer period of time.
- Any additional investment cost (if any) for round ductwork is probably not significant since labour cost is considerably reduced. Furthermore, any higher investment cost for a higher quality duct system should be considered based on Life Cycle Costs (LCC) due to the energy savings.

2 Technology push : Support the development of airtight products

A profound technological development occurred in Scandinavia from the 1950s up to today where 90-95% of installed ductwork is now spiral-seam steel circular ducts with factory-fitted sealing gaskets (Class C or better). This technical development was initially driven by 'market pull', later by 'regulatory push'. But other factors have played a role...

'Technology push' means that the many benefits of round duct systems over traditional rectangular duct systems, has been a strong incentive for HVAC manufacturers to develop and market steadily improved products. Manufacturers of duct systems elsewhere in Europe dominated by rectangular ductwork, may need support for retooling to catch up.

The situation in Norway is a good example of the effect of 'technology push'. Even while the minimum requirement is normally Class B, and leakage testing is no longer standard practice, 90% of installed ductwork has Class C or better. What are the reasons behind? Firstly, this is what ductwork suppliers deliver throughout Scandinavia. Secondly, such ductwork is known to have many other benefits over rectangular ductwork, including space efficiency and cost !

3 Regulatory push

Possibly the most important measure to force a market transformation, is to establish trade guidelines & requirements for duct system airtightness, and verify them in a cost-efficient way in each project, ideally with predefined incentives or penalties.

Trade guidelines

Each country should establish trade norm or requirements on duct systems in verifiable terms. Swedish and Finnish regulations require generally minimum class C ductwork. Technical guidelines and/or standards exist in every Scandinavian country. There is the VVS AMA in Sweden ; the national standard NS 3420 in Norway ; the Danish code DS 447. This should be referred to/specified in tender and contract documents.

Energy performance requirements

Penalties on the energy label are another way to encourage building professionals to pay attention to duct leakage. Duct leakage can be included as a parameter in the national Energy Performance Calculation method. For example, in France, the default leakage rate corresponding to 15% of the nominal air flow rate (about 3 times worse than airtightness Class A in the EN standards. If no documentable information is available on the ductwork airtightness then one has to assume the default value. Belgium has a similar approach.

Include them in building contracts

These are made valid when they are referred to in the contract between the owner and the contractor - which is practically always the case in Sweden, for example. This ensures that proper attention is paid to commissioning of ventilation and air conditioning systems.

...and verify them in each project, with predefined penalties

All ventilation and air conditioning systems should be carefully commissioned. Building contracts should include the cost of leakage testing, and describe what method is to be used, and what happens if the requirements are not met. This is a strong incentive for the HVAC contractor to install an airtight system, and avoid extra costs of remedial work due to failing the leakage test. VVS AMA is a very good model to use.

6 CONCLUSIONS

Through Work Package 5 of the ASIEPI project, we have identified that while key elements for a market transformation on envelope airtightness are under development in many member states, the duct market is still in a state of status quo.

The market is changing towards better envelope airtightness in many member states. This is due to a combination of measures that push the market, in particular, the EP regulation, which in some cases, significantly rewards good airtightness, as well as pilot and research projects; and measures that pull the market, for instance, awareness raising seminars and campaigns, etc. The lack of practical tools (e.g., catalogues of construction details) to build airtight envelopes is probably a significant barrier to a faster transformation. Three major practical recommendations to drive a market transformation of envelope airtightness can be drawn from our analysis of success stories:

1. **Create a regulatory push**: Fair reward in EP regulation and measurement as a precondition for claiming rewards, labels or subsidies.
2. **Create a technology push**: Cooperation with building professionals and industry through pilot projects, and development of practical tools to help professionals built airtight.
3. **Create a market pull**: Global dissemination strategy around communication, events and trainings.

The situation is quite different for ductwork airtightness. It may be explained, in many countries, by a combination of a lack of attention paid to the design and commissioning of ductwork and the limited use of pre-fitted seals even though they are proven to be very effective. Awareness raising among prescribers, designers, and craftsmen, as well as the availability of adequate tools to help ductwork designers seem essential to widen the use of pre-fitted seals which is obviously one very effective response to this problem. A market transformation will require three major steps:

1. **Create a market pull**: Increased awareness of the benefits of quality round ductwork with pre-fitted seals.
2. **Create a technology push**: Support industrial development of efficient products
3. **Create a regulatory push**: Performance requirements in regulation, Guidelines & Standards, and penalties for non compliance (Establish trade guidelines, Energy performance requirements, Push to include requirements in building contracts)

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