CRITICAL STEPS FOR WIDE SCALE IMPLEMENTATION OF BUILDING AND DUCTWORK AIRTIGHTNESS

Editors **François Rémi Carrié - Peter Wouters**

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It includes a number of publications from the Intelligent Energy Europe programme and its predecessor, namely from the ASIEPI project, SAVE-AIRWAYS, and SAVE-DUCT projects.

Some of the information collected in this ebook can be found at the following websites:

www.asiepi.eu www.aivc.org www.buildup.eu

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www.bpie.eu www.europeanclimate.org www.eurima.org www.inive.org

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FOREWORD

The route towards the generalisation of nearly zero-energy buildings which is required by the recast of the Energy Performance of Buildings Directive (Directive 2010/31/EU) includes major challenges. One of them is the market transformation that has to occur to improve envelope and ductwork airtightness, as both the potential energy savings are large and the barriers are great to overcome. Awareness raising among professionals is certainly one key to get over these barriers; sharing knowledge and experience through learning from pioneer work and success stories is another one.

The TightVent Europe platform has been launched January 1st, 2011 with the specific aim to address these issues. The release of this electronic book is one of the channels towards this end. It has been designed with the following objectives:

- First, to provide the reader with key information on building and ductwork airtightness that appear as major challenges in the route towards nearly zero-energy buildings;
- Second, to increase the visibility of the results of several European projects, namely the IEE-ASIEPI, SAVE-AIRWAYS, and SAVE-DUCT projects that have produced considerable amounts of information on envelope and ductwork airtightness.

On behalf of the TightVent partners, I wish you a pleasant and informative reading.

Peter Wouters, Manager INIVE EEIG

The TightVent Europe platform receives the financial and technical support of the following organisations:

- BPIE - Buildings Performance Institute Europe (www.bpie.eu)
- ECF- European Climate Foundation (www.europeanclimate.org)
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In this paper, we have identified 5 major steps for a successful wide-scale implementation of envelope and ductwork airtightness which is, or will be a growing concern in many EU Member States given the objective to generalise nearly zero-energy buildings by 2020:

- *Step 1 consists of defining relevant requirements – in particular with an appropriate knowledge of the leakage status – and implications of better airtightness in terms of energy, Indoor Air Quality (IAQ) and cost.*
- *Step 2 deals with the encouragement of professionals, including awareness raising strategies and training schemes for designers and workers.*
- *Step 3 addresses the control schemes, which must be realistic to be effective, and suggests several points of attention and ways to explore namely the robustness of testing schemes, as well as the development of intermediate testing and quality management approaches.*
- *Step 4 explains the importance of monitoring schemes, Research and Technology Developments (RTD) and the stimulation of front-runners to make a feed-back loop for policy revisions.*
- *Finally, in all steps, particular attention should be paid to fostering local, national and international networking (step 5, transverse to the other steps), which is essential to learn from each other and therefore to shorten the learning curve.*

Concrete examples, including lessons learnt from past or pioneering experience, illustrate the contents of those steps. This paper can be used as a basis for a roadmap for policy makers for national or regional initiatives on building and ductwork airtightness.

INTRODUCTION

Research bodies, industries, practitioners and policy makers have investigated building and ductwork airtightness with a very fluctuating degree of interest in time and space over the last 50 years. Interesting illustrations of this variability include: the regulatory envelope airtightness requirements gradually brought into force in the United Kingdom since 2002 [3]; the recent revived interest for building airtightness issues in Sweden, a pioneering country on this subject in the nineteen seventies [4]; the excellent ductwork airtightness achieved in Nordic countries in contrast with field observations in other countries [16][17]. Since the energy impact of envelope and ductwork leakage is becoming more and more significant compared to the other energy uses of low-energy buildings, airtightness issues have gained attention since several years. As an example to illustrate this, for a house in a moderately cold region (2,500 degree-days in K days), the energy impact is in the order of 10 kWh per m^2 of floor area per year for the heating needs and 0 to 5 kWh per m^2 of floor area per year for the ducts plus the additional fan energy use. Therefore, with the implementation of the Energy Performance of Buildings Directive (EPBD) and more recently with its recast [5], discussions take place on these subjects in many countries. In fact, the EPBD recast sets ambitious targets for the year 2020, including the obligation for EU countries to implement regulations to increase the number of nearly zero-energy buildings (NZEB) in the next few years, and to generalise nearly zero-energy targets in new buildings and major renovations. To reach this objective, envelope and ductwork airtightness are key players, although policy makers often do not perceive well the related energy savings potential, neither the possible ways to explore in order to improve the situation [14].

Therefore, the objective of this paper is to clarify these issues for policy makers and to underline the key challenges to overcome in order to adopt a wide-scale policy on building and ductwork airtightness implementation at country or regional level. Figure 1 shows the critical steps discussed in this paper.

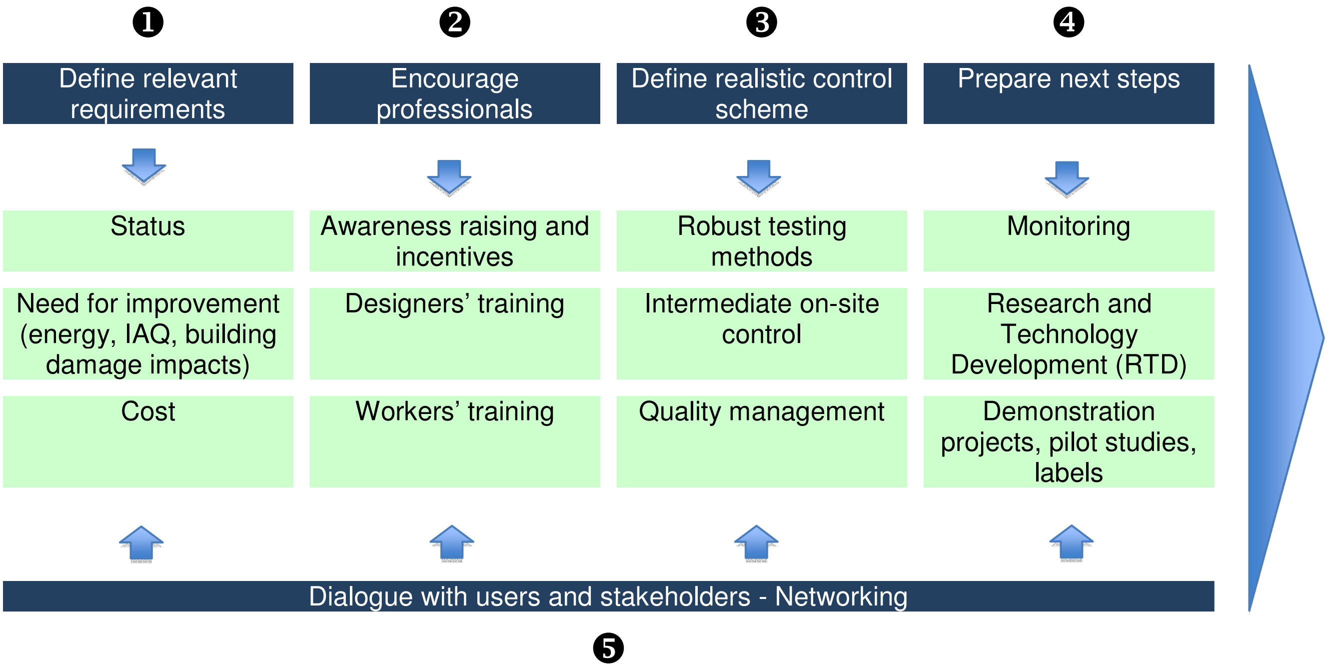

Figure 1: Critical steps for a wide-scale implementation on building and ductwork airtightness

1 DEFINE RELEVANT AIRTIGHTNESS REQUIREMENTS

Relevant requirements should be set based on energy, IAQ, building damage and cost implications of better envelope and ductwork airtightness. This implies some knowledge of the status of airtightness in new and existing buildings. Energy impacts can be estimated with calculation tools.

■ Status of building and ductwork airtightness

The wide-scale implementation of a policy implicitly assumes that the issue has been identified as a bottleneck. In our case, this preliminary step requires to know that envelope and/or ductwork leakage have a significant impact, e.g. on energy use, indoor air quality, or building damage. This means that the policy makers have some knowledge of the status of building and ductwork airtightness. However, in most countries, this status is poorly known and based on a limited number of measurements, especially when sub-divided into climate zones and building or system types. This requires a specific effort, which is underway in some countries.

To achieve progress, some countries have in parallel heavily encouraged, either directly or indirectly, good building and/or ductwork airtightness based on expert statements and at the same time taken steps to collect the measurement data induced by this encouragement. Note that in the longer term, this effort is also needed to monitor the progress made for future revisions of the policies (see below).

■ Proper estimates of energy impacts with appropriate EP calculation methods

Having appropriate tools to estimate energy impacts is key as it will form a major driver for the market. If the energy performance calculation method includes energy losses due to envelope and ductwork airtightness, designers can compare airtightness improvements with various options, e.g. increased insulation levels or solar collectors for domestic hot water. However, the comparison has to be fair; otherwise it distorts competition between the various options.

With an appropriate calculation tool[1], it is relatively easy to perform sensitivity analyses to find out the impact of envelope and ductwork leakage in various conditions. This should highlight if specific actions must be undertaken e.g., for a given building usage. In fact, one could think that the energy reward for good airtightness may be sufficient by itself to drive the market. However, for instance in the UK and more recently in France, or for labels such as PassivHaus or Effinergie®, it was preferred to set a minimum requirement to give a clear signal to the practitioners. Figure 2 shows fictitious examples of results of sensitivity analyses that are useful to take such decisions.

Note that heating and cooling energy impacts should be considered. This is

[1] *Several studies have shown how energy losses due to envelope and ductwork leakage can be estimated. EN 15241 and 15242([11][12]) give several approaches that can be implemented in an energy performance calculation tool[16]. EN 15242 allows one to calculate the airflow rates including infiltration while EN 15241 gives the characteristics of the air passing through an air treatment plant as well as the power involved for its treatment. Today, several energy performance calculation methods include EN 15241/15242 with varying degrees of complexity.*

obvious for ductwork airtightness if the duct system is used for cooling. For envelope leakage, the variability in additional cooling energy needs is large. In some cases (e.g., high internal loads in moderate climate), reaching extreme envelope airtightness levels can even be counter-productive energy-wise as it may increase cooling energy needs more than it reduces heating energy needs. In many other cases, improving airtightness reduces significantly the total energy use of air-conditioned buildings. Note that both for envelope and ductwork, in cooling conditions especially in hot and humid climates, the impact of air leakage on humidity conditions must be considered because it can affect significantly the latent load. In sum, this is a complex issue for which national or regional studies are most relevant to draw conclusions.

■ Analysing indoor air quality and building damage impacts

The impact of ductwork leakage on IAQ and building damage is fairly straightforward if the ventilation airflow rate is reduced either globally or in some building parts, or if pollutants enter the duct system through leaks. If the fan compensates for the leaks to provide sufficient air renewal, aside from energy use implications, we do not expect adverse effects on IAQ or building damage.

It is more subtle for envelope airtightness because:

- on the one hand, good airtightness helps ventilation systems (whether natural or mechanical) function better; namely, it allows for better control of the airflow rates in the different building zones. In many cases, it reduces condensation risks in the building structure as small amount of air flows out through building leaks;
- on the other hand, inadequate airtightness improvements or inappropriate tightening products may induce condensation damage. One trivial example lies in the positioning of the vapour barrier (often used as an air barrier as well) which, if inappropriate, can cause condensation. Another example consists in tightening the envelope without taking provisions for adequate ventilation, the worst case being a combustion appliance without outdoor air intake.

Solving the latter adverse side effects of inadequate tightening does not appear to be a major challenge in new European buildings. National regulations and standards usually cover these issues. For the existing building stock however, the task is considerably more complicated. Of course, there are a number of existing buildings for which the approach can be similar to new buildings. However, for instance, if water enters through a wall by capillarity, e.g., because of a construction defect or because it is a rubble construction without foundation, this problem obviously needs to be fixed before air tightening is performed.

In sum, while adverse side effects can be dealt with, they have to be carefully analysed to prevent improper initiatives, especially for the envelope airtightness improvement of existing buildings. If mandatory envelope airtightness improvements are envisioned for the existing stock, they must be included in a framework that addresses IAQ and building damage issues—e.g., to take provisions for adequate ventilation together with envelope tightening.

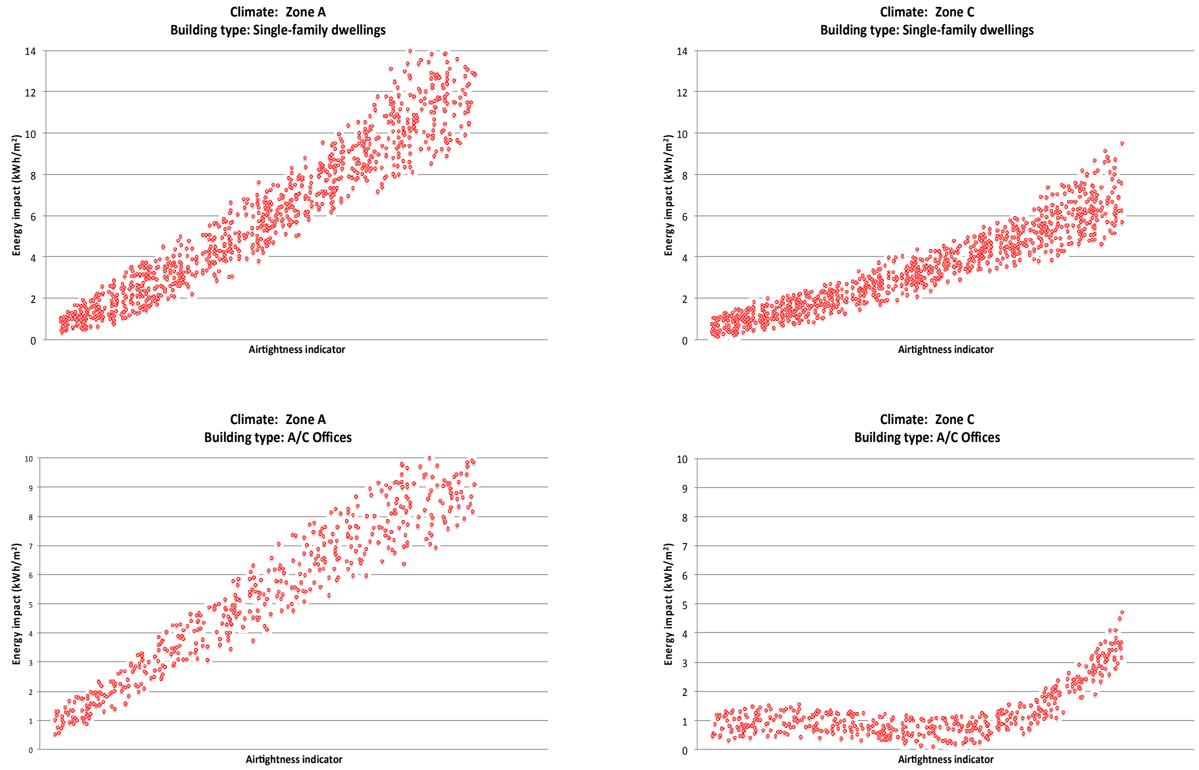

Figure 2: Fictitious examples of sensitivity analyses of the energy impact of building airtightness. Such analyses can help fine-tune the desired airtightness levels depending on e.g., building usage or climate.

■ Cost implications of better airtightness

The level to which airtightness has to be raised will be the result of a trade-off between the need (based on energy and IAQ implications) and the cost involved.

Proper cost analyses should take into account at least initial and operating costs. These costs vary from one country to another and especially from one time to another. Such analyses are available for ductwork systems in the SAVE-DUCT project report [1][13]. For envelope airtightness, Table 1 gives an example of the outcome of such an analysis conducted in France based on expert statements.

Cost estimates (in Euros exc. VAT)	
Cost for airtightness material and workmanship	500 to 1,000 €
Cost for airtightness testing	500 € (50 to 100 € with a quality management procedure)
Estimated energy savings	30 to 150 € per year
Savings on customer service with a QM procedure	1,500 €

Table 1: Cost estimates for reaching 0.6 $m^3/h/m^2$ (about n50 = 2.5 ach) in new individual dwellings in France. The savings on the customer service are based on feed-back from builders who have implemented such approaches [2].

2 ENCOURAGE PROFESSIONALS

Improving airtightness calls into question the traditions in design and workmanship. Appropriate awareness raising campaigns, incentives and training should be thought out to encourage professionals to integrate these challenges into their common practice.

■ Awareness raising and incentives

Although envelope and ductwork airtightness are in many cases very cost-effective measures to improve energy performance, practitioners are rarely aware of this potential. This is the reason why local or national bodies have set up information campaigns in several countries. The Holdtett campaign (http://www.holdtett.no) in Norway is one interesting illustration of such initiatives whose number remains unfortunately much too limited compared to the need.

Regarding incentives, at present, many countries have a range of financial stimuli to accelerate the implementation of energy efficient investments in buildings, e.g., subsidies, fiscal deduction, attractive loans, etc. Typically, a number of conditions have to be met in order to receive the benefits.

Quite often, the requirements are expressed in a descriptive way—e.g., installation of high efficiency glazing, of a condensing boiler, of a ventilation system with heat recovery, of good envelope airtightness. Although this approach is quite simple, attention is required to the fact that it fragments the design into partial objectives that are not necessarily integrated in a global strategy.

An alternative approach is to relate the benefit to the achieved energy performance as the quantitative basis. In such schemes, envelope and ductwork airtightness can compete fairly with other measures only if they are fairly rewarded in the calculation method (see paragraph about energy estimates above).

■ Designers and on-site workers training

It remains a common understanding that on-site workers are nearly the unique key to good airtightness. However, envelope and ductwork airtightness must be viewed as systems which are specified in the programme, designed, detailed in calls for tender, checked and corrected if necessary.

While designers should play a major role, it takes time and effort before they efficiently contribute to better airtightness. In fact, achieving better airtightness often questions their traditional design options and they do not necessarily have the resources to search for the sparse literature on envelope and ductwork airtightness design. This is where training programmes are useful, because they allow the designers to better understand the shortcomings of their standard methods and to take shortcuts to derive alternative solutions. Experience of successful designers training initiatives shows that practice-oriented approaches work well, e.g., with examples of construction details for various interfaces[2] in addition to the

[2] *See for instance one outcome of the PREBAT MININFIL project providing over 200 construction details for the French market. It took 3 years to develop the documents that can be downloaded from www.rt-batiment.fr or www.cete-lyon.developpement-durable.gouv.fr. Note that these construction details would need to be adapted to local regulations and customs if applied in a different country.*

general discourse on the overall approach to airtightness design.

Once the designers have properly detailed the provisions for airtightness, it becomes much easier for the project manager to explain what he expects from the workers. Detailed drawings are essential at this stage. Also, experience shows that hands-on training programmes for workers are extremely useful. Such programmes can be organised in a specific training centre (independent or part of an industry) or on a specific building site. The major challenge here is represented by the logistics involved in demonstrating good practice on real building or ductwork components.

In sum, it is clear that training designers and on-site workers is one essential ingredient to the success of the improvement of building and ductwork airtightness, because it implies new design and installation practice. Qualification processes attached to these trainings would bring added-value to the professionals, and therefore could attract more potential candidates. However, such trainings—including qualification or not—entail a tremendous effort because of the large number of potential trainees and the logistics implied. Therefore, they should be planned to achieve an impact with optimal use of financial and human resources. National or regional levels appear to be the relevant scale for such plans e.g., integrated within the national roadmaps that are to be defined in the context of the BUILD UP Skills initiative.

3 DEFINE REALISTIC CONTROL SCHEMES

Experience shows that control schemes represent one crucial aspect to foster improved building and ductwork airtightness among professionals. Voluntary controls or quality management approaches are very instructional. These issues should be addressed in a consistent framework that includes e.g., certification procedures for testers, encouragement for on-site testing, quality management approaches.

■ Robust testing methods and certification schemes for testers

Because of the weight of tradition in building design and construction, it is unlikely that a real market transformation will occur on such subjects without control procedures. This is also the reason why the EPBD recast in article 18 gives requirements for independent control. But this implies that the testing methods are homogeneous between inspectors.

Although various standards exist to perform envelope or ductwork pressurisation tests (European Standards 13829, 12237, 1507, 13403, 14239 [6][7][8][9][10]), experience shows that there remains room for interpretation which is difficult to narrow down at the international level, e.g., because of assumptions in the calculation method in which the test results are used. In particular, the following questions need to be addressed:

- How is the building prepared for an airtightness test to remain consistent with the inputs of the calculation method?
- How is the leakage-flow normalised and how does this affect the EP calculation input?
- How can airtightness tests results from parts of a building or duct systems, e.g.,

in a multi-family or a large building, be used to extract EP calculation inputs?
- How to measure ductwork falling under various standards (e.g., circular and rectangular ductwork)?
- Should there be a tolerance in meeting minimum requirements in order to account for measurement uncertainty?

Also, testers need to be trained. Finding out which openings should be sealed or closed during a pressurisation test, or how to interpret measurement data is not a trivial task. Performing such measurements requires some background on the EP regulations and HVAC systems, as well as experience with data analyses and field constraints. To our knowledge, such schemes are operational only for envelope measurements and only in the UK (www.bindt.org), in Germany (www.flib.eu/certifications.html) and in France (www.qualibat.fr, [2]). The certification procedure may imply an examination of several test reports produced by the candidate and examination in real testing conditions. It may be reduced to certain building or ventilation system types that require less experience and knowledge. All in all there is a trade-off between training cost, need for testers[3] and certification credibility and impact, that has to be considered in national or regional contexts.

[3] *The number of testers needed can be roughly evaluated on the basis of the number of tests performed per year on average. A high estimate of that number is 100.*

■ Intermediate voluntary site controls

Envelope and ductwork leakage are in general the only inputs for an EP calculation method that require testing at commissioning, if default values are not chosen for these items. However, it is very risky to wait until the end of the construction to find out if airtightness has been correctly dealt with. In fact, once finished, it is usually much more difficult to correct defects than during the construction phase: for instance, it is nearly impossible to seal ducts located in shafts once these are closed e.g., with a gypsum board, but relatively easy before. For this, it is advised to perform envelope and ductwork pressurisation tests during the construction to seal what can be sealed at this stage. This practice is fairly common for envelope airtightness for building professionals aiming at low-energy targets. Also, experience shows that such tests are very instructional for designers and workers as they better realise the weak points, as well as ways for improvement of their contribution. Such tests can be encouraged for instance through pilot projects supported at national or regional level.

■ Quality management approaches

To deepen this concept, the encouragement of quality management approaches appears one interesting path to be explored by policy makers. As of today, to our knowledge, this has been tried in the UK, Finland and France (in France, since 2006, and both for envelope and ductwork starting in 2011). In general, it introduces the possibility to claim for a better value than the default airtightness value in the EP-calculation, without systematically performing a test, provided that an approved quality management approach be applied [2][3].

The basic requirements for the quality management approach to be approved may be:
- to identify "who-does-what" and when;
- to trace each step of the approach;
- to prove that the approach is effective based on measurements on a sample;

- to propose a scheme to ensure that the approach will remain effective with time, based on measurements on a sample.

Of course, such a scheme needs to be carefully evaluated to make sure that it is sound and effective, but it presents two key advantages:
- first, it gives the signal to building professionals that envelope and ductwork airtightness must be viewed as an issue of concern for many actors, and certainly not only the carpenter, the plumber, or the electrician for instance. Airtightness has to be designed and properly dealt with generally by a number of professionals;
- second, it is a pragmatic approach to the cost induced by pressurisation tests and availability of qualified testers.

4 PREPARE NEXT STEPS

Action plans for better envelope and ductwork airtightness should be evaluated to prove whether they are effective or need to be revised. Monitoring is an important aspect for this. Policy revisions should also build on demonstration projects, pilot studies, labels and RTD developments.

■ Monitoring the progress in building and ductwork airtightness

Implementing a policy on building and ductwork airtightness implies that an evaluation scheme is set up; otherwise little can be learnt from this experience, for instance, for future revisions. This evaluation can be a one-shot effort, with the evaluation of a sample in a specific study. An alternative is to have a continuous monitoring scheme with a continuous data collection process. Both can be done with the help of a network of testers who provide their measurement data to the body in charge of the analyses. Note that one virtue of certification schemes for testers is that it can ease the collection of measurement results: as part of the certification, testers may be required to send their data to the certification body with the usual privacy precautions.

This work may look trivial, but it requires considerable human and financial resources to structure the database, to check the consistency of the data and to analyse the results. To our knowledge, this effort is underway in three countries only (France, Germany, USA) although it should be considered together with the implementation of an ambitious policy.

■ Demonstration projects, pilot studies, labels

Demonstration projects and pilot studies represent an interesting mechanism to entrain small groups of professionals to change their practice, hoping that their success stories will inspire their competitors. Several interesting initiatives include:
- organising project-specific training sessions;
- organising on-site information sessions for workers;
- financing intermediate and/or final airtightness tests;
- financing third-party evaluation of strength and weaknesses and ways to explore for improvement.

Specific requirements can also be introduced for evaluation of demonstration projects, for instance though labels (e.g., Passivhaus, Minergie®, Effinergie®) or based on expert statements. This has been successfully tried in various countries.

Overall, these schemes appear to be very effective for convincing professionals, especially when they are well inter-connected with dissemination actions. Evaluation of design and installation practices is also very useful to prepare policy revisions.

■ Research and technology developments

Although specific and efficient methods and products exist in order to achieve good building and ductwork airtightness, there remain areas where RTD would be useful to ease professionals' work.

One area concerns the renovation of buildings where, although the easiest and technically preferable approach is to conduct a one-step integral renovation, it is clear that the largest fraction of the building stock will be renovated step-by-step. This raises a specific problem for building and, to a lesser extent, ductwork airtightness that needs to be considered at all steps, e.g., to make sure that early measures do not prevent adequate treatment of leakage sites later on. The integration of airtightness and ventilation issues in a step-by-step or in an integral approach renovation is also a problem. There is little work on these subjects to support method and product developments.

Other areas that deserve deep investigation are: the durability of the buildings seals over the building's lifespan, the analysis of vapour transfer through leaks and through the building structure, the development and testing of new sealing methods and products, and the life-cycle cost of air tightening.

Research should also support the development and analysis of leakage databases for monitoring purposes, estimates of energy and IAQ implications, as well as pressurisation test protocols.

5 DIALOGUE WITH USERS AND STAKEHOLDERS - NETWORKING

Dialogue, although essential for a successful policy implementation, is challenging as few structured users and stakeholders networks exist on envelope and ductwork leakage. TightVent Europe can help fostering national and international networking on these issues, which would also be useful for other purposes, e.g., sharing experience on training programmes, control schemes, RTD, etc..

Dialogue with users and stakeholders is of course one key to the successful implementation of such policies. In most other energy performance related subjects, policy makers can rely on associations to have resource-efficient feedback on field practice and possible adverse or positive implications of policy orientations.

As for airtightness, some formal or informal structured networks have emerged mostly in the past few years. We have identified networks in 7 European countries. However, the vast majority focuses almost exclusively on building airtightness measurement techniques, which means there is a gap on the other issues mentioned in this paper.

There are some local initiatives on the issues raised herein, such as the development of air leakage databases or on workforce training schemes. Sharing practice and research experience and taking advantage of the lessons learnt from pioneering work would be mutually beneficial, and encourage other initiatives. However, to our knowledge, there is no structured communication between initiatives taken in various countries or towards other parties facing similar problems.

Fostering national and international networking is one main focus of the TightVent Europe platform (www.tightvent.eu) initiated by the International Network for Information on Ventilation and Energy Performance (INIVE EEIG), with at present the financial and technical support of the following partners: Buildings Performance Institute Europe (BPIE), European Climate Foundation (ECF), Eurima, Lindab, Soudal, Tremco illbruck, and Wienerberger. All partners are strongly interested in setting up a European wide collaboration and using the knowledge gathered through TightVent Europe for raising the awareness among all building professionals, for developing improved training courses, and for helping professionals in the development of quality management approaches. The partners also believe that TightVent Europe can play a major role both in terms of research development and dissemination in the RTD areas aforementioned. Also, TightVent Europe will make use of its network of well-known specialists around the world and will put forward synergies between national initiatives.

CONCLUSION

There are great challenges towards a wide-scale implementation of building and ductwork airtightness. The major pitfalls and cornerstones are identified in this paper. Together with the analysis of existing work and lessons learnt from previous experience, this can form a strong basis for a roadmap for national or regional initiatives on building and ductwork airtightness. One aspect which is not detailed in this paper is the time needed to implement such policies, but the UK, and more recently the French experience, show that market transformation on these issues takes time: 5 to 10 years seems a reasonable estimate. This is an important parameter to keep in mind given the 2020 objectives of the EPBD recast.

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AIRTIGHTNESS OF BUILDINGS AND DUCTWORK: THE TIGHTVENT EUROPE PLATFORM

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Building and ductwork airtightness represent a key challenge towards very-low energy buildings and therefore towards the ambitious 2020 targets set in the recast of the energy performance of buildings directive. Results of the EU ASIEPI project (www.asiepi.eu, [6]) have shown that for most European climates, leaky envelopes and duct systems have a severe impact on the total energy use of the building, e.g., on the order of 10 kWh per m^2 of floor area per year for the heating needs in a moderately cold region (2500 degree-days) and 0 to 5 kWh/m^2/year for the ducts plus the additional fan energy use [2][10]. Few European countries have taken steps to overcome this challenge, but whether good or bad, their experience is worth sharing to accelerate the market transformation needed on these issues [4][8][9].

This paper gives an overview of the TightVent Europe platform that started in January 2011 and its scheduled activities for year 2011. More information can be found on the TightVent Europe website (www.tightvent.eu).

CHALLENGES FOR NEARLY-ZERO ENERGY BUILDINGS

The EPBD recast [1] sets ambitious targets for year 2020 including the obligation for EU countries to implement regulations to increase the number of nearly zero-energy buildings (NZEB) in the next few years, and to generalize nearly zero-energy targets in new buildings and major renovations. Therefore, as illustrated in Figure 1:

- Because of the demonstrated energy impact of envelope and ductwork leakage, the implementation of the EPBD recast will for most climates automatically lead to specific attention to building airtightness (1);
- As a result of the increased attention for building airtightness, the need for appropriate, energy efficient, ventilation systems (2) will grow. Issues such as correct airflow rates, air quality, acoustics, draught, energy optimisation, economics, etc. will have to be handled. At present, we know that poor ventilation system performance is common in many European countries.
- Indirectly, the move towards nearly zero-energy buildings will lead to a greater need for ventilation systems, whether mechanical, natural or hybrid (3).
- In addition, there are tremendous challenges for the existing building stock. Although there will be in most countries more time for implementation and, in absolute terms, probably less severe targets, in addition to challenges similar to the new stock, there are specificities that considerably

complexify the improvement of ventilation and airtightness.

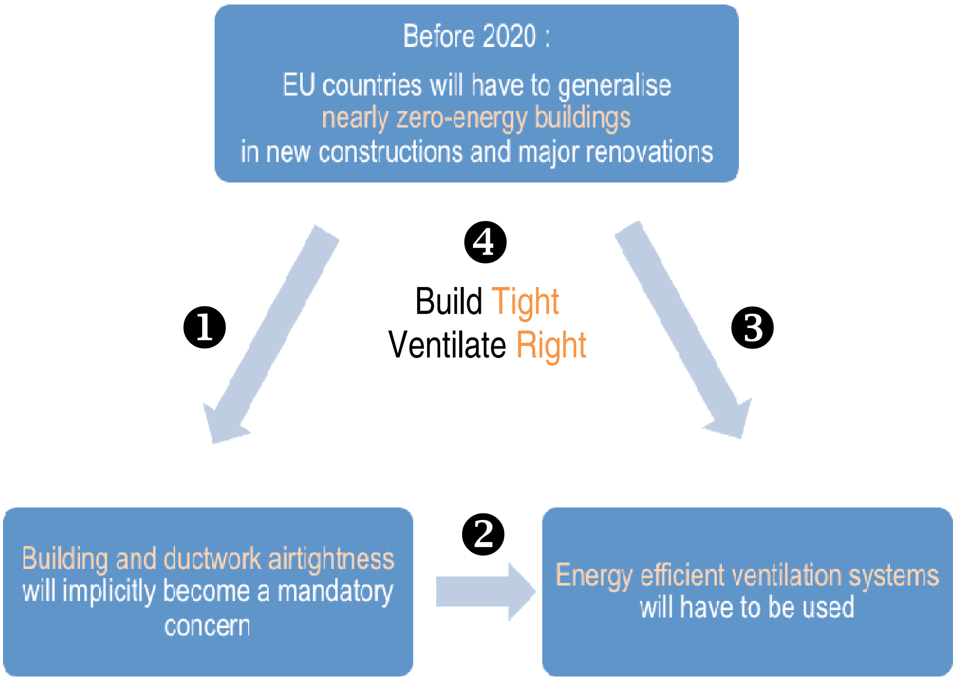

Figure 1. Diagram representing interactions between energy targets, ventilation, and airtightness

WHAT IS TIGHTVENT EUROPE?

Since there are to a rather large extent similar challenges for the whole of Europe, the TightVent Europe platform aims at meeting the obvious need for a strong and concerted initiative to overcome these challenges. Indeed, sharing experience on practical issues such as specifications, design, execution, control, ... and taking advantage of the lessons learnt from pioneering work will help improve airtightness quality while keeping in mind the need for adequate ventilation.

TightVent Europe has been initiated by INIVE EEIG (International Network for Information on Ventilation and Energy Performance) with at present the financial and/or technical support of the following partners: Buildings Performance Institute Europe, European Climate Foundation, Eurima, Lindab, Soudal, Tremco-Illbruck, and Wienerberger. All partners are strongly interested in setting up a European wide collaboration and using the knowledge gathered through TightVent Europe for raising the awareness among all building professionals, for developing improved training courses, and for helping professionals in the development of quality management approaches. The partners also believe that there are areas that need further investigation (for example, the durability of seals, the integration of airtightness and ventilation issues in renovation projects, the variability of the energy impact with climate, etc.) where TightVent Europe can play a major role both in terms of research development and dissemination.

The target audience of the TightVent Europe activities is wide and ranges from the research community over designers, practitioners, supply industry to European, national and regional government policy makers. It is clear that awareness raising is key in the starting up phase, whereas in time the emphasis should move to providing the appropriate support tools and getting the knowledge into the market.

ENVISAGED DELIVERABLES OF TIGHTVENT EUROPE

■ A project-oriented platform involving expert organisations from various countries

One key concept of TightVent Europe is to organize or encourage efforts in a consistent manner around specific topics, e.g., to develop a philosophy on airtightness requirements, to encourage the development of airtightness networks, to improve and encourage quality management. For this, TightVent will make use of its network of re-known specialists around the world and will put forward synergies between national initiatives. For instance, on the subject of airtightness requirements, this might take the form of a project involving a group of experts from various countries with a series of workshops and webinars including lessons learnt from national approaches. The foreseen publications, conferences, webinars, and BUILD UP community described below fall under this project-oriented approach, i.e., they are linked to project deliverables.

■ Publications under preparation

A publication on the challenges for building and ductwork airtightness is foreseen in spring 2011. It will include an introductory paper browsing the issues of concern and collect a series of technical documents, namely those produced within the ASIEPI project as well as within the SAVE-DUCT and AIRWAYS projects [1][5].

We are also working on a more extensive publication that will give an overview of envelope airtightness issues and policies to achieve a market transformation. It is primarily targeted at policy markers, but it will include relevant information for building professionals such as project owners or managers or consultants as well, for instance on energy and indoor air quality issues associated with airtightness.

■ Two major conferences in Berlin (May 6) and Brussels (October 12-13)

One important aspect of TightVent Europe's strategy is to bring added-value to existing initiatives rather than duplicating efforts. One illustration of this strategy lies in the partnership established with the BUILDAIR conference, which was held in Berlin, May 6. This conference has been for a number of years a major event on airtightness issues in Germany (www.buildair.eu) and has more recently drawn attendees from several European countries. The association with TightVent Europe is expected to bring more visibility of this conference at EU level.

TightVent Europe is also combining forces with the Air Infiltration and Ventilation Centre (AIVC — www.aivc.org), which is the IEA information centre on energy efficient ventilation. In practice, the 32nd AIVC conference, which is the major international event on air infiltration and ventilation, is combined with the 1st TightVent conference. The programme includes 2 parallel tracks:

- One track focusing on airtightness related issues;
- The other track addressing ventilation issues in general.

The conference will consist of a mixture of:

- Well-prepared workshops (typical duration 1.5 hours);
- Presentations on invitation;
- Presentations from call for papers.

The deadline for abstract submission is May 15.

■ Webinars

Besides the publications, conferences, and BUILDUP community mentioned above, TightVent Europe key activities in 2011 will also include the organization of webinars. Some will be targeted at a specific region (the first webinar will be specifically focused on Romania), some at the specific topic (e.g., sharing national experience on air leakage databases), some at training, some at industry.

■ BUILD UP community on airtightness of buildings and ductwork

Today, there is for many issues of interest not a lack of information but, at the same time, it is for most professionals difficult to easily find the information one is looking for. The BUILD UP platform (www.buildup.eu) is the official EU platform on energy efficiency in buildings, and TightVent Europe is actively supporting this through facilitating a community on the "Airtightness of Buildings and Ductwork". Part of the information in BUILD UP can also be accessed on www.tightvent.eu.

SCIENTIFIC COMMITTEE AND AIVC COLLABORATION

In order to guarantee high quality deliverables and an unbiased view, the TightVent scientific committee has been set up, with as primary objectives:

- To pay attention to the overall scientific approach of the platform;
- To take care of a correct balance between energy concerns and indoor climate concerns;
- To organise a review process for publications and to give advice to the steering committee.

It is made of internationally re-known individuals in the field of energy efficient ventilation and infiltration. In a concern for efficiency and focus, some of these experts are also members of the Air Infiltration and Ventilation Centre (AIVC).

CONCLUSION

The TightVent Europe platform has already initiated a number of activities in its starting up phase since January 2011, ranging from the organization of two international conferences in 2011 to the preparation of publications and webinars, including the dialogue with users and stakeholders. Its ambition is to play a major role in dissemination and research activities on airtightness and ventilation issues, namely by bringing added-value to existing initiatives, gathering experts around common concerns, and producing reference documents. This way it will contribute to the obvious need for international collaboration on building and ductwork airtightness, which is a major challenge for EU countries to reach the 2020 targets. For more information, visit the TightVent Europe website at www.tightvent.eu.

ACKNOWLEDGEMENTS

The TightVent Europe platform receives the financial and/or technical support of the following organizations: Buildings Performance Institute Europe, European Climate Foundation, Eurima, INIVE, Lindab, Soudal, Tremco-Illbruck, and Wienerberger.

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EPBD BUILDINGS PLATFORM

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ASIEPI

More information can be found at the ASIEPI project website: *www.asiepi.eu*

Similar Information Papers on ASIEPI and/or other European projects can be found at the Buildings Platform website: *www.buildingsplatform.eu*

Implementation of Energy Performance Regulations: Opportunities and Challenges related to Building Airtightness

This information paper discusses some critical aspects that have to be dealt with to stimulate the market towards better envelope airtightness in the Member States. This includes how airtightness may be taken into account in an energy performance regulation as well as the role of standards, low-energy labels, professional networks, financial incentives, industry, training, and regulatory control in helping the market uptake.

1 > Introduction

Building airtightness is not a new topic of interest. In the nineteen seventies, deep research has been performed on building airtightness in the Nordic countries. In the Air Infiltration Review (AIR) of August 1980 (ref. 22) (Figure 1), an article entitled 'Build tight – ventilate right' already described the challenges very well.

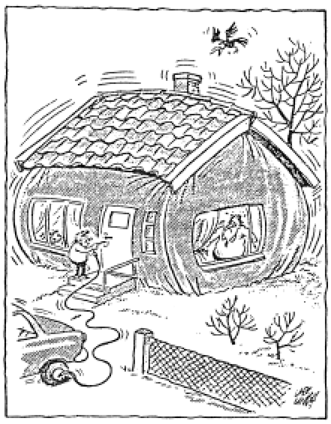

Figure 1 : Illustration used in the Air Infiltration Review of August 1980.

The Air Infiltration Review was the newsletter published by the Air Infiltration Centre (AIC). In 1980, the AIC published a guide entitled 'Air Infiltration Control in Housing – A Guide to International Practice'. This guide, primarily based on Swedish experience, described very well, and in more detail than the AIR article, the various aspects of building

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Directorate-General for Energy and Transport airtightness, including the energy and air quality issues, the airflow modelling, and the measurement methods. Airtightness has also been the central topic of the annual AIC conferences between 1980 and 1983 as highlighted by the titles of these conferences, e.g. 'Instrumentation and measurement techniques' (1980), 'Building design for minimum air infiltration' (1981), 'Air infiltration reduction in existing buildings' (1983). The full papers of these conferences can be found in the literature database AIRBASE developed and managed by the Air Infiltration and Ventilation Center (AIVC, *www.aivc.org*). The AIC became AIVC in 1987 to better reflect its activities. In fact, because of the close interactions between building leaks and ventilation systems, including fans, air terminal devices, heat recovery units and so on, ventilation issues were naturally addressed within the AIC.

Many AIVC publications on building airtightness have followed, including more recently three so-called 'Technical Notes' (TN) and one 'Ventilation Information Paper':

- TN 34 – Airflow patterns within buildings: measurement techniques (1991)
- TN 55 - A review of international ventilation, airtightness, thermal insulation and indoor air quality criteria (2001)
- TN 51 – Applicable models for air infiltration and ventilation calculations (1999)
- VIP 8 – Airtightness of Buildings (2004)

In addition, research or operational work has lead to many envelope leakage measurements, some of which can be found in the AIVC numerical database.

With the recent trend toward very low energy buildings, there is a regain of interest for envelope leakage. In fact, in such buildings, the envelope needs to be extremely airtight compared to standard practice. This trend has also been one key reason behind the success of the BlowerDoor conferences held in Germany since 1993, whereby building airtightness and related issues are the central theme. The first European edition of this conference took place in 2006 with a broader audience (over 150 attendants), which shows the growing interest for this topic in the last few years. The abstracts and papers of these conferences can be found in AIRBASE.

Therefore, this quick review of the work performed on airtightness confirms the abundance of contributions from research and practice; however, this work remains fragmented. Therefore, it is difficult, especially for policy makers, to have clear picture of the challenges and opportunities based on experience and lessons learnt by the Member States. The objective of this paper is to contribute to this clarification by giving an overview of the ongoing work motivated mostly by the Energy Performance of Buildings Directive and the initiatives taken within the Member States towards very low energy buildings.

2 > Requirements in the EPBD

The Energy Performance of Buildings Directive (EPBD) (ref. 1) imposes to the Member States requirements as regards:

- the general framework for a methodology of calculation of the integrated energy performance of buildings;
- the application of minimum requirements on the energy performance of new buildings;
- the application of minimum requirements on the energy performance of large existing buildings that are subject to major renovation;
- energy certification of buildings; and
- regular inspection of boilers and of air-conditioning systems in buildings and in addition an assessment of the heating installation in which the boilers are more than 15 years old.

According to article 3, the methodology of calculation of energy performances of buildings shall include at least the following aspects:

- thermal characteristics of the building (shell and internal partitions, etc.). These characteristics may also include **airtightness**;
- heating installation and hot water supply, including their insulation characteristics;
- air-conditioning installation;
- ventilation;
- built-in lighting installation (mainly the non-residential sector);
- position and orientation of buildings, including outdoor climate;
- passive solar systems and solar protection;
- natural ventilation;
- indoor climatic conditions, including the designed indoor climate.

As such, the EPBD does not explicitly impose to take building airtightness into account but clearly gives a signal to pay attention to building airtightness. The deadline for implementation of the above listed requirements was January 4, 2006. The Member States had the possibility to postpone the deadline until January 4, 2009 only if they were able to prove the lack of qualified and/or accredited experts. Information about the practical status of implementation of the EPBD by the Member states can be found in the Information Papers on Country Status reports as published by the EPBD Buildings Platform (*www.buildingsplatform.eu*).

3 > The role of standards

An overview of ventilation related standards can be found on the AIVC website (*www.aivc.org).* At the European level CEN, the European Committee for Standardization (*www.cen.eu*), has published different documents that promote a harmonised consideration of building airtightness in the framework of the EPBD.

A first important standard (EN 13829:2000) describes the measurement method of air permeability of buildings through fan pressurization. Due to different surface and volume calculation methods in the EU member states, measured airtightness data (usually expressed in terms of the infiltration air flow rate at 50 Pa divided by the cold surface area or the building volume) are not fully comparable. A general agreement on these calculation methods would give a more international status to the measurement data and would ease the comparison between the Member States. 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, heating and cooling load calculations, summer comfort and indoor air quality evaluation. The documents cover dwellings (EN 13465:2004), buildings in general (prEN 15242) and commercial buildings (prEN 15241). Some countries have already partially implemented these methods in their regulatory energy performance calculation tools. This allows energy consultants in particular to evaluate in detail the energy impact of envelope leakage for a given building and ventilation system in a given climate. The disadvantage is that the underlying airflow modelling is sophisticated compared to the simpler approaches used in the past in some countries.

Finally, other documents like EN 13779:2004 or TR 14788:2006 give guidance on the maximum n_{50}[(1)] value for buildings.

4 > Approaches for integrating building airtightness in energy performance regulations

Although building airtightness is presently included in many energy performance related regulations (e.g., in Belgium, Denmark, France, Germany, Slovenia, the Netherlands, Norway, United Kingdom), in practice there are major differences in the way it is taken into account:

- In some countries, a better airtightness than the default value can only be taken into account if proven by measurements at commissioning, whereas other countries also allow the use of quality management approaches (e.g., in France, Finland);
- There are countries with a minimum requirement (e.g., in Denmark, Norway, Slovenia, the United Kingdom). Some countries have guidelines for the maximum envelope leakage (e.g., Germany);
- The default value for building airtightness differs from country to country, which is not surprising given the differences in building traditions and construction types;
- The precise calculation procedure regarding building airtightness differs from country to country.

5 > Market uptake of attention for building airtightness

Several countries have had requirements for many years or at least strong recommendations regarding airtightness. Interesting developments from the last few years are the mandatory requirements for large buildings in the UK and the airtightness requirements for passive houses.

5.1 UK requirements on large buildings

Since 1 April 2002, when Part L2 of the Building Regulations (ref. 88) came into force in the UK, new buildings with excessive air leakage are no longer acceptable. All new commercial and public buildings over 1000 m² must be

[1]The metric n_{50} is defined in EN 13829. It represents the airflow rate that passes through the building leaks at 50 Pa divided by the building volume.

tested by an accepted testing body for airtightness. The regulation requires that air permeability should not exceed 10 $m^3/h.m^2$ at an induced pressure difference of 50 Pa across the exposed envelope.

This regulation has been strengthened in 2006. Testing is now mandatory for new dwellings, as well as commercial and public buildings over 500 m^2. The airtightness required remains the same.

5.2 Passive houses

Passive houses are characterised by extremely low transmission and infiltration losses in combination with high efficiency heat recovery ventilation systems. The airtightness requirement (i.e., $n_{50} \leq 0.6\ h^{-1}$) are very severe. It is clear that such a severe airtightness requirement is a major driver for a rational approach to airtight building concepts, whereby good building design in combination with appropriate products and execution techniques is essential. Therefore, today there exists a range of products specially designed to achieve excellent airtightness at given penetrations. Besides, the architects are particularly attentive at the design and construction phase to the way the penetrations will be addressed to minimise leakage and thermal bridges. In summary, the severe airtightness requirement ($n_{50} \leq 0.6\ h^{-1}$) is commonly achieved in these passive houses using similar robust methods and products.

5.3 BlowerDoor conference

As mentioned above, the existence of an international conference specifically focused on the issue of building airtightness is a good indication of the growing interest for this issue. We expect a further increase in the interest for gathering and exchanging experience on airtightness as many issues remain problematic, such as the testing of large buildings or the methods and products to be developed for the renovation of buildings.

The interest for energy efficiency issues in buildings has grown spectacularly in the last few years and this for all kinds of decision makers. Within this context, it is logical to expect that building airtightness will gain in importance. How this will happen in practice will be influenced by a number of decisions and trends. Some of these aspects are briefly described here.

6 > Challenges and opportunities

6.1 Effective ways for dealing with airtightness in regulations

Energy performance regulations

One key idea of energy performance regulations is the fact that the performance assessment (and related requirements) is focusing on the total energy performance of a building and not on the performance of individual components. As such, the designers and contractors have a large freedom in the approach to achieve a given target. Especially in very price-competitive markets, those measures with a high energy saving per invested € will be the most attractive. (This is often the case for airtightness and thermal bridge measures.) Therefore, it is essential that the calculation methods used by the Member States foresee the possibility to include the building airtightness results. It is also critical that the reference and default values used in the regulatory calculation tools be set correctly. (In particular, the setting of the default value is delicate as extremely leaky buildings can always be found.) If not, it may diminish considerably the energy-based and cost-based motivation to invest in an improved building airtightness.

Explicit air tightness requirements

Whereas a requirement based on an overall energy performance calculation procedure does not give any guarantee that attention will be paid to building airtightness, an explicit attention to building airtightness can be obtained by requiring minimum airtightness levels. Such an approach can be interesting if there is sufficient evidence that investing in building airtightness is among the most relevant measures and/or that a better building airtightness is needed (e.g., for thermal comfort or indoor air quality reasons, in particular as tightening after commissioning remains quite challenging). The risk for such a requirement is that the cost-benefit ratio may be too high in some cases. In Norway, a combination of the two above-mentioned approaches (inclusion of envelope leakage in the calculation of the energy performance and explicit airtightness requirement) has been recently adopted. This way, the motivation for achieving good or excellent airtightness is mostly driven by the calculation; however, a minimum requirement prevents leaky houses, far beyond the default value, to comply with the regulation. This may be a good way to address the default value issue raised above.

6.2 Financial incentives - Subsidies and fiscal deduction

At present, many countries have a range of financial stimuli to accelerate the implementation of energy efficient investments in buildings, e.g., subsidies, fiscal deduction, attractive loans, etc.

Typically, a number of conditions have to be met in order to receive the benefits. Quite often, the requirements are expressed in a descriptive way—e.g., installation of high efficiency glazing, of condensing boiler, of a ventilation system with heat recovery. In case of such an approach, one has to convince the policy makers to include building airtightness in the list of acceptable measures.

An alternative and more attractive approach would be to relate the benefit to the achieved energy performance improvement whereby the energy performance calculation method can be used as the quantitative basis. As far as we know, such an approach has not been implemented in any Member State yet.

6.3 Availability of appropriate materials and systems

Achieving a good building airtightness is much more feasible when appropriate materials and systems (e.g., airtightness layers, specially-designed tapes, pre-compressed expandable foams, connecting elements for ducts and cables, etc.) are available. During the last decade, a whole range of such products have become available in several countries. It is important that these products be available to all EU countries.

6.4 Training - making building airtightness predictable

The achievement of a certain airtightness level through ‘trial and error’ is not the appropriate approach for a wide scale market uptake of building airtightness since it will be too expensive and too difficult to integrate in the building process.

Therefore, appropriate training tools and courses are critical. The availability of guidance on building details and appropriate execution technique is very important. With this respect, international collaboration would be very useful as many countries could be inspired by the experience of others and success stories in specific market segments and states.

6.5 Efficient framework for quality control and certification - Control of regulations

Various studies have shown that in practice, many buildings do not comply with the requirements despite the statements of various actors involved in the construction process. The risk for deviations between actual and stated values is probably quite high for airtightness results without an efficient compliance control scheme in force. Such a framework can be based on systematic control measures, on random control measures and/or on quality control of those who are in charge of the works or a third party.

No matter the approach used, it is important that building airtightness control measures be possible at economically attractive conditions. Several ways can be explored to improve the cost-benefit ratio of these approaches:

- The development of a framework whereby the building contractor can carry out control tests. This may be restricted to certified contractors within a quality management procedure, in which case, the certification framework must be defined;
- The development of sampling rules for selecting units in multi-family buildings to ease the control of these buildings (one can probably learn from Swedish experiences regarding ductwork airtightness – see Figure 2);
- The development of cheap and small systems for testing the airtightness of apartments.

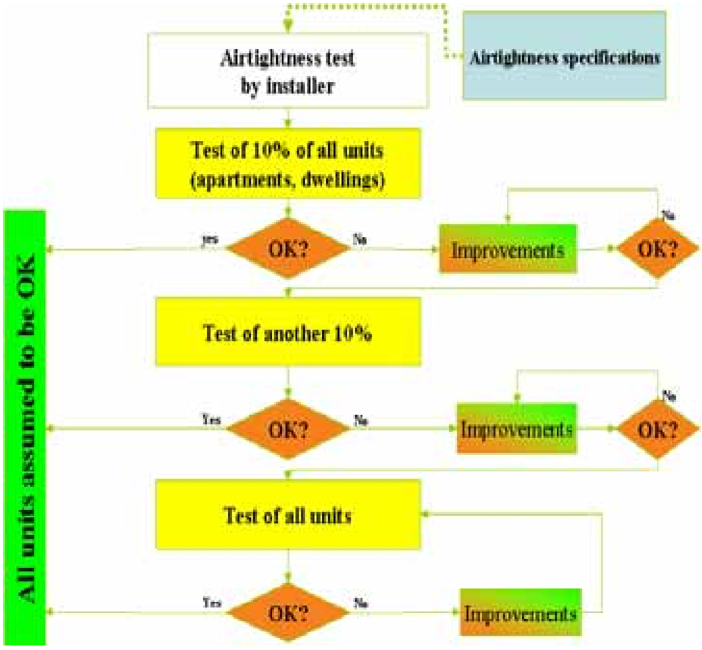

Figure 2: Possible framework for envelope airtightness test on a sample of units in multi-family buildings.

6.6 Optimal building airtightness

It is well known that the cost for reducing the U-value of a building component from 0.4 to 0.2 W/m²K is much higher than from 1.0 to 0.8 W/m²K. Similar conclusions can probably be drawn for improvements in building airtightness but the quantification of the cost induced by better airtightness remains unclear. This aspect certainly needs to be analysed in depth as it is key to identify airtightness levels with a good cost-benefit ratio to set regulatory requirements as well as to specify a specific target for a building project. The appropriate level has to be seen in the specific context of a given project, whereby the construction type (wooden structure, masonry, etc.), the available experience, or the overall energy requirement level may be important boundary conditions.
Imposing airtightness levels which in a given context require too high investment costs may be counter productive and may reduce the interest in building airtightness. A gradual increase of the regulatory requirements or a gradual enlargement of the building targets as implemented in the UK should give the market the opportunity to learn how to achieve a given airtightness level in a cost effective way.
Note also that the 'optimal building airtightness' will change with increasing demands on the overall building energy performance. This is due to the fact that the energy use due to infiltration remains about the same in absolute terms, and therefore has an increasing share in the total building energy use.

6.7 Airtightness and existing buildings

Obviously, a very substantial improvement of the energy efficiency of the existing building stock is a major objective in the medium (approximately, 2020) and long term (approximately, 2050) strategies of many member states and the EC. The Action Plan on Energy Efficiency envisions 20% savings in 2020. The potential contribution of a reduction of infiltration losses to the achievement of this target is quite large. However, appropriate techniques and execution methods for existing buildings are sorely needed, although some pilot projects have demonstrated that good airtightness could be achieved in renovation. Moreover, many existing buildings have no or inappropriate ventilation systems and therefore the installation of appropriate ventilation systems in combination with envelope sealing would be relevant.

7 > International collaboration on the handling of building airtightness in the context of energy performance regulations

One objective of the EU IEE supported project ASIEPI (Assessment and Improvement of the EPBD Impact, October 2008 until March 2010) is to study the issue of building and ductwork airtightness. The specific work package 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 —where available— on the impact of the measures taken to transform the market. The project will collect information to answer the following specific questions for envelope and ductwork airtightness:

- What are the different strategies implemented in the Member States?
- What is the impact of envelope and ductwork leakage on the energy performance?
- Which control measures are taken depending on building size or usage (if any)?

- What is done in case of renovation?
- How effective are those strategies?
- How is training organized? What kinds of training schemes are available in Europe?
- What kind of actions have been successful, including evolution of the regulation, support of pilot projects, training, research and development?
- Which tools can be used to help owners, designers, builders, and craftsmen to build tighter?
- What kind of test equipment is available, including for large buildings or very airtight dwellings?
- How to carry out cost-effective control measures in multi-unit complexes (e.g., apartments)?

Once collected, this information will be structured and synthesised to allow dissemination among policy makers as well as other key market actors.

8 > Conclusions

The growing concerns about climate change and depletion of fossil energy resources have become a very strong driver for increasing the energy efficiency of the new and existing buildings. Moreover, the EPBD obliges all EU Member States to impose minimum energy efficiency targets for new buildings and for major renovations of large buildings. There is no doubt that, given the increasing share of infiltration losses with increasing building energy performance, more and more attention will be paid to improved building airtightness. This is already the case in some member states (Belgium, France, Germany, The Netherlands, United Kingdom, Norway among others) who have defined requirements in regulatory frameworks that stimulate improved airtightness. However, the practical impact appears to depend strongly on the way various challenges are handled, including the approaches to defining the requirements, estimating the energy impact of envelope leakage, training designers and contractors, and ways to comply and check the requirements.
We expect that the ASIEPI project will provide an interesting framework for international collaboration on this issue and therefore, will accelerate the identification and implementation of appropriate cost-effective measures in the Member States.

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International comparison of envelope airtightness requirements & success stories that could inspire the EC and other MS

1 > Introduction

This information paper discusses international comparison of envelope air-tightness requirements and brings out success stories that could inspire the EC.

2 > Envelope air-tightness requirements in Europe

Requirements on envelope air-tightness are usually expressed as maximum levels of total measured leakages through the envelope, related to either the building volume (n_{50}), the floor area (w_{50}) or the envelope area (q_{50}). Several countries have had air-tightness requirements related to building elements for some time (windows etc, related to area). Fore these countries the inclusion of joints between elements in requirements may be a relatively new situation. Difference in expression of requirements introduces some challenges if one should compare nominal requirement levels between countries. Crude conversion between the two first is often relatively easy, as volume results from the product between floor area and standard height to the ceiling. Looking into this in more detail though reveals some challenges as ways of measuring and inclusion of different volumes vary between countries.

Ways of expressing the requirement reflect different ways of building (requirements based on volume, n_{50}, are easier to achieve in larger buildings than in smaller ones, etc). Comparing neighbouring countries often reveals similarities, but regulations are revised at different intervals in different countries and this may give some differences. Many countries often have more or less publicized plans of revisions and long time goals, and a general trend is towards more ambitious energy saving requirements.

Expert questionnaire: The ASIEPI project has submitted a questionnaire to 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 also included some questions dealing with the way envelope and ductwork air-tightness is taken into account in the regulation.

Most countries investigated (10 out of13 : BE, CZ, DE, DK, ES, FI, FR, NL, NO, PL) take into account envelope air-tightness in their energy

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performance calculation procedures (Figure 1). At least 7 out of these 10 countries give the possibility to reward good envelope air-tightness as it results in lower "regulatory" energy consumption. Six countries also have minimum requirements on envelope air-tightness (CZ, DE, DK, ES, NL, NO); in Spain specific requirements apply only to windows. In general, there is no requirement for existing buildings except in case of major renovation (CZ, DE).

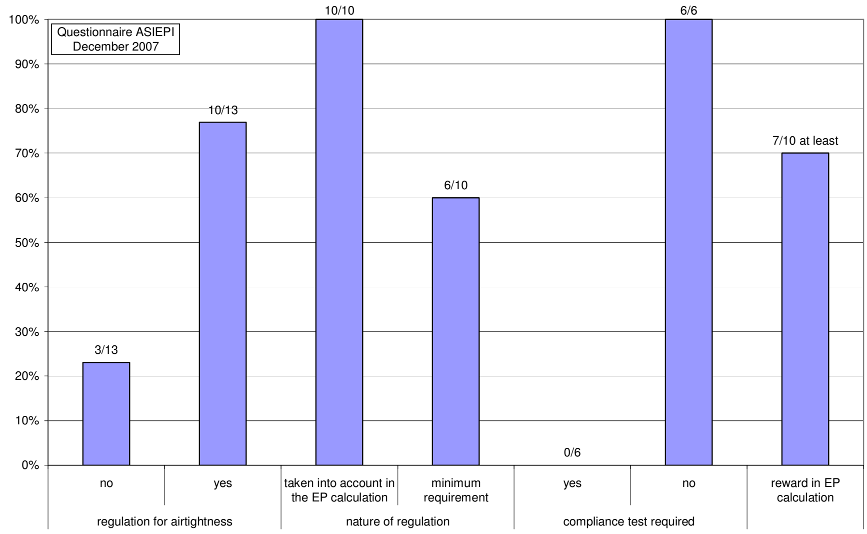

Figure 1: Overview of envelope air-tightness in national regulations

The compliance schemes to the regulation obviously depend on the nature of the requirements. Most of the time, a pressurization test has to be performed to be able to claim for a reward for good envelope or ductwork air-tightness. 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 pressurization tests are compulsory since 2006 in all new buildings. 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.

3 > Success stories

During the last few years the Energy Performance of Buildings Directive (EPBD) and the change of national regulations have renewed focus on air leakages and its consequences on energy use in the building industry in many countries all over Europe. This renewed attention has led to a series of success stories from some countries and these are leading in the right direction. These processes could be encouraged in all the other countries:

Low energy labelling: In recent years and in several European countries there has come up different ways of labelling buildings as having low-energy properties. The German PassivHaus concept has led the way. Some governments have sponsored low-energy building economically. A precondition for government funding of these houses has then been the documentation of air-tightness by pressurization measurement. This has led to an increase in measurements and to an increase in awareness about this important property.

The recent regulation-based BBC-Effinergie label in France, has very significantly impacted the market there in just one year. The perspective of the generalization to all new buildings of this label that includes air-tightness requirements for residences is a strong driver for change.

An example of resulting success development can be the one in a firm in northern Norway. This firm developed a building site with a series of low energy buildings. The site could be characterized as specially exposed to cold winds for large parts of the year.

Higher ambitions require changes: the firm had little experience of actually measuring air tightness when confronted with these preconditions from government funding. They were used to building houses that met their customer's expectations in a windy cold climate, and having just recommendations from the guide to national regulations quantifying this to n50 not exceeding 4 /h. In these low energy houses n50 were aimed at more challenging n50 < 1,5 /h. Compliance scheme: our institute was spreading our message to the building industry at the time, suggesting a scheme that included pressurization measurement both in early wind-tight stage and in finished stage, giving the firm a possibility of better feedback from different phases of the building process.
The two houses being tested in early wind-tight stage, B1 and B3, had results surrounding the target value; a great relief to the builder. There were some weak points observed, mainly connected with chimney and other perforations of the wind break layer.
When we returned some months later, the builder experienced that the completion of the houses, insulating and adding a new inner layer with vapour barrier, etc. did not improve the results; on the contrary, one of the houses had become much leakier! Investigating this, the conclusion was that the carpenters had done their job fairly well, but the ventilation firm had probably not been sufficiently included in the information process: they had sawed out the holes for the ventilation ducts with little concern for the carpenter's skillful prior achievements.

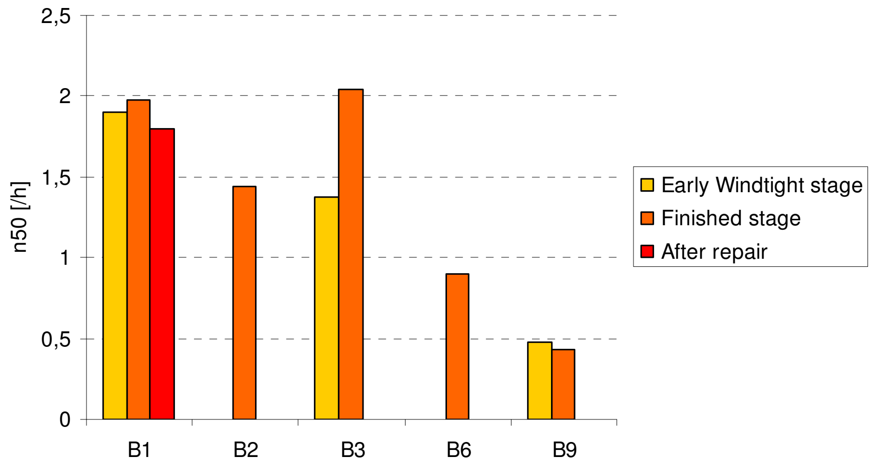

Figure 3: Air tightness results from five low energy buildings erected by the same team and measured over a period of two years.

Locating leakages is challenging: the first house was measured a third time after repair. The results were not improved as much as one had hoped. There can be several reason for this, one being that repair work was not sufficiently planned and performed. One common experience is that pinpointing remaining air leakages is increasingly difficult as the leakage air flow gets to a more and more ambitious level. Repairing minor defects and overlooking the larger ones is a possibility and a real challenge.

Compliance through Quality Assurance schemes: It has become more and more clear that compliance to air-tightness requirement must be documented by some level of mandatory blower door testing, preferably in combination with thermography. There exists one challenge to this form of compliance documentation. Pressurization tests of a given building are typically performed long after documentation of energy properties is handed inn and building permit is granted. Quality assurance schemes that document “common practice” in a given firm is a way of solving this.

Quality management approaches are rewarded in Finland and in France: if a builder proves that he has implemented a quality management approach to obtain good envelope air-tightness, 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 air-tightness measurements on a sample of buildings. A few dossiers are being processed in 2008.

A firm showing a development as seen in the above example is very likely to perform well if air-tightness is measured after buildings are erected.

Spread of tools and knowledge: Spread of knowledge about air-tightness is an important tool to lead the building industry into improvements. In France campaigns and events addressing the issue reach out to a growing number of participants.

Since the middle of the 1990s seminars and conferences about building air tightness have been held in Germany. Since that time about 3000 people have been qualified in air-tightness through the EUZ. This means that practically all people who have a blower door also have passed training. Since 2003 there is a certification for blower door measuring and about 230 people have achieved a certificate.

The German “Foundation of the Association for Air Tightness in the Building” was founded in the year 2000 through the initiative of the EUZ. It now has more than 260 members from Germany, Austria and Switzerland and some also from other European countries. Most of them are engineering companies which are measuring air tightness. Similar forming of interest groups can be observed also in some other countries, but at a much lower number of participants.

An important key word in this context is the link to a scientific group that can ensure good quality among the performers.

Robust design: The traditional main route to good air-tightness has always been good design. A special path of this route has been explored in the UK some years ago, based on the adoption by builders of especially “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 tested buildings failed.

The UK experience puts into question the relevance of the more recent French and Finnish approaches through quality management schemes, 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. Therefore, especially if found successful, these approaches should be carefully evaluated, in particular to identify the keys to success and barriers, so that other countries could benefit from their experience.

The example that follows illustrates how the understanding and participation in a total process is of importance.

Some years back, a house builder firm in windy western Norway had a complaint case: a house that the buyer felt was too drafty. Unfortunately for the firm, a pressurization tests, very rarely performed, showed large total air leakages; and other measurements located the fault mainly to the junction between foundation and outer walls. The firm turned these resulting large repair expenses into a positive challenge. It started a systematic process of becoming better on air tightness.

Design process: a while later the firm built a series of low energy houses. These houses were carefully designed in the firm's main office. In addition to this they made an emphasis on their strategy to perform a "Design-on-site" process, together with their skilled and experienced workers. In this process the designers got feedback on the workability on the details that were planned. In addition they went through also the details that were not thought about in the planning phase. There were some challenges with the use of relatively new materials and details; how to manage large sheets of wind-break materials very much resembling sails in wind very fit for sailing, being one example. This dialogue resulted in general principles being understood by all participants all through the process.

Funding sponsoring pressurization tests: again documentation of air-tightness by measurement was a precondition for government funding of these "low energy" houses. The goal was to achieve a leakage number, n50 of not higher than 1.5 /h.

Record breaking: envelope pressurization tests were performed in early wind tight stage, with n50-values around 0.3 /h for three measured similar houses. In finished stage these houses ended up with n50-values less than 0.2 /h, with fairly little difference between the houses.

After this achievement, the firm set out to try to build a house with much more ambitious details, and at the same time try to break their own leakage number record: they succeeded, with a n50-value less than 0,1 /h in early wind-tight stage!

Figure 4 : Building with ambitious details, with a n50-value less than 0.1 /h in early wind-tight stage.

Quality, at what cost: there was a considerable interest among house builders on what it had cost extra to achieve these very good results. Obviously, it was made quite a lot of extra effort in these buildings, and this was announced by the firm, but they also told us that "we did not really build very differently from how we now build in ordinary projects".

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Airtightness requirements for high performance building envelopes

Especially for high performance buildings, which go beyond national energy performance requirements, infiltration losses become a significant factor for the energy performance. This information paper presents an overview on the existing building surface airtightness requirements in different European countries and compares them to the requirements for high performance buildings. Airtightness measurement results of realised high performance buildings show what can be achieved in practice.

1 > What is a high performance building?

Buildings that do not only fulfil the national requirements, but are designed to use considerable less energy, are often called high performance buildings. There are different terms used in this area, from low energy building over passive houses and 3-litre houses to zero energy or zero emission buildings and many more. An information paper [1] soon available on the Buildings Platform summarises the used terms and definitions as well as the currently realised number of high performance buildings in the EU Member States. Though the definitions of the various types of high performance buildings differ from each other, the very most of them imply a building airtightness that is better than for regular buildings.

2 > Existing building envelope airtightness requirements in the EU Member States

The implementation of the Energy Performance of Buildings Directive (EPBD) [2] has caused in most of the EU Member States more severe requirements for the energy demand of buildings. In order to meet these requirements, not only buildings components with better U-values and more efficient building systems have to be used, also the ventilation losses have to be reduced. A contribution to this necessary reduction is the improvement of the building envelope airtightness, mainly the airtightness of building components and joints. With the EPBD implementation or even before some of the countries have included minimum airtightness requirements in their building codes.

According to an investigation at the end of 2007 in the ASIEPI project [3] 7 of 14 EU Member States have minimum requirements regarding the building envelope integrated in their building codes. These are: the Czech Republic, Germany, Denmark, the Netherlands, and Great Britain. Spain has partial requirements focussing on windows. The existing minimum requirements that refer to new buildings (residential and non-residential)

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differ from country to country and are presented in the following table.

EU Member State	Air tightness requirements at 50 Pa pressure	
	Natural ventilation	Mechanical ventilation
Czech Republic	4.5 1/h	w/o heat recovery: 1.5 1/h with heat recovery: 1.0 1/h
Germany	3.0 1l/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)	

Existing airtightness requirements in European Union Member States.

It has to be stated though that in all countries with air tightness requirements, except in the UK, there is no generally required compliance test. However, in Germany and Denmark pressure tests are required in some cases. In Denmark the pressure test is generally optional but can be required by building authorities. In Germany the pressure test has to be made if a mechanical ventilation system is considered in the calculation of the energy performance certificate of a new building. The reduction of the ventilation losses can only be taken into account if the airtightness was proven.

In Finland the basic air leakage rate for calculation of the energy performance can be reduced if a pressure test or some other accepted method presents better performance.

North view (above) and South view (below) of the passive house buildings monitored incl. airtightness tests.

3 > Air tightness requirements for high performance buildings

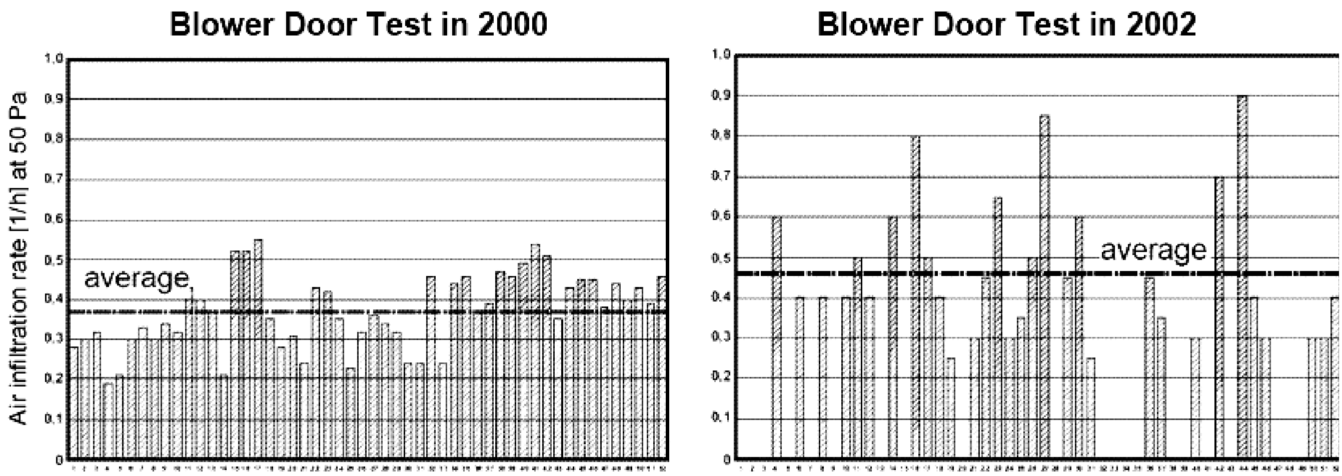
As written in the introduction high performance buildings require in general an improved airtightness of the building envelope. Otherwise the desired low energy demands can't be achieved. Most of the various high performance buildings however have not specified values that have to be fulfilled.

Example 1: Passive house (Germany)

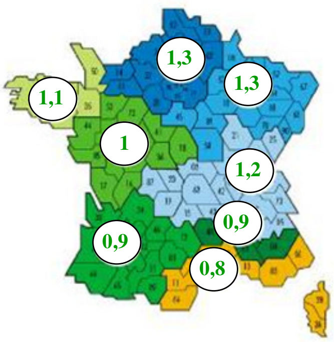
An exception is the so-called passive house. The passive houses originally created in Germany are calculated with a procedure that differs from the national German energy performance calculation standard, mostly in the area of the ventilation losses. The net heating energy demand of these houses has to be 15 kWh/m²a or lower and the primary energy demand for heating, ventilation, domestic hot water and household electricity shall not exceed 120 kWh/m²a. In the definitions set by a private organisation in Germany, which are applied in some other central European countries as well, the infiltration rate at 50 Pa overpressure is set to 0.6 1/h.

As the passive houses generally include a mechanical ventilation system which is also used for heating purposes, this value has to be compared to German air tightness requirements for buildings with mechanical ventilation systems: 1.5 1/h. The airtightness of a passive house is supposed to be more than twice as good as for a regular house.

Experiences from many pressure tests at the Fraunhofer Institute for Building Physics show that values below 1.0 1/h are difficult to achieve. However the Institute has tested some buildings, also some passive houses, which do meet this requirement in practice. The figure on the left shows two exemplary photos of a series of row houses built according to the passive house definition in Stuttgart, and which were monitored by the Fraunhofer Institute for Building Physics [4]. The results of the Blower Door tests made right after the construction phase (2000) and two years later are presented in the following figure.



Results of airtightness measurements at 31 passive houses in Stuttgart, Germany measured right after the construction phase and 2 years later.



Climate factors [6]

Single-family house with BBC-Effinergie label [5]

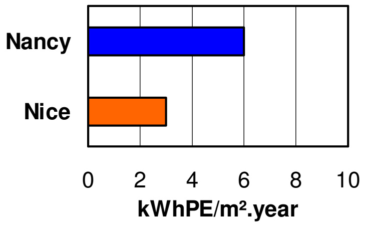
The results of the air leakage test show that the average infiltration rate of all 52 row houses measured right after the construction phase was 0.37 1/h and the average value of 31 of the houses measured two years later was 0.46 1/h. That proves not only that the very low leakage rates are possible, but also that they were only slightly worse after two years of building use. Yet in 5 of 31 buildings measured in 2002, the original goal of 0.6 1/h which was met at the end of the construction period could no longer be achieved.

Example 2: BBC-Effinergie (France)

The BBC-Effinergie label was created jointly by the Ministry of Housing and Effinergie association in 2007. Requirements to obtain the BBC-Effinergie label in new buildings are as follows [5]:

- The global energy consumption in dwellings shall be less than 50 kWh/year/m² multiplied by a factor depending on the altitude and the climate zone, resulting between 40 and 65 kWh/year/m².
- The airtightness must be measured and less or equal to 0.6 $m^3/h.m^2$ under 4 Pa for single-family houses and less or equal to 1 $m^3/h.m^2$ under 4 Pa for multi-family houses.
- The global energy consumption in tertiary buildings shall be 50% less than the level of RT 2005.

For existing buildings, the Ministry of Housing has not yet issued a label.



Primary energy consumption increase due to the deterioration of airtightness in a single-family house (from 0,6 to 1.3 $m^3/h.m^2$) [6]

Effinergie association released a first label on the following bases [5]:

- In dwellings, the global energy consumption shall be less than 80 kWh/year/m^2 multiplied by a factor depending on the altitude and the climate zone, resulting between 64 and 104 kWh/year/m^2.
- The airtightness must be measured and less or equal to 0.8 $m^3/h.m^2$ under 4 Pa for single-family houses and less or equal to 1.3 $m^3/h.m^2$ under 4 Pa for multi-family houses.
- In tertiary buildings, the global energy consumption shall be 40% less than the level of RT 2005.

The calculation of consumption in both cases is performed with tools based on Th-CE rules for new buildings and on Th-CEex for existing buildings. The reference area for the airtightness measurements is the envelope area minus the floor area. Measurements must be performed by authorised technicians.

In low energy buildings, infiltration losses represent an important part in the heat balance. To have the possibility to correct infiltration defects, Effinergie association suggests to make an intermediate measure before closing the casing. The airtightness required for the BBC-Effinergie label is more than double as good as for the notional building (1.3 m^3/hm^2). The saved consumption due to the improvement of the airtightness in a typical family house in cold and hot climate (Nancy and Nice) is presented in the figure on the left.

4 > Conclusions and recommendations

Infiltration losses have a significant influence on the energy use of buildings. The relative influence becomes bigger when the total energy use is lower, e.g. in high performance buildings. Especially in mechanically ventilated buildings the building shell should be airtight. Yet only few EU Member States have requirements for the airtightness for new or existing buildings included in their building codes and only two high performance building definitions could be found that contain specific requirements to the airtightness of the building shell. It was also shown that very low air infiltration rates (< 0.5 1/h at 50 Pa) can be achieved in practice and nearly retained for two years of building use.

Based on the analysis of requirements, but also on earlier information papers on airtightness available on the Building Platform (IP 72 [7] and IP 137 [8]) it is recommended that:

- Member States include airtightness requirements in their national building codes
- Member States add a requirement or at least a recommendation to measure the airtightness of the building during the construction phase in order to find and fix leakages. This would prevent the building from having air leakages that can't be fixed during commissioning.
- Member States add a requirement to measure the airtightness of the building shell after the construction phase before reduced ventilation rates for mechanical ventilated buildings can be used in the calculation of the energy performance (proof of airtightness).
- European standardisation committee proposes airtightness requirements or airtightness classification of buildings. These could include climatic grading.
- Definitions for high performance buildings should include even stronger requirements for the airtightness of the building shell (at least < 1.0 1l/h at 50 Pa)

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Airtightness Testing of Large and Multi-family Buildings in an Energy Performance Regulation Context

In many European countries, the Energy Performance (EP) regulations defined or revised with the implementation of the Energy Performance of Buildings Directive (EPBD) take into account envelope air tightness in their calculation method. This paper discusses subsequent practical issues for large and multi-family buildings, especially regarding the test procedures that must be harmonized to allow a homogenous evaluation of the air tightness value that will be used as input in the EP calculation.

1 > Introduction

The growing interest for airtight building envelope, which is driving a market transformation in some European countries, is very likely to continue and increase. This is due to the potentially large energy savings associated with good envelope airtightness (see for instance information paper P 157) combined with the proven feasibility to achieve much better envelope air tightness than what is observed today in common buildings.

The objective of this paper is to discuss some details concerning the measurement practice, the preparation of the buildings according to what is needed for the energy calculation showing the problems of and finding solutions for unclear definitions for testing separate zones concerning large and multi-family buildings.

General information and in some cases practical information about the handling of large buildings are available by ATTMA (Air tightness testing and measurement association), in a "Technical Standard" *[1]*, by BSRIA *[2] [3]*, ISO 9972 *[4]*, EN 13829 *[5]* and several information papers from AIVC *[6]* and other organisation *[7] [8] [10] [11] [12] [15]* and companies *[9] [13] [14]*.

2 > Background on airtightness measurement of large buildings

To carry out the measurement of large buildings, the natural reference in Europe is EN 13829 [5] that mentions that for buildings whose volume is "approximately greater than 4000 m³", a very large fan or several fan-units can be fitted into the opening(s) of external door(s). It is clear that large buildings involve more work on installing the fan(s) and more organisational tasks in preparing the test *[8,9,10]*. Hundreds of measurements with more than two and up to ten standard fans (fig. 1) or with one single "king size fan" *[10]* (fig. 2) have shown that such tests can be carried out *[11,12]*, in order to test the complete building as one zone. It must be possible to achieve an even pressure distribution in the entire building, e.g. by opening internal doors *[8]*. The pressure differences

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inside should deviate less than 10% from the pressure difference measured between the interior and the exterior. It is important to ensure this throughout the building during the test. Note that the opening size of a normal door (2 m x 1 m) = 20 000 cm^2 creates a pressure difference of only 1 Pascal when 6 000 m^3/h passes through it. Therefore, it usually is not an issue provided that the stack effect (i.e., the pressure difference variation with height) remains negligible.

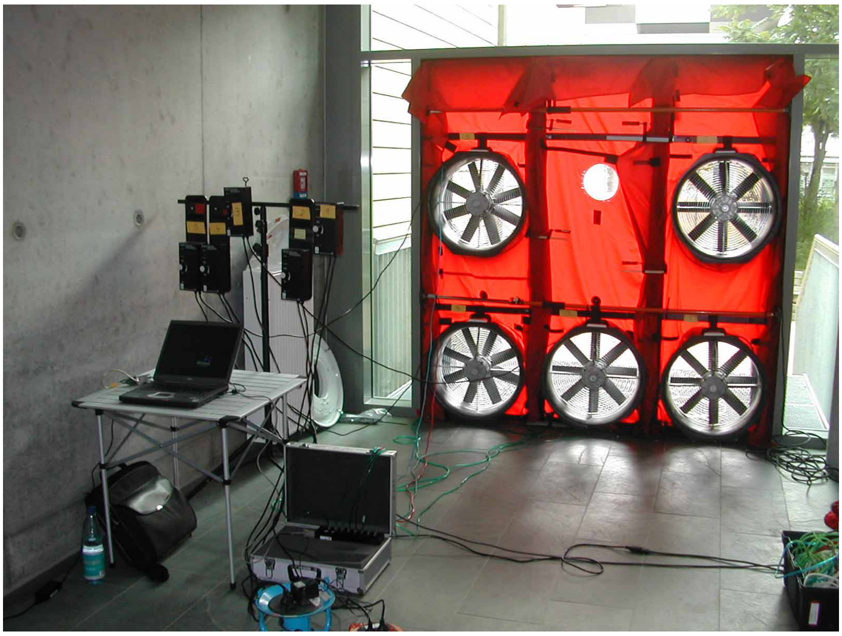

Fig. 1: Installation of 5 single Minneapolis Blower Door. Source: Blower Door GmbH, D, www.blowerdoor.eu

Fig. 2: Mobile fan, King size Fan, Source: www.bsria.co.uk

In practice, buildings as large as 100 000 m^3 can be tested with test equipment available today; if the buildings have an excellent air tightness, such as Passive Houses, it is possible to test volumes as large as 200 000 m³. To illustrate this, assuming one fan supplies 6 000 m³/h, 10 fans supply 60 000 m³/h. Therefore, the largest building that can be tested with 10 fans assuming an airtightness of n_{50} = 1 1/h is 60 000 m³; assuming n_{50}=0.5 1/h, the maximum volume that can be tested is 120 000 m³.

Expressed in terms of air permeability per unit area of exterior walls (q_{50}), a building with an external wall area of 12000 m² and q_{50} = 5 m³/(h m²) can be tested; if q_{50} = 1 m³/(h*m²), the limit goes up to 60 000 m² of external walls.

Organisation of measurement

To limit time and personnel expenditure for the measurement, it is necessary to prepare and organize the test carefully. In particular with large buildings, it is useful to do a site inspection before the measurement *[13]*. This allows the technician to assess the condition of the air barrier, to inspect possible locations for the installation of the measuring devices and to determine where to temporarily seal any openings (e.g., ventilation system). The date for the test is scheduled based on the knowledge acquired during the inspection. If the technician is short of time, it may often have to be scheduled during nights or weekends.

Cost of a measurement

It is always difficult to give a cost range as it can vary considerably between specific contexts, regions and even more between different countries, but it is possible to describe the expense for a measurement of a 10 000 m³ building as follows:

- Organisation, site inspection 3 hours
- Deduction of the apparatus
- Preparation 4 hours of 2 persons,
- Searching for leakage and report 3 hours of 2 persons,
- Measurement half an hour (2 persons),
- Reporting 4 hours.

In summary, the cost is in the region of 22 person-hours plus the deduction of the apparatus.

Overall, there are no major practical problems with the air tightness testing of a large building *[12] [13]*.

3 > Preparation of the building

General

The Standard of EN 13829 describes two types of methods:

- Method A: (test of building in use) means, that the condition of the building envelope should represent its condition during the season in which heating or cooling systems are used. There are no further measures to improve the air tightness. All air terminal devices of mechanical ventilation or air conditioning systems shall be sealed. Other ventilations openings, (e.g. openings for natural ventilation) shall be closed.
- Method B (test of the building envelope): "Any intentional opening in the building envelope shall be closed. All adjustable openings shall be closed and remaining intentional openings shall be sealed. All air terminal devices of mechanical ventilation or air conditioning systems shall and other ventilations openings, (e.g. openings for natural ventilation) shall be sealed."

In most countries, there are no precise guidelines indicating whether method A or B should be used, although EN 13829 can be ambiguous or even misleading. In many cases, method A and B lead to the same building preparation (i.e., the same openings are either closed or sealed) and therefore to the same result. However, there are also many cases where method A and B will lead to radically different results: this can happen in the presence of construction openings (e.g. burning gas outlets, lift shafts).This issue is being discussed in a few countries. The Belgian Building Research Institute has written a paper as a working document explaining the way it is addressed in Belgium; this paper is available at the ASIEPI website.

Preparation of large buildings

With large buildings or multifamily houses, there are in general only a few unclear situations: the large openings to the outside in lift shafts, openings in technical shafts, temporarily turned on ventilation systems (e.g., kitchen exhaust hood), individual combustion appliances that take combustion air from the room. To use the result of the measurement to calculate the heat losses and energy use of the building, these openings must not be sealed (method A) unless their influence is taken into account in the calculation method used. To use the result to prove the airtightness of the envelope, it is possible to seal these openings (method B). Because it may be ambiguous, it is very important to record the temporarily closed and sealed openings in the measurement report.

4 > Evaluation of "air tightness of a whole building" based on tests of separate zones

There are many cases where a building cannot be tested as a whole, for instance, when:
- two floors cannot be connected with an internal airflow path, or
- e.g. 25 apartments (flats) are not connected with an airtight stairwell, or
- the building is too large.

Besides, it is often more practical and less expensive to test a sample of flats in a block rather than to test the whole block as one zone.

In all cases mentioned above, the building must be divided in different areas that are tested separately. There is no widely accepted method to perform and to analyse such tests. In practice, the major issues that are raised include:
- Does the test need to be performed on all building zones?
- If not, how should the tested zones be chosen?
- How should the test be performed on those zones?
- Which airtightness requirements in those zones?

It is clearly not the role of the EPBD to resolve those issues. These should be addressed in standards (e.g., in EN 13 829 / ISO 9972) or guidelines, but this is not the case today.

Besides the described technical reasons there is of course a financial reason why only a fraction of the building zones should be measured. The measurement can be less expensive, e.g. when all identical flats do not have to be checked.

Sampling method under discussion in Germany for multi-family buildings

The current proposal of the Fachverband Luftdichtheit im Bauwesen e.V. (FliB e.V., *www.flib.de*) in Germany (Association for Air Tightness in the Building Industry) in buildings is that at least 20% of the total number of apartments, in a building should be tested. At least one tested apartment should be at the top floor, one at an in-between floor and one at the ground floor.

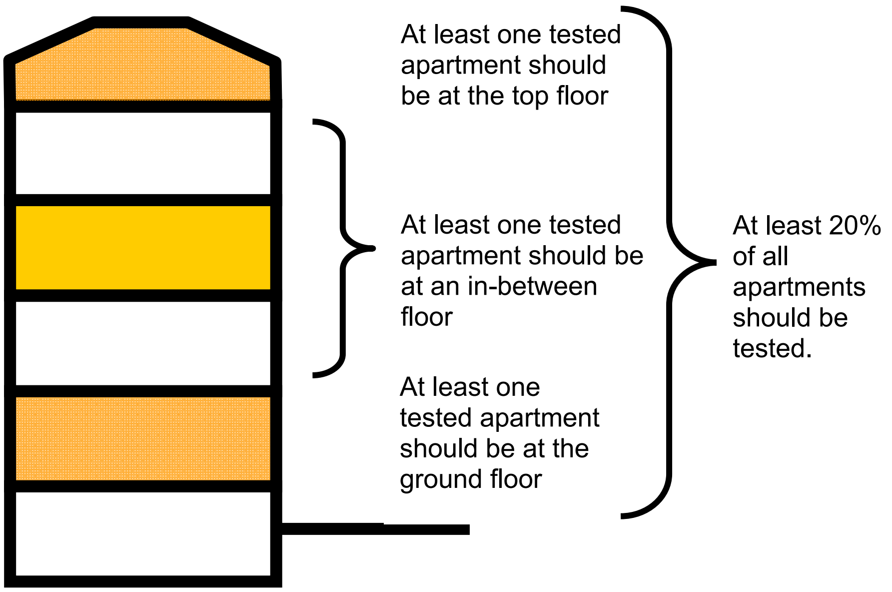

Fig. 3: German proposal of sampling method

Limit values of air tightness for discrete building parts

Regulations standards, or guidelines for the evaluation of the air tightness of the building envelope, have been defined for entire building. On the other hand, when evaluating the measuring results of a building measured in sections, the air permeability measured can include flows through leaks to adjacent, heated or cooled building parts (internal leakage).

Extrapolating measurements after sampling method in Germany

In Germany, (FLiB e.V.) a weighted average from the results in the separate zones can be calculated, based on the volume (or other basis provided that it is consistent with the airtightness metric used) and compared with the limit value required. The zones can be up to 30% leakier than the limit value for the whole building. This is due to the fact that a) the zone measurement takes into account leaks between zones; and b) untested zones can be tighter. On the other hand, it implicitly neglects the fact that untested zones including other apartments, halls, stairwells, etc. can be leakier. In practice, if one zone (flat) exceeds the limit value plus 30%, leaks to neighbouring apartments and leaks to outside must be corrected until readings fall below that value.

This means that conventionally, the weighted average is equivalent to the value that would be measured on the building as a whole.

Sampling methods in other countries

In the UK, zone testing should cover 20% of the building's exterior walls area. The ATTMA rule says that the limit value for every measured flat is 10% smaller than that of the whole building. Thus, unlike in Germany, some provision is taken to account for untested zones including other apartments, halls, stairwells, etc. which can be leakier than the zones measured. Therefore, it is assumed that this 10% margin gives confidence in the achievement of the limit value for the whole building.

An alternative to testing is in UK for a third party expert to carry out a full design review/audit and also carry out site inspections of air barriers. This can be reinforced with some sample testing, whether this is mock-up testing or small zones.

France or Norway also allow zone measurements in some cases, although the methods used do not always have an official status. In France, in multi-family buildings, 3 apartments have to be measured if the building has 30 units or less, 6 apartments otherwise. The sample is chosen based on the length of floors and windows. This sampling rule is being discussed because a) the sample is found to be too small in many cases; and b) floor and window lengths are sometimes ambiguous and complicated to extract.

In France or Germany, by convention, the permeability of the building is extrapolated with the weighted average of the measurements on the sample. Note that in Belgium, such extrapolations not allowed. The measurement must be carried out on the whole building or on each and every part separately.

Guarded zone pressurisation technique

Another approach to perform measurements by separate zones is to create a pressure in the neighbouring rooms/zones equal to pressure in the test room. This method is commonly called the "guarded zone pressurisation technique". This way, air flows between neighbouring zones are prevented, which allows one to measure accurately the air leakage flow rate to outside through the envelope area. In Germany the FLiB proposes that, for the sake of simplicity, such zone measurements can also be up to 30% leakier that the limit value.

Limitations of sample-based methods

The evaluation of the airtightness of the entire building, based on tests on separate zones, has one major fundamental limitation: a very leaky zone which is not selected in the sample tested could lead to radically different conclusions. For instance, the lift shafts and technical shafts are usually ventilated to the outside and can cause significant leaks; in case of multi-family buildings, sampling is generally focussed on apartments, and there can be significant leakage in halls or stairwells for instance. Therefore, a side effect of such sampling methods could be that great attention is paid to building parts that are systematically excluded.

Another limitation lies in the lack of feed-back from the use of the above mentioned methods. It seems that these methods have been derived according to expert intuition but without solid argumentation. In fact, such argumentation would imply costly studies with large measurement campaigns, which in addition may be difficult to conciliate with the agenda of regulation revisions.

5 > Results of the measurements and limit values: q50 instead of n50 for large buildings?

In Germany, the results of the measurements of large buildings almost always meet the requirements stipulated in the German Energy Savings Regulation in terms of air change rates (n_{50}). Experience shows that the n50-values are always significantly lower than for smaller buildings. There are normally two reasons for these seemingly better results. Large buildings usually have less connection points per m² of envelope area, i.e. less possibly critical points, than small buildings. In addition, low A/V ratios (area-to-volume ratio) lead to relatively lower leakage air flow rates for large buildings. In comparison to the large internal volume, the building envelope area through which air can enter or leave the building is relatively small.

Based on this experience, a limit based on the leakage flow rate per m^2 of envelope area (e.g., q_{50}) seems more appropriate than based on the leakage flow rate per m^3 of the building's volume (e.g., n_{50}). The relationship between the n_{50} and q_{50} is:

$n_{50} = q_{50} * (A/V)$

where :
q_{50} is the air permeability divided by the envelope area [$m^3/(h\ m^2)$],
V is the internal volume [m^3],
A is the envelope area [m^2], and
n_{50} is the air change rate at 50 Pa [1/h].

Figure 4 shows the correlation between n_{50} and q_{50} for various values of the A/V ratio. The different A/V ratios are based on examples of different types of buildings:
1.2 for a bungalow (366 m^3);
0.8 for a single family house (600 m^3);
0.5 for a small multi-family building (2600 m^3);
0.3 for a multi-family building (10000 m^3);
0.2 for a storage building (42000 m^3).

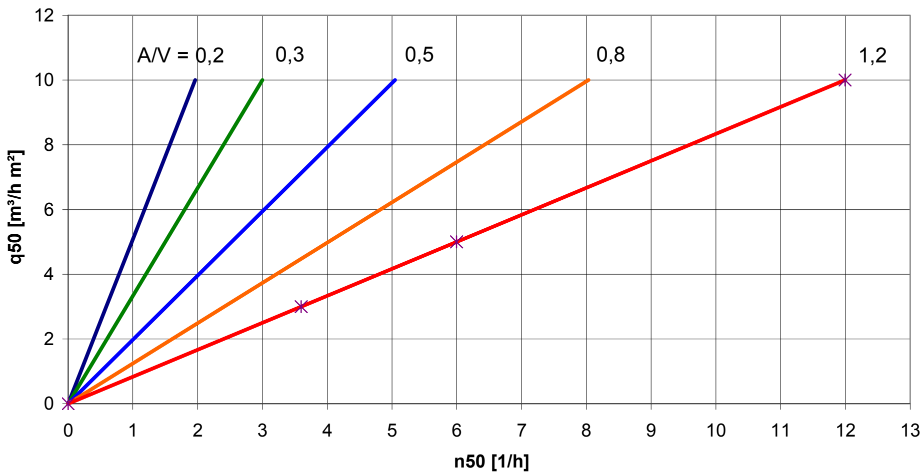

Fig. 4: Comparison between n_{50} and q_{50}. Example: a large building with A/V = 0.2 and with q50 = 5 corresponds to n_{50} = 1 h^{-1}.

If we establish a direct correspondence between q_{50} and n_{50} values based on q_{50} the limit value of 3.0 $m^3/(h{\cdot}m^2)$ for residences recommended in the German Standard DIN 4108-7 and the above A/V ratios, we obtain for instance :
$n_{50} \leq 1.5$ [1/h] for an A/V ratio of 0.5 (small multi-family building);
$n_{50} \leq 0.9$ [1/h] for an A/V ratio of 0.3 (multi-family building);
$n_{50} \leq 0.6$ [1/h] for an A/V ratio of 0.2 (storage building);

The same exercise for a q_{50} limit value of 1.25 $m^3/(h{\cdot}m^2)$ (which is achievable in single family houses since it corresponds to n_{50} = 1 1/h would have lead to n_{50} values of 0.63, 0.38 and 0.25 respectively.

The problem remains to define the appropriate limit values, but this cannot be done at an EU-scale, since should take into account climate and usage, which are key parameters influencing the impact of envelope leakage.

6 > Conclusions and recommendations

The major issue here is to be able to evaluate the airtightness of large or multi-family buildings so it can be used as an input in the calculation

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method or as proof of compliance; and to have a set of clearly defined rules that are robust in case of legal disputes.

Significantly different methods are used in some countries to overcome this problem. They should be evaluated to make sure that they do not generate problems in practice. Then they should be harmonised and find there way into regulations.

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Duct System Air Leakage — How Scandinavia tackled the problem

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Fig. 1 System with failed tape, and omitted fasteners, in USA [© Weldin Engineering]

Fig. 2 Circular ducts in a compact Norwegian plant room [foto: SINTEF]

Apart from Scandinavia, many countries in Europe have generally very leaky ventilation systems [16]. 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 is no commissioning.

Conversely, in Scandinavia, 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 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.

This paper describes the Scandinavian approach, giving recommendations on how it can be adopted in other countries. More details are given in the full ASIEPI WP5 Technical Report [1]. This paper focuses on metal ductwork, but mentions other materials.

1 > Today's situation

Duct airtightness classes A to D (see Fig.3) are defined in European Standard EN 12237 [10] for circular ducts and EN 1507 [6] for rectangular ducts. A new standard for airtightness of ductwork components is in preparation: prEN 15727 [14]. The leakage test method for system commissioning is described in EN 12599 [11]. Airtightness classes for air handling units (L1 to L3) are defined in EN 1886 [7]. ASHRAE's classes are different. System standards, in particular EN 13779 [12], give further recommendations for airtightness class selection for different purposes.

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

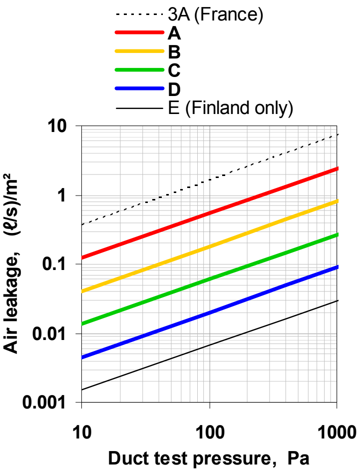

Fig.3 Illustration of duct leakage classes listed in Table 1 (with exponent 0.65) Special classes in France (3A) and Finland (E) are also shown

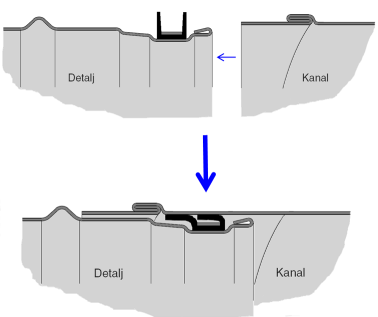

Fig.4 Cross section of circular duct joint with double gasket, giving airtightness Class D. Single gaskets generally achieve Class C, but there are other factors that affect airtightness, such as roundness and flatness of seams at the joints. [Lindab]

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*' [3] which give recommendations for duct systems and its commissioning. This consolidated a common stance on ductwork airtightness in Scandinavia.

90~95% of ductwork installed in Scandinavia is spiral-seam steel circular ducts (Fig.2) with factory-fitted sealing gaskets (Fig.4), 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[9]. 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 certified by 3rd-party laboratories.

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[2]. 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 [13]. 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 (Fig.4).

VVS AMA requirements on commissioning of duct systems

- This is done by HVAC contractors as part of the contract. AMA requires contractors 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 motivates contractors to ensure that the work is done properly in the first place.

Fig.5 Collar saddle for in-situ tees [source: L.A.Matsson]

Fig.6 Factory made tee with low flow resistance and airtightness Class D (©Lindab)

Fig.7 Rectangular duct with standard length [Lindab]

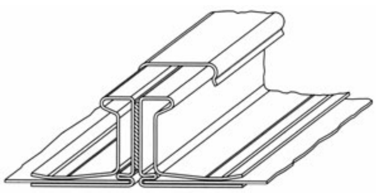

Fig.8 Close up cross-section of a flange for connecting two rectangular ducts. Cleat slides on the top to hold the two flanges together.

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.

Norway

The building regulations state merely that *"Ducts and air-handling units shall be satisfactorily airtight"*. Neither the building regulations, nor the national standard for building specs (NS 3420), give quantitative minimum requirements for airtightness; so it is up to the building owner to specify in each case. In practice, the specified minimum requirement is normally Class B [20]. 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 common until the mid 1990s. Norway has exactly the same commissioning approach as AMA. Since the 1990s, testing has become uncommon as it is now rarely a contractual obligation. Nevertheless, major ventilation contractors still recommend their own employees to perform pressure tests on their own systems to uncover installation faults at an early stage of construction, not just before handing 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.
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 in the Scandinavian market. 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[25]. Air leakage can amount to 5~7 % of the total ventilation flow rate in a commercial Norwegian building[21]. 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 [24]. Examples are flexible ducts, plenum collars, VAV-box collars, and pressed saddle taps (Fig.5)[22][25]. The latter are a popular alternative to tee pieces (Fig.6, which are both more airtight and aerodynamic) because they simplify fitting, but poor workmanship can leave gaps between the collar and the duct.

Finland

The Finnish situation 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. 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.

For commissioning, Finland has adopted the Swedish principle of random tests but permits random tests if the duct system components are Class C or better. The random tests shall cover 20% of the ductwork surface area in the case of Class C, and 10% in the case of Class D or better. 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.

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.

Denmark

The Danish code of practice for mechanical ventilation installations is DS 447 [5]. 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 at commissioning. Systems normally fulfill at least Class B and often Class C, just as in Norway and Finland.

Other countries

In other European countries, rectangular ducts are more common than in Scandinavia. Flange systems (Fig.7 & Fig.8) are often used with metallic rectangular ducts and with other components that need to be dismantled regularly for maintenance. Round ducts are still generally sealed in-situ using duct tape (Fig.11) 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 (Fig.9). 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 (Fig.10 & Fig.1) can fail or loosen with age [22]. In conclusion, ductwork airtightness in these countries depends a lot on workmanship and materials.

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[16][18]. Field studies suggest that duct systems in Belgium and in France are typically 3 times leakier than Class A (Fig.12). Studies in USA show a similar or worse pattern [24]. Analysis of specific cases indicates that leakage drastically affects overall system performance. Duct leakage therefore probably has a large energy impact outside of Scandinavia.

2 > Other duct materials

Besides metal ducts, other available duct types include:

- *Rigid insulation ducts*: These can be rectangular (made of 'duct-board', Fig.9) or round (Fig.13). 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 [22][24].

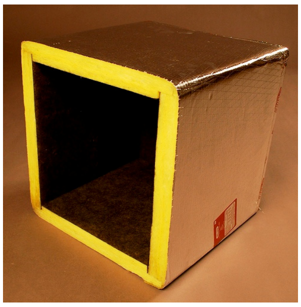

Fig.9 Example of duct-board

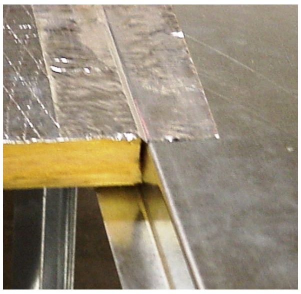

Fig.10 Duct-board tape seal

Fig.11 Conventional duct tape (i.e., fabric-backed tape with natural rubber adhesive) fails more rapidly than all other duct sealants [22]. It has also been shown that the trade standard for advanced tapes (UL 181) does not guarantee durability [22].

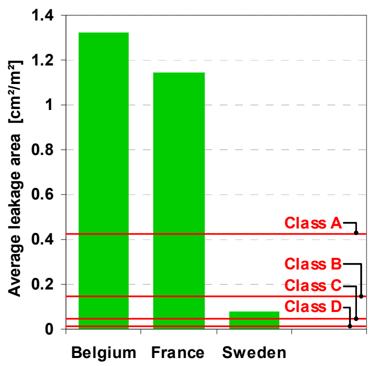

Fig.12 Comparison of average measured duct leakage in Belgium, France & Sweden [16]

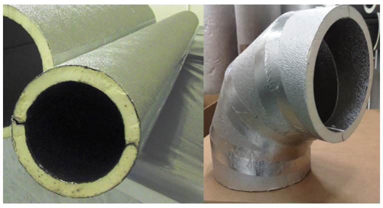

Fig.13 Round foam duct

Fig.14 Flexible duct

Fig.15 Round plastic duct [23]

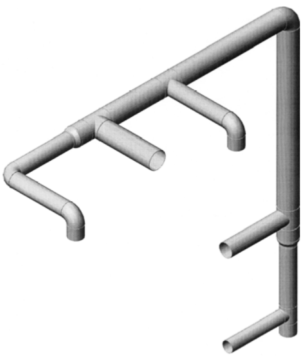

Fig.16 Round plastic duct system with Class C [23]

Fig.17 Example of a machine for manufacturing spiral ducts [Spiro Tubeformer]

In addition, the clamps required by the trade standard (UL 181[4]) can fail and their durability has been questioned [22]. Good airtightness can potentially be achieved with durable mastics applied with by good workmanship. In this case, round insulated foam ducts (Fig.13, which can achieve airtightness Class C when new) may share many of the benefits of round metal ductwork.

- *Flexible round ducts* (Fig.14): 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 ductboard, they flexible ducts pose a challenge with respect to achieving airtight connections (see [22]).
- *Plastic ducts* (Fig.15): Round plastic ducts exhibit the same benefits as round metal ducts. Because of their flamibility, 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 poly-propylene, with many components (bends, tees etc., Fig.16) available with the same self-sealing joint that achieves Class C airtightness [23]. Other types of plastic ducts are used for underground ductwork, with watertight joints, because of their corrosion resistance.

3 > HOW DID WE GET TO WHERE WE ARE? The evolution of duct airtightness in the last 50 years

Here we summarize the chain of events that led to the solution of the ductwork airtightness problem in Scandinavia [15][16]. More details are given in the full ASIEPI WP5 report [1]. The problem of leakage was first identified in the 1950s, when mainly rectangular, prepared on site, and little attention was given to airtightness, balancing, or energy performance. This decade also saw the world's first Spiro Tubeformer (Fig.17), a machine for making revolutionary spiral ductwork. In 1966 the seminal AMA defined two airtightness 'norms' A and B, to be spot-checked by the contractor. The 1970s and 80s saw growing use of round ductwork, and further breakthroughs in product quality, such as rubber gaskets which replaced putty and tape that had been used before. Airtightness Class C was introduced in the 1983 revision of AMA; later Class D was added in 1998. In the early 2000s CEN standards on airtightness were published, based largely on Nordic experiences.

4 > 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) compliance testing. Obviously, if quality is not demanded, there are no penalties or incentives, and no checks made, quality will not be provided [15].

(i) 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[16] 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.

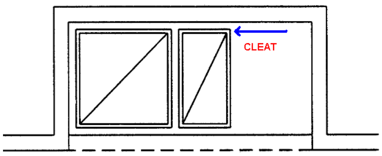

Fig.18 The need for access space to install cleats makes it difficult to use the whole shaft area with rectangular ducts [16]

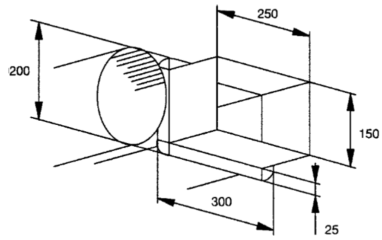

Fig.19 Rectangular duct (with flanges) and circular duct with same height requirement and same free duct area [16]

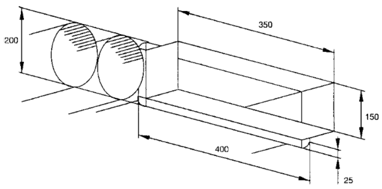

Fig.20 A flat rectangular duct can often be replaced by several parallel round ducts. The example here shows equal height and free duct area [16]

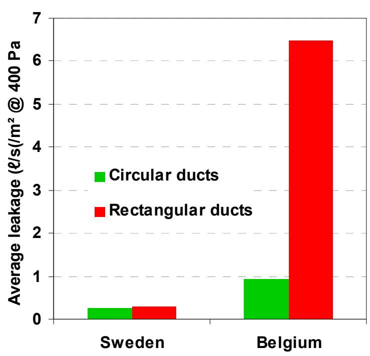

Fig.21 Rectangular versus circular ductwork in Sweden and Belgium [16]

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 (Fig.18). 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 (Fig.19 & Fig.20) [17].
- 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 [17]). If considered early in the design phase, it is possible to influence the architectural planning to ensure sufficient space for round ductwork.

Leakage

- Fig.21 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.
- Round ducts are tighter. Larger duct systems (≥ 50 m^2 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 (Fig.22 & Fig.23). 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.

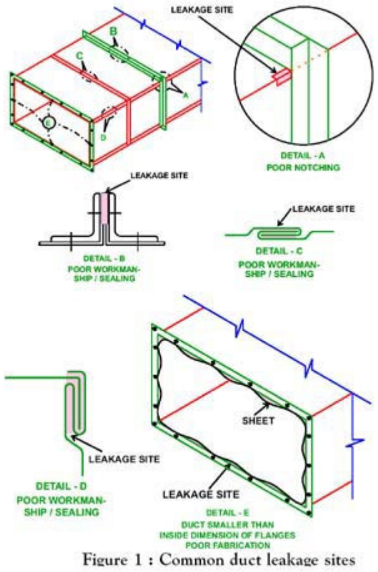

Fig.22 Illustration of typical leakage points for rectangular ductwork [source: AC&R J.]

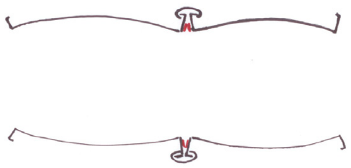

Fig.23 Cross section of a rectangular duct under pressure – causing the flange gasket seal to open [source: L.A.Matsson]

Fig.24

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 [19]. 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 [19].
- The overall cost (sum of material and assembly costs) is normally lower, approximately by 25% [19], 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.

(ii) Establish guidelines & requirements, ideally with incentives

Trade guidelines

Each country should establish trade norm or requirements on duct systems in verifiable terms. This should be referred to/specified in tender and contract documents.

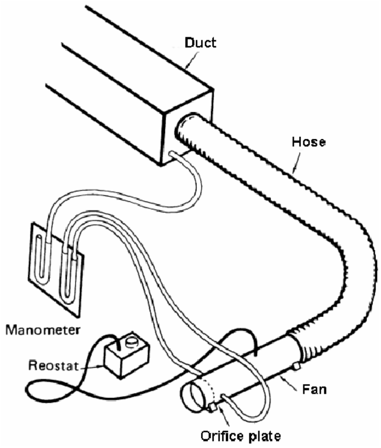

Fig.25 Illustration of test setup for leakage testing [20]

Energy performance requirements

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.

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.

(iii) 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. VVS AMA is a very good model to use.

Fig.26 Example of Scandinavian duct leakage testing equipment [Swema]

Fig.27 Another example of Scandinavian duct leakage testing equipment [Lindab]

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and Community Systems Programme

Air Infiltration and Ventilation Centre

An overview of national trends in envelope and ductwork airtightness

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1 Introduction

This paper summarises presentations and discussions that took place during the workshop entitled " Trends in national building ventilation markets and drivers for change" held in Ghent, Belgium, in march 2008 with a specific focus on envelope and ductwork airtightness. Before this workshop, experts were asked to provide information regarding the trends in ventilation in their country and the difficulties they felt to improve the situation in terms of market penetration of innovative systems, indoor air quality and energy use requirements, and compliance check schemes. This has resulted in a set of Ventilation Information Papers published in the same series. Based mostly on these papers and on the workshop discussions, this paper starts summarising energy savings estimates and energy regulation measures ; it continues with a number of issues that have been stressed by the experts such as indoor air quality impacts, airflows through insulation layers, airtightness databases and metrics, and finally, ways to explore to achieve good airtightness.

2 Estimates of energy impacts

One key reason behind the interest for envelope and ductwork leakage lies in their potential impact on the energy performance of a building. Three countries provided quantified information with this regard for the workshop. In Belgium and in Germany, it is estimated that envelope airtightness accounts for about 10% of the energy performance level. In addition, these countries estimated that the potential benefit of better envelope airtightness is similar to the installation of solar collectors. These orders of magnitude apply also to France, where the energy wastage due to envelope leakage lies between 2 to 5 kWh/m^2/year per unit of n_{50} for the heating needs. For ductwork airtightness, the range is 0 to 5 kWh/m^2/year for the heating needs; in addition, fans also use more electricity in leaky ductwork systems. In the US, there exists a significant body of literature on duct leakage with rough estimates of 10 kWh/m^2/year for commercial buildings on the fan energy use. A typical California house with ducts located in the attic or crawlspace wastes approximately 20% of heating and cooling energy through leaks and draws approximately 0.5 kW more electricity during peak cooling periods.

Figure 1 gives some examples of the impact of envelope leakage on the energy consumption in France. These estimates are based on the EP-calculation method, which includes an hourly simulation of the thermal behaviour of the building as well as a pressure-network code based on EN 13465 to calculate the airflow rates.

3 A growing concern in many countries

Envelope and, to a lesser extent, ductwork airtightness are taken into account in the energy performance calculation methods in many countries. These concerns have probably grown due to the uptake of low-energy buildings and their actual impact on the energy performance, as shown above. In sum, only 4 countries out of the 16 represented during the workshop have not included envelope airtightness in their EP-calculation procedure, two of them stating that it was probably not a critical issue due to local standard building practice.

Among the other 12 countries, there remains significant differences in the way envelope airtightness is taken into account. Most of the time, it is possible to reward good envelope

airtightness as it results in a lower "regulatory" energy consumption. However, in some cases (PL, PT, JP), specific requirements apply to components such as windows. Some countries also have minimum requirement (e.g. DE, NO), but only the UK has compulsory testing of new buildings.

As regards ductwork airtightness, four countries represented (BE, FR, UK, USA) take into account the impact of leaky ductwork in their energy calculation procedure, although it is sometimes limited to some building types. Note that ductwork leakage has been identified as a major source of energy wastage in Nordic countries (DK, NO, FI) for several decades. It has been resolved with the widespread use of duct components with pre-fitted joints and therefore, does not seem to be a critical issue in these countries.

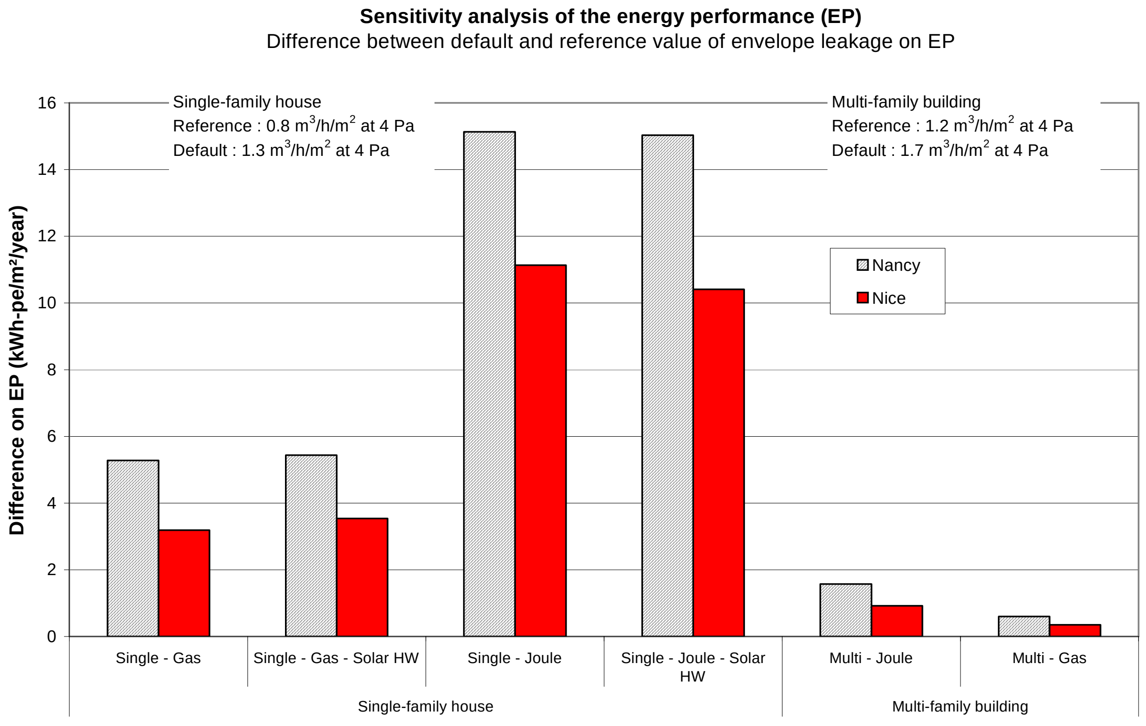

Figure 1: Examples of the energy impact (in kWh of primary energy) of envelope leakage in a single-family house and a multi-family building for the climates of Nancy and Nice (France), for extract-only relative humidity controlled ventilation systems.

4 Compliance

The compliance scheme to the regulation 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, this is done only in the UK, where envelope pressurisation tests are compulsory since 2006 in all new buildings. This requirement extends the previous one in force since 2002 for large buildings (over 1000 m^2). 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 exists alternative routes to pressurisation tests. Quality management approaches are rewarded in Finland and in France. In other words, if a builder can prove 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.

An alternative route had been explored in the UK as well some years ago, 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 details. These approaches appear similar in principle, but they include important differences in their implementations. Therefore, especially if found successful, these approaches should be carefully evaluated, in particular to identify the keys to success and barriers, so that other countries could benefit from their experience.

5 Envelope airtightness and indoor air quality (IAQ)

Several countries have stressed in their presentation the link between envelope airtightness and indoor air quality. Indeed, good airtightness can help better ventilate a building, provided that an adequate ventilation system be installed, which is not always the case. Therefore, there appears to be frequent problems in renovation of existing buildings originally ventilated by building leaks in the Czech Republic or in Poland. The replacement of windows with more energy-efficient and tighter ones can drastically reduce the infiltration rate and therefore the ventilation rate in the building. These problems have also been identified in France in the 1980s. For this, the new regulation for existing buildings requires that provisions be taken to assure that ventilation is not impaired by the replacement of windows. This translates most of the time into self-regulating air inlets integrated in the window frame, unless a balanced mechanical ventilation system is installed.

IAQ problems associated with under-ventilated residences were mentioned in the USA as well : in new tighter buildings, the ventilation requirements remain very low although the ventilation air provided through building leaks is significantly lower than the infiltration rate in older and leakier buildings. Besides, the traditional assumption that people open their window and use natural ventilation to supplement does not hold any longer.

6 Airflows through insulation layers

In Japan, the reduction of the thermal resistance of insulation materials has been identified as the first reason to address airtightness. In fact, laboratory experiments performed in Germany on a 1 x 1 x 0.14 m insulation panel have demonstrated that air flowing through the panel because of a 1 m x 1 mm slot could reduce the thermal resistance by a factor of 4.8. Therefore the thermal performance of insulation exposed to outdoor air, for instance, in ventilated attics or crawlspaces, installed on the exterior part of a façade, or even installed internally, can be significantly affected. This remark is not relevant when a dynamic insulation strategy is used because the degradation of the thermal resistance is expected to be compensated by the heat recovered as the air flows through the insulation material.

Good airtightness is also desirable to prevent condensation damages due to exfiltrations. Indoor warm air gets colder as it flows out through an insulation layer. In this process, condensation within the insulation may occur. This aspect has been stressed in the Japanese presentation only, but it has been identified in the past in many other countries as well.

7 Airtightness status and monitoring

7.1 Databases

Although many tests may be performed in some countries, the data is rarely collected. This work has been performed in the USA where over 100 000 tests have been integrated in a database. It is envisioned in Germany : a database should be operational in 2009.

There are many ways such databases can be used: one is to provide a status on envelope and ductwork airtightness ; another one may be to monitor the progress over time, for example due to regulations or other incentives ; a third one may be to back out statistical models to estimate the envelope or ductwork leakage to help refine regulations.

Apart from the USA and Germany, the data collection schemes seem limited to some research data. The likely uptake of pressurisation tests in some countries could be an excellent opportunity to set up national schemes to collect airtightness data.

7.2 Comparing envelope airtightness between countries : a difficult exercise

It would be very useful to compare airtightness levels observed, recommended, or required between countries. However, although there exists an international and European standard covering envelope airtightness, there exists an array of metrics adopted locally. These metrics usually comply with the standards that define three different possibilities to normalize the leakage flow rate usually estimated at 50 Pa:

- the infiltration airflow rate divided by the internal volume gives the n_{50} in air changes per hour at 50 Pa;
- when divided by the cold wall surface area, one obtains the q_{50} in $m^3/h/m^2$;
- w_{50}, expressed in $m^3/h/m^2$, is derived by normalizing to the heated floor area.

The key advantage of the n_{50} is that it can be easily used as an input in an airflow simulation tool in which the volume is usually necessary to evaluate the dynamic behaviour of contaminants. However, this is not the case in thermal simulation tools that do not require the building volume as an input to calculate the energy use. In such tools, the surface area of cold walls is usually known, which explains why some countries use the q_{50} in their regulation. On the other hand, the rationale behind the w_{50} metric lies in the ease to have access or calculate the floor area.

One common problem of these indicators is that, although they are specified in the standard, there remains some variation between countries or even regions or technicians in their precise definition. For example, standard EN 13829 states that the floor area used to calculate w_{50} is calculated according to national regulations. In some countries, the cold wall surface area used to derive q_{50} includes the lower floor whereas this area is excluded in others. Finally, because building shapes are often complex, the volume calculation may differ between operators.

Still, it was concluded that the n_{50} was probably the most appropriate indicator for international comparisons, although some other indicator may be used in the EP regulation. Therefore, it would be relevant to give some guidance on the volume calculation beyond those stated in EN 13829 to enhance the reliability of the n_{50}s reported.

7.3 Method A or B ?

EN 13829 describes two methods to perform a pressurisation test named methods A and B (the newest version of ISO 9972 mentions 3 methods). The key difference between the methods lies in the openings that are sealed for testing. Method A assumes that the heating or cooling systems are left operational, whereas all intentional openings must be closed or sealed for method B. Of course, the choice of method A or B may lead to major differences in the measured airtightness, for instance, if a fireplace damper is sealed, closed, or left open. (This is why publications should systematically indicate the method used.)

There may be good reasons for using either methods. For example, if the EP calculation includes the effect of a given opening, it is relevant to seal it for the test to use the measured airtightness as an input. However, in most countries, there does not seem to be information available on this subject for technicians who perform tests. The only publicly available information we found is a paper recently published in Belgium (Delmotte, 2007).

Therefore, work is needed to guide technicians in their measurements beyond EN 13829. This aspect is also important both to estimate correctly envelope leakage impacts for a specific building with an energy calculation tool, and to compare airtightness results between constructions.

8 Ways to stimulate good envelope and ductwork airtightness

With regard to envelope leakage, most regulations put emphasis on the result, i.e., a good airtightness can be rewarded (sometimes significantly as shown in

In most countries not familiar with this process, a learning phase seems necessary a) to raise awareness among prescribers, designers, and craftsmen; and b), to provide tools to designers to help them design adequate junctions. This phase can be accelerated locally, in particular with technical conferences with these specific target groups and adequate training of designers who are well placed to forward this message to craftsmen. The success of the local events recently held in France with a specific focus on this issue, some being supported locally by low-energy buildings programmes, is very interesting with this respect. Over 700 persons have participated to 5 events held in various regions. These have contributed to a growing demand by the designers themselves for practical tools to design and achieve good airtightness. The actual result will heavily depend on the capacity of designers to effectively integrate this issue.

As regards ductwork airtightness, the situation is more confusing: excellent ductwork airtightness seems common in Scandinavian countries with the widespread use of duct components with pre-fitted seals, although this aspect may not be pushed by regulations; some countries (BE, FR, USA) reward good ductwork airtightness in their energy performance regulations but have poor results; other countries do not consider ductwork airtightness in their regulations and are likely to have poor results. Maybe the design plays an important role: the use of duct components with pre-fitted seals is clearly a relevant answer to the problem, but it requires a more careful design as these components cannot be used with as much flexibility as raw components. For example, the benefit of a pre-fitted tee-junction vanishes if the component has to be customized on site because a water pipe is in the way. Probably, designers' training can contribute to improve the situation.

9 Conclusions

The stimulation of good envelope or ductwork airtightness should not rely uniquely on regulatory measures that reward good results. Experiences in different countries show that awareness raising and training among prescribers, designers and craftsmen is essential to trigger a market transformation, beyond regulatory measures. It seems that the envelope airtightness market is changing in some countries that go in this direction, or at least that there is a growing interest on this subject. With few exceptions, this does not seem to be the case with ductwork airtightness, although some regulatory measures may have been taken. However, most of these experiences are very recent and the overall schemes set up to improve airtightness have not been evaluated yet. A careful evaluation of these schemes, including the analysis of measurement datasets and impact of training programmes, would be very beneficial to the countries themselves as well to other countries that could be inspired by success stories.

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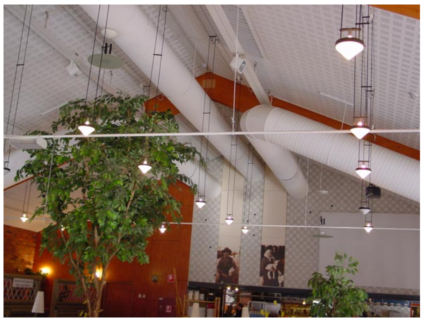
4.1031/Z/99-158

AIRWAYS

Source book for efficient air duct systems in Europe

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TIGHTVENT 73

FOREWORD

This document was written within the framework of the European AIRWAYS project (Save II program - Project 4.1031/Z/99-158 – DG TREN).

SAVE is the European Union non-technology energy efficiency programme.
One of the goals of this programme is the implementation and completion of Community-wide measures taken to improve energy efficiency in the domain of buildings.

The objective of the AIRWAYS project is to provide guidance for designing and maintain energy efficient air duct systems, and bringing to light energy saving opportunities in parallel to health, safety, and comfort issues.

This book is targeted at decision-makers concerned with indoor climate issues, including policy makers, architects, and designers. It provides condensed information on reasons behind better air duct system design and how this can be achieved.

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Thanks are also due to the external organisations that provided pictures to illustrate the present book:

- ABB
- Aldes
- Bergschenhoek BV
- Lindab

Link to an other document

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HOW SHOULD THIS BOOK AND THE ENCLOSED CD-ROM BE USED

This book presents a global approach to the design of efficient air duct systems and is available in both a printed version and an electronic version on CD-ROM.

The technical note on ductwork for ventilation systems, produced in the name of the Airways project, is not available in a printed version but is available on CD-ROM. [Ref 6]

Check lists for important design issues are available in printed form in the book and also available in printable form on the CD-ROM. They are intended to be used in the practical design of ventilation systems.

The documents on the CD-ROM have been recorded in PDF-format. You need Adobe® Acrobat® Reader (version 4.0 or later) to be able to read the PDF files.

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TABLE OF CONTENTS

1 INTRODUCTION

One aim of this source book is to increase HVAC designer awareness of the important role the ductwork plays with respect to function, costs and energy use of the HVAC system. Another aim is to point out the connection and co-operation that is necessary between the HVAC designer and the architect when working with building design and space requirements. To illustrate how this can be done the book provides case studies demonstrating good examples and, in a few cases, less fortunate examples (§ 12).

1.1 WHY IS IT IMPORTANT TO DESIGN A WELL-FUNCTIONING DUCTWORK?

1.1.1 General

This chapter describes some of the philosophies behind the design of a ventilation system, the ways to decide upon correct airflow and the importance of guaranteeing that the air really will be of use. The ductwork thereby plays a most important role in safeguarding air quality, good thermal climate and occupant wellbeing.

As soon as a ventilation system is connected to more than one room, there is a need for a distribution system – a ductwork – to connect the different rooms to air-handling units and extract fans. The airflow that is decided suitable for ventilation and thermal comfort reasons has to be transported to and from the rooms. The air distribution to and from the rooms – the supply and extract air flows – has to be adjusted to the correct values by achieving correct pressure drops through the pressure resistance in ducts, dampers, registers, air terminal devices, and other ductwork components.

As described in this book there are many ways whereby a duct system will function in a less efficient way. The air flow distribution might differ due to influence from wind and outdoor temperature (§ 3.3), air may leak into and out of the ducts through small holes (§ 4.2), high air velocities might create unwanted noise (§ 7.8), dust and other impurities in the duct system might cause health problems unless dealt with (§ 7.4). These and other factors should be taken into consideration during design, installation and maintenance of the duct system and the following chapters will show how this can be done in order to achieve an efficient and well functioning duct system at a low investment and low life cycle cost.

1.1.2 The air should be transported to the areas in the building where it is most needed

Air transport is often necessary for maintaining good air quality in a room. The ventilation calculation is thus normally based on an assumed emission of CO_2 and moisture from occupants, dust and gases emitted from furnishings, furniture, interior surfaces and activities. In this case the airflow is needed to dilute the emissions and transport them out of the room.

The other main reason why transporting air to and from a room might be needed is to control the thermal climate. In this case transporting heat to or from the room with the air controls the room temperature. If the room needs to be cooled, the excess heat will be carried out of the room by supplying air at a lower temperature than the desired room temperature. If the room needs to be heated this will be done by supplying air at a higher temperature than the desired room temperature.

In both cases - air quality or thermal climate - the airflow is calculated to correspond to the assumed loads of emissions or, similarly, to the heat/cold load. A given heat/cold load and a suitable temperature difference between the supply and the room temperatures will correspond to a required airflow. A given or calculated emission load and an acceptable emission level increase between the supply and the room concentration levels will similarly also correspond to a required airflow.

It is therefore vital that the correct airflow is transported to and from the rooms accordingly. To be efficient, the air should neither be allowed to leave the supply duct nor be allowed to enter the extract ducts through leakage openings. It is hence important that the airflow is adjusted to the correct values before the plant is taken into operation.

The ways of adjusting the airflow and the different methods to measure airflow in ducts and at registers with an acceptable amount of accuracy is also described in this book (§ 10.4).

1.1.3 Air quality – emissions should be diluted and safely transported from the rooms

"*Dilution is not the only solution to pollution*" [1]. This means that the first way to reduce high and unhealthy pollution levels in rooms should be by reducing the strength of the emissions sources – by choosing low emitting materials and components wherever possible. There are many national and international research programs in operation for labelling building and interior materials. These take the emission to the room air during normal operation into consideration.

[1] This good rule was defined at the first international conference on Healthy Buildings (Stockholm 1988).

Today's' knowledge on this still lacks maturity. However, in time, this approach might be used to calculate airflow rates based on IAQ demands. Hereby the cost for higher ventilation airflow could be compared to the initial, operating, and Life Cycle cost of less emitting furnishings and finishing materials

If the emissions are due to activities in a room it is important to prevent the hazardous or disagreeable pollutants from being inhaled by the occupants. The air has thus to be supplied to and extracted from the rooms with this in mind. The air should be supplied to the part or the room where occupants are to be found while the air should be extracted from that part of the room where the highest concentration of pollutants can be expected (e.g. at the kitchen stove, above polluting machines). This safety in preventing hazardous pollutants to enter breathing zones can be still increased if the source of pollution is enclosed to a high degree only leaving small openings for the extract air to enter. The under-pressure in the enclosure or hood compared to the ambient pressure in the room makes it hard for the pollutants to enter the room. There are many articles and handbooks covering this item. One common principle is that the design of the hood should take into account the laws of nature. If the emitted pollutant is warmer than the room temperature, the hood (e.g. a kitchen hood) should be located above the pollution source to be able to take care of the upward air movement. If the pollutant (e.g. particles emitted from a grinding machine) is released with a velocity the hood should mainly be covering the area in the direction of the pollution flow. A commonly used metaphor is the goalkeeper's glove – to catch the ball where it arrives.

1.2 THERMAL COMFORT – NO DRAUGHT

Ventilation air is used as an aid to creating a better thermal indoor climate by transporting excess, or lack of, heat and moisture out of or to the room respectively. But this advantage is often reduced by simultaneous disadvantages from the same air. It might create disagreeable fast air movements in the room. In wintertime a person is more sensitive to draught than in summer. In winter the acceptable air velocity is normally below 0.15 m/s while in summer – when the air movement is often longed-for and agreeable due to the higher room temperature - the maximum air velocity is normally 0.25 m/s.

This influences the choice of ventilation system. The air is supplied to the room via supply air registers that have to be chosen in such a way that the corresponding air velocity in the occupied zone is acceptable. This determines the size and number of the registers and the distance between them and to the occupants. Displacement ventilation systems, where the supply air is delivered at a lower temperature and at floor level might be more difficult to design than a mixing ventilation system.

The ultimate goal for the design of a ventilation and air handling system is to satisfy the needs and wishes of the occupants without creating any inconveniences like draught or noise. It stands to reason but is not always the case; this book points out some of the problems that should be examined – before they become problems!

1.3 LOW ENERGY USE

The energy use of a ventilation system should be reduced as much as possible without decreasing the benefits of the system regarding thermal comfort and indoor air quality. The annual energy needed for transporting the ventilation air through the system is proportional to the fan power and the number of operation hours per year.

Both these values can be influenced. The fan power is proportional to the airflow and the total pressure difference through the system and inversely proportional to the efficiency of the fan with its motor.

Normally the pressure drop in the system is roughly equally distributed between the air handling unit and the duct system. How the latter is calculated is described more in detail below (§ 7.3), where it is shown that the pressure drop increases with the square of the air velocity. By keeping low air velocities in the ducts, i.e. choosing ductwork with ample dimensions, the energy can thus be reduced which, if the annual number of operation hours is high, will lead to substantial energy savings. Another advantage of low air velocities in the ductwork is that the risk of emitting noise from the ductwork is diminished.

Often the supply air is heated or cooled before being supplied to the room. If the ducts are properly insulated, the temperature difference will be kept between the air in the duct and the cooler or hotter surroundings of the ductwork. This will reduce the need for any extra thermal energy input in the air handling units to cover thermal losses.

In both these cases – i.e. reducing the transport energy by sizing the ductwork and reducing the thermal losses by insulating the ductwork – the investment cost will be higher than the one for a poorer installation.

As the ducts probably will be used for many years these possible energy and cost savings vs. the extra investments should be considered on a Life Cycle Basis – discussed below (§ 6.3).

1.4 AVOID NOISE TRANSMISSION THROUGH THE DUCTWORK

Ducts are normally connected to adjacent rooms which might create an unnecessary path for noise to be transmitted between them. During normal operation when the fans are running this is not normally a problem but should they be stopped e.g. after normal office hours, conversation in one room might be overheard in the other. In cases where there are more strict requirements on privacy between rooms, the ducts have to be designed and installed in a way that corresponds to the chosen sound insulation of the adjacent wall. One of the case studies presented in this book (§12) shows how this can be done in a building with very high demands on privacy between rooms.

1.5 DO THE DUCTS HAVE TO BE HIDDEN?

There is a trend among some architects today to let part of the building installations be visual to the user. They regard that the installations are necessary for the function of the building and not something that has to be hidden. One of the case studies in this book (§ 12) could be seen as an example of this trend. The brightly coloured circular ducts are running up through atria in the office building. On the different floor levels, the ducts are also visible and not hidden above false ceilings which is normally the case in office buildings.

Besides resulting in lower building costs, this normally also presents an advantage for the thermal climate in the building. The lack of false ceilings results in a larger ventilated room volume. The extra space thus created at the ceiling, where the emissions are normally at a higher concentration, results in a better use of the ventilation airflow. The direct contact between the ventilation air and the bare concrete ceiling also enhances the possibility to use cool night air for comfort cooling of the building.

This visual installation of ductwork in e.g. office buildings is however only acceptable if the workmanship of the installation is of a high standard and should otherwise be avoided.

1.6 FIRE HAZARD AND DUCTWORK

The ductwork could present a fire hazard in a building when the ducts run through fire classed walls. There are different building code requirements in different countries but they all have one thing in common – the duct penetrating the wall must not lead to a reduction in the fire safety of the building. The technical solution chosen should thus be compared to the case of the wall without any penetrating duct.
Even though the national requirements differ, there are mainly two different demands required for fire safety in this case, namely fire insulation "I" and tightness or "integrity", "E". The first requirement, "I", is covered if duct penetration through the wall is thermally insulated in such a way and to such a degree that the heat from a fire on one side of the wall will not be able to set fire to anything on the other side. Tightening the space between the outside of the duct and the wall opening fulfils the tightness requirement, "E". Both these requirements, for E and I, are combined with a figure expressed in minutes during which the construction has to withstand the effect of a standard fire as defined in international standard. A normal requirement for walls in office buildings is fire class "EI 60".

But there is yet another demand – the ducts on both sides of the fire wall have to stay in place during the fire. The duct hangers thus also have to withstand the strain from a fire during the same time required for the duct itself. This mechanical strength demand during fire is expressed in international standard as an "R"-demand and should thus for the office building above be expressed as "R 60" for the duct hangers.

There are different ways of arriving to a safe solution. The ducts may be fire insulated on both sides of the wall or the duct could be connected to the wall opening via a fire damper tested to fulfil e.g. "EI 60" as in the example given above. The fire dampers are normally officially tested and provided with certificate showing that they close tightly and withstand the heat during the time required. The fire damper can however only provide safety if it works properly and closes when the fire starts. Therefore some countries require that fire dampers are regularly tested and that this requirement is stated in the operation manuals of the installations. The fire dampers normally used today thus have to be equipped with damper motors used to open the damper after the test.

Sometimes the chosen solution is a combination of these alternative ways - duct insulation and fire damper – providing an alternative as safe as the wall itself.

1.7 HOW ARE THE DUCT DESIGNERS, AND OTHER PARTICIPANTS, WORKING WITH DUCT DESIGN AND REQUIREMENTS TODAY?

Designers of HVAC systems, installers, contractors and building owners in different European countries have been interviewed or asked to answer enquiries sent out to provide a background on what tools and facilities are used. They were also questioned on what the quality requirements on ductwork are and how they are expressed and controlled [Ref 1].

The evaluation of this material shows that there is a certain difference between the way technicians in northern and southern Europe use ductwork. The former seem to be more accustomed to using circular ducts as a standard solution whenever suitable while technicians in southern Europe use more rectangular ductwork. The differences in working with these two types of ductwork are discussed in different following chapters in this source book (§ 8). A third lesser used alternative, the flat-oval ducts, does not seem to be of common use by interviewees and are not available on the market in most of the countries.

The answers mainly show that ductwork in many countries is considered as an important part of the building installations and that this part of the design work is done meticulously. This is gratifying as the ductwork normally accounts for about half of the installation costs of the HVAC plant.

The ductwork is also indirectly involved to a large degree in the life cycle costs if not designed in a proper way. These questions are dealt with in several of the following chapters in this source book (§ 6.3).

In some countries, e.g. in Sweden with its half century old "AMA-system", which is described in § 5.3.4, quality requirements for duct installations have been specified for many years. These demands are normally stated in building specifications, expressed in controllable units and controlled by testing before the contractor is released from his commitments.

In other countries the awareness is not as clearly expressed. Ductwork tightness requirements of ductwork are. neither expressed in building specifications nor tested before the building is taken into operation. These different philosophies and different methods were also found in an earlier EU SAVE-project "Improving ductwork – A time for tighter air distribution systems" [Ref 2] where ductwork in Sweden was found to be about 25-50 times tighter than ductwork used in Belgium and France (§ 7.10.6).

1.8 HIGHLIGHTS OF THE BOOK

The present sourcebook comprises the following main content:

- Chapter 2 gives an overview of different ventilation principles and components used in such systems.
- Chapter 3 explains some reasons why and how a ductwork system should be carefully designed.
- Chapter 4 describes how less energy can be used in the duct system.
- Chapter 5 gives examples on how better ductwork can be introduced in Europe.
- Chapter 6 discusses the cost elements and whether a better ductwork really costs more than one of lower quality.
- Chapter 7 shows different ways of integrating a duct system into the building, how to reduce noise transmission and fire hazards, system flow and tightness characteristics, and maintenance requirements.
- Chapter 8 compares space requirements and costs for circular and rectangular ducts.
- Chapter 9 describes duct manufacture and installation.
- Chapter 10 describes how the quality of the system is controlled before being put into operation.
- Chapter 11 points at the importance of maintaining the duct systems during its lifetime.
- Chapter 12 presents several practical examples and case studies of duct installations, good and bad.
- Chapter 13 comprises a large number of ductwork checklists that can be used by those concerned from the programming phase to operation and maintenance.
- Chapter 14 includes references to literature and relevant duct standards.

An air distribution system generally consists of a network of ducts, wall cavities, or plenums whose key role is to provide clean air (sometimes at required specific thermodynamic conditions) to rooms so as to dilute or extract pollutants and/or to condition spaces. Note that ducts are not always necessary to distribute the air in a building; however, they are often the most flexible and practical option.

2.1 VENTILATION PRINCIPLES

There are 4 major types of air distribution systems:

- Natural (N) (self draft) systems (also called "Natural ventilation")
- Natural supply and mechanical extract (E) systems (also called "Fan assisted exhaust ventilation")
- Mechanical supply and natural extract (S) systems (also called "Fan assisted supply ventilation")
- Mechanical supply and extract (SE) systems[2] (also called "Fan assisted balanced ventilation")

Among those types, it is customary to distinguish between constant airflow (CAV) systems and variable airflow (VAV) systems. A final distinction is usually made between systems whose function is solely to provide fresh air to the rooms (ventilation only), and those whose ventilation function is combined with heat recovery, heating or cooling, humidifying and/or de-humidifying the air (also called HVAC systems).

The term "VAV" is often associated with air conditioning systems where the load provided to a room is controlled with the airflow rate, while the term "DCV" (Demand-Controlled Ventilation) denotes systems where the fresh air delivered to a space is controlled based on air quality demands (e.g., presence or CO_2 concentration).

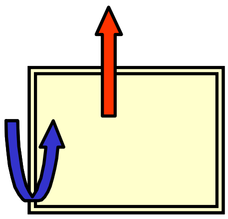


Figure 1. Schematic representation of a typical natural stack ventilation system. In this figure, the air comes naturally into the building through cracks, slots, trickle ventilators, or other devices, and exits naturally through vertical ducts. The air motion is due to temperature differences or wind or both.

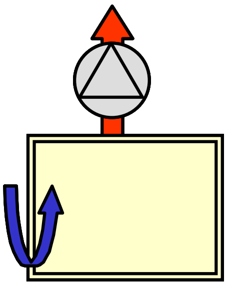


Figure 2. Schematic representation of E system. The air comes naturally into the building through cracks, slots, trickle ventilators, or other devices, and is mechanically driven out through a central exhaust duct system.

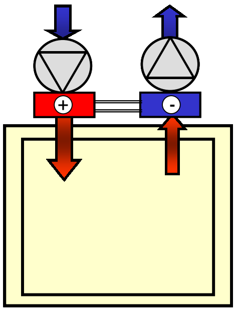


Figure 3. Schematic representation of balanced SE system. The air is mechanically supplied and extracted through two separate ducted systems. The air handling unit includes a heat recovery unit to transfer the energy of the outgoing air stream to the incoming air stream.

Table 1 summarises the advantages as well as the critical issues that have to be dealt with for the major types of air distribution systems.
As regards the most frequently-used ducted systems in new construction, the European Union can roughly be divided in the three major zones described in Table 2.

Hybrid ventilation systems are another type of ventilation system that have gained increased attention over the past few years, especially in the framework of IEA Annex 35 (1998-2002) [Ref 14]. These systems combine natural and mechanical ventilation principles. Hybrid ventilation is defined as a "two-mode system which is controlled to minimise energy use while maintaining acceptable indoor air quality and thermal comfort. The two modes refer to natural and mechanical driving forces." Nowadays, hybrid ventilation is implemented mostly in a few low-energy prototype buildings.

[2] This category is sometimes divided into balanced systems with both supply and extract fans and re-circulation systems with only one fan. Balanced systems almost always incorporate heat recovery.

	Advantages	Critical issues	Typical applications	Cost/energy issues
Natural	• No fan energy • No fan noise • Low space demand although the ducts must be large to minimise pressure drop	• Very difficult to control air distribution • Very difficult to maintain ventilation flow rates • Normally no filtration of incoming air • Normally no heat recovery possible • Noise transmission through openings	• Dwellings • Low-energy prototype buildings	• Low initial cost • No fan energy use, but heating/cooling energy cannot be recovered from extract air streams
Natural supply and mechanical extract	• Moderate space demand • Pollution control at the source • Possible heat recovery for other purposes than air heating (rarely implemented)	• Difficult to control air distribution • Increased infiltration • Noise transmission through openings • Normally no filtration of incoming air	• Dwellings	• Moderate initial cost • Fan energy use to be considered • Recovery of heating/cooling energy from extract air streams rarely implemented
Mechanical supply and natural extract	• Moderate space demand • No contamination from outside • Possible to combine with air treatment (but no heat recovery or recycling implies large energy use)	• Difficult to control air distribution • Increased exfiltration • Pressurised building can create moisture problems in outside walls • Not possible to include heat recovery • Noise transmission through openings • Supply ducts should be clean.	• Clean rooms (the rooms are pressurised to avoid entry of polluted air) • Urban ventilation	• Moderate initial cost • Fan energy use to be considered • Not possible to recover heating/cooling energy
Mechanical supply and extract	• Possible to control airflows in rooms • Possible to combine with air treatment • Possible to include heat recovery units	• Balanced systems need at least two fans, which implies greater fan energy use • Noise to be prevented • Space demand (more ducting) • Increased maintenance • Supply ducts should be clean	• Dwellings (in extreme climatic regions) • Offices and commercial buildings	• High initial cost • Fan energy use is very significant • Reduced heating/cooling energy use due to heat recovery

Table 1. Overview of major ventilation system types. The table contents apply to most systems. Note, however, that there may be exceptions.

Northen regions	Balanced mechanical ventilation with heat recovery (SE); air heating and/or cooling with heat recovery (SE)
Middle regions	Mechanical exhaust ventilation (E); air heating or cooling (SE)
Southern regions	Air conditioning (commercial buildings) (SE)

Table 2. Frequently-used ducted systems in Europe

2.2 MAIN DUCTWORK COMPONENTS

2.2.1 Straight rigid ducts

They are made of:

- Metal (galvanised sheet metal, stainless steel, hot-rolled (and painted) steel, aluminium, or sheet metal with aluminium-zinc coating); or
- Synthetic material (PVC, polyamide, etc.).

Their cross-section is circular, rectangular, or "flat-oval". Their interior surface is in general smooth.

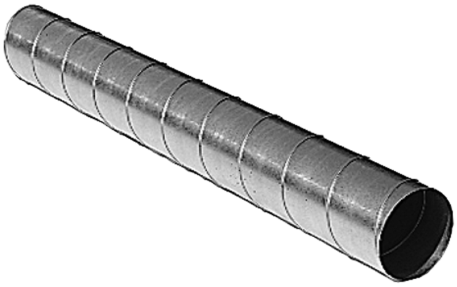


Figure 4. Straight rigid spirally-wound duct.

2.2.2 Flexible ducts

These ducts can be shaped by hand. They are made of:

- Synthetic material (PVC, polyamide, etc.) wrapped around a metal spiral coil; or
- Metal (stainless steel or aluminium).

Their cross-section is circular. Their interior surface is in general either rough or bumpy (e.g., if the material is wrapped around a metal coil). Although widely used mainly because they seem easier to install, these ducts generate much higher pressure drops than rigid ducts.

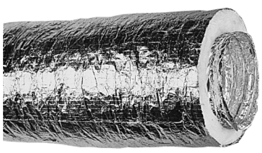


Figure 5. Insulated flexible duct with external vapour barrier.

2.2.3 Bends and branches

These components allow a change in flow direction.

Figure 6: Pressed bend (left). Segmented bend (right).

Figure 7: Tee junction.

2.2.4 Reducers

They allow a change in duct size and/or form.

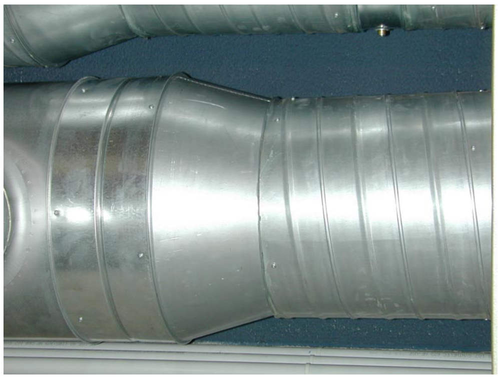


Figure 8. Circular reducer.

2.2.5 Support systems

These include hangers and supports that ensure the mechanical stability of the ductwork.

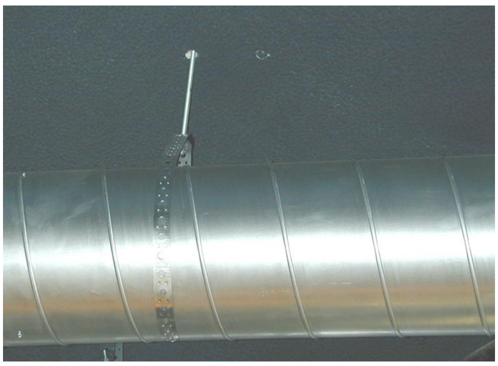


Figure 9 : Hanger.

2.2.6 Smoke / fire dampers

These are meant to avoid the spread of smoke or fire through the ductwork.

Figure 10 : Fire damper for circular ducting.

2.2.7 Turning vanes

These are used to guide the air through rectangular bends so as to avoid flow disturbances within and downstream of the bends as well to as to reduce pressure drop through these components.

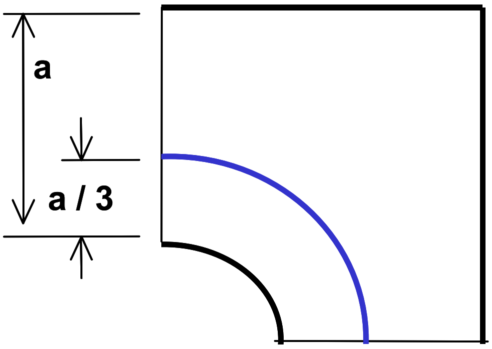


Figure 11 : Schematic representation of turning vane

Often only one vane is used in the elbow. It should then be installed as shown in the drawing. At higher air velocity, above ca. 6 m/s, the vane could produce disturbing noise.

2.2.8 Regulating dampers

These are manually set or dynamically controlled flow resistances that permit changing the airflow rate.

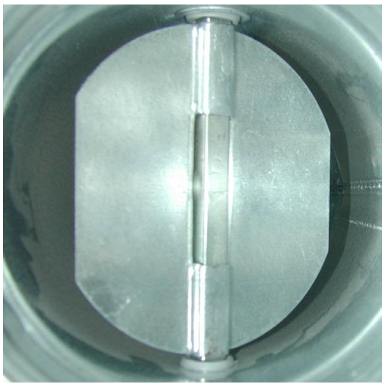


Figure 12 : Single-blade regulating damper. The blade angle can be manually adjusted or controlled with a motor.

2.2.9 Silencers

These components limit the noise transmission through the ductwork. Most of them are made of ventilation duct shell in an inner casing of perforated steel plate. The void between the shell and the plate is filled with mineral wool, leaving a free section bounded by the perforated plate for air passage.

Figure 13 : Silencer

2.2.10 Inspection or service access doors / openings

These include openings or doors, at the air handling unit (AHU) for inspection and servicing/replacement of parts (e.g., filter change), or in the ductwork itself to inspect and clean the installation.

Figure 14: Bend with separate outlet for cleaning.

2.2.11 Filters

In an air distribution system, they are usually made of multiple layers of porous or fibrous material where gaseous and particulate pollutants deposit as polluted air flows through them.

Figure 15 : Air handling unit for an SE system. The AHU includes two fans for the supply and extraction air streams and a heat recovery device including filters to avoid the fouling of the coils and the ductwork.

2.2.12 Plenum boxes

These are usually large cavities either:

- at the interface between a ductwork and one or many air terminal devices; or
- at the interface between the air handling unit and the ductwork.

Besides a simple branching interface, they can serve or can include numerous functions such as:

- velocity and pressure profiles flattening at an air terminal device;
- airflow and pressure measurement and control at an air terminal device;
- noise attenuation.

Figure 16. Plenum box connected to an air terminal device. Includes a regulating damper and acoustical cladding.

2.2.13 Air terminal devices

They are the final link between the duct system and the environment where the air is supplied or extracted.

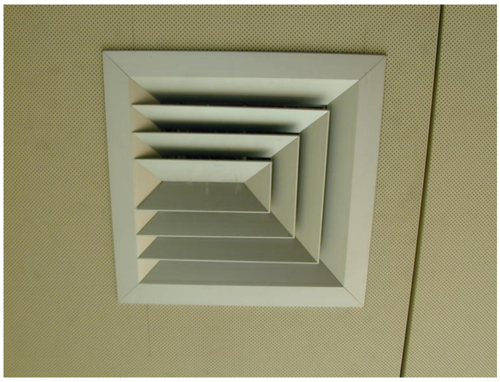


Figure 17. Rectangular supply air terminal device.

2.2.14 Insulation

Insulation may be used:

- to avoid energy losses, especially with air heating or cooling systems or ventilation systems with heat recovery;
- to prevent the spread of fire;
- to prevent the transmission of noise through the ductwork;

and for any combination of these reasons.

It is usually made of mineral wool or fibreglass wrapped around or lined inside the duct[3] (see also § 7.5). A vapour barrier may be applied to avoid condensation problems.

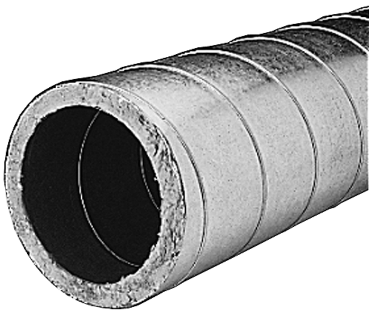


Figure 18. Straight double-cased insulated duct.

[3] Exposed fibreglass may be detrimental to indoor air quality. Note also that air infiltration through the insulation lined inside a duct affects its thermal performance.

3.1 WHY BOTHER?

A first question that arises is of course – is it worthwhile to invest efforts in both time and money in ductwork design? Our answer is "yes, it is"! The ductwork will normally be used for a long time to come. Regarded as a long time investment even small improvements of the design and the installation quality will result in an interesting payback of the investment. Another aspect that is discussed in this book (§4) is the energy use of the duct system and how it can be influenced by the choice of air velocities in the duct system and the layout and extension of the system. Normally the total energy use of the air-handling system is of the same magnitude for the two main parts, the air-handling units and the duct systems for air supply and extraction.

Another aspect that has to be considered is the acoustical role the ductwork plays both as noise silencer, as noise producer and as noise transmitter between two rooms.

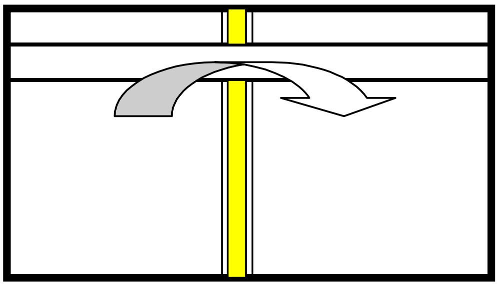


Figure 19 Noise transmitted between two rooms via the ductwork.

Here only careful design and use of common sense will result in an acceptable solution. The duct system being part of an installation that probably aims at providing the building users with a good thermal climate and good air quality should not be considered as a nuisance due to noise produced while doing so. Many individuals look forward to the time after office hours when the ventilation systems are stopped and silence is back. This dissatisfaction with a noisy ventilation system is something that should be avoided. The efforts made at system design stage should be of equal proportions in all aspects to ensure the well being of occupants. Silence – or lack of noise – is often lacking today and this can lead to stress and discomfort. A careful and knowledgeable design and installation can avoid noise problems from arising. One thing should be kept in mind here – it is easier to deal with this before the problems have appeared – afterwards it is more difficult, more costly, and more time-consuming to deal with. Once the users have already been dissatisfied, they are harder to please.

3.2 DUCT DESIGN SHOULD BE BASED ON CO-OPERATION

The design of the duct systems has to be done in close co-operation with the architect of the building. Starting this collaboration at an early stage in the building design phase could result in solutions that are of positive value for both parties.

Some of the case studies (§12) show examples in how the ductwork has even been used as an integrated part of the interior design of the rooms. False ceilings might be needed for acoustical reasons, to reduce the reverberation time, but are perhaps not as necessary if their only function is to hide the ductwork and other building installations. In this case the money saved on not installing any false ceilings could instead partly be used for an improved (and perhaps painted) ductwork.

Good design and excellent workmanship during installation can thus result in ductwork installations that can be left visible as an ocular demonstration of the role they play in the function of the building. But – this can only be accepted if the appearance of the ducts is good enough. If that is not the case, it is better to put them out of sight.

Figure 20 You don't always have to hide the ducts. Here false ceiling (seen to the left) has only been used where needed for acoustical reasons.

3.3 AIRFLOW AND LAWS OF NATURE

A well-designed duct system will make airflow measuring and adjustment easier – this should always be done before occupancy. How the adjustment and measurement is done is described in chapter 10. The careful design shall also consider the laws of nature: How is the system influenced by wind blowing on the façade? How is the airflow affected by stack effects in wintertime?

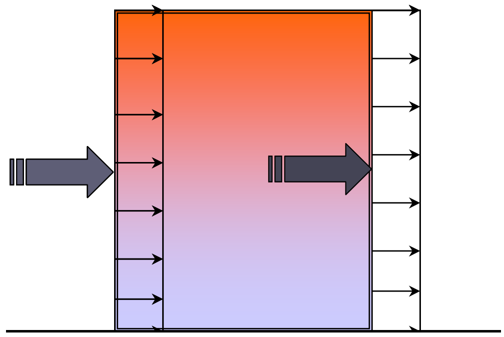


Figure 21 : Wind force on the façades affects the ventilation

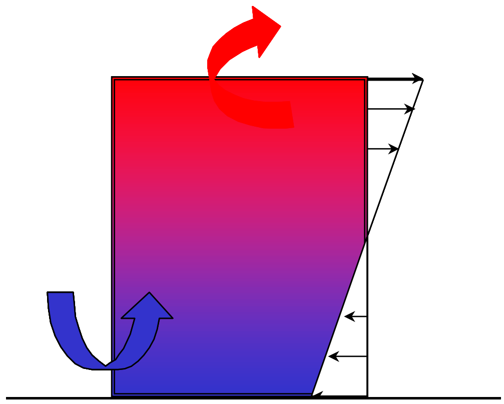


Figure 22 : The airflow differs between winter and summer due to the stack effect

In a high rise building the airflow could otherwise differ quite considerably between summer and winter, the air might even go backwards through the registers!

3.4 KEEP THE SYSTEM HEALTHY

There is an increasing awareness of the possible risk of the ducts serving as growing ground for mould. The best preventive measures against this risk are:

- keeping the ducts dry by
  - using the right type of air intake louver
  - having low air intake velocity, normally a velocity below 2.5 m/s will prevent rain drops and snow flakes from entering with the supply air
- locating the air intakes where the outside air is as clean as possible, e.g. high up and towards the court yard instead of the street
- not having the intake ducts clad with insulation material on the inside
- inspecting the inside of the air intake duct regularly for signs of cleaning need. This requires that the ducts are provided with inspection lids.
- providing the intake ducts with drain outlets.

There is an increasing demand in many countries to have the ducts cleaned on the inside to enhance the air quality of the supply air and reduce one of the risks of the sick building syndrome (SBS).

The methods for cleaning ducts, and the need for it, are described in chapter 1. During the design the future cleaning of the ducts should be simplified by showing suitable locations for clean-out openings.

Duct systems account for a large fraction of the energy use in a building. However, there exists a significant body of literature that shows that there are great energy saving opportunities in this field. These are linked to various aspects of the duct design mentioned in Figure 23 and described below.

4.1 LAY-OUT

The duct system layout has a major influence on pressure drop, therefore on the fan energy needed to transport the air through the ductwork. While the duct designer should try to avoid long and tortuous paths, building design issues such as the poor positioning of shafts may dictate inefficient ductwork layout. Therefore, at the early stages of the building design, there must be a collaborative effort between the architect and the ductwork designer to assign enough space to the ductwork installation.

4.2 DUCTWORK AIRTIGHTNESS

Various studies have shown that duct leakage can be a severe source of energy loss. There are two major ways to waste energy through duct leakage:

4.2.1 The fan has to work harder

The airflow passing through the fan is directly affected by duct leakage. In order to meet the required airflow rates at the air terminal devices, the fan must be sized and operated at detrimental conditions for energy use. If the fan power scaled approximately with the third power of the airflow rate for an existing duct system, a leakage flow rate of 6% should imply a fan power demand increase of 20% ($=1/(1-0.06)^3 - 1$). Normally the increase is about 15%.

4.2.2 There may be net thermal losses when the ducts pass through unconditioned spaces

Supply make-up air leaking out to unconditioned spaces is simply lost along with the energy that was used to condition that air. Insufficient heat recovery or recycling may also result from duct leakage in extract and return ducts.

Duct leakage may also affect the ventilation rates of a building, and therefore ventilation energy losses. Other benefits of airtight ducts are described in the SAVE-DUCT handbook (Carrié *et al.*, 1999). [Ref 2]

4.3 INSULATION

Ductwork insulation is key for energy conservation measures when a thermodynamic function is combined to the system. Energy losses associated to insufficient insulation are commonly called conduction losses (Figure 24). Performance loss in terms of Watts per meter or °C per meter of duct length can be easily evaluated with standard heat transfer equations. The designer should evaluate the need for higher levels of insulation based upon the significance of those energy losses.

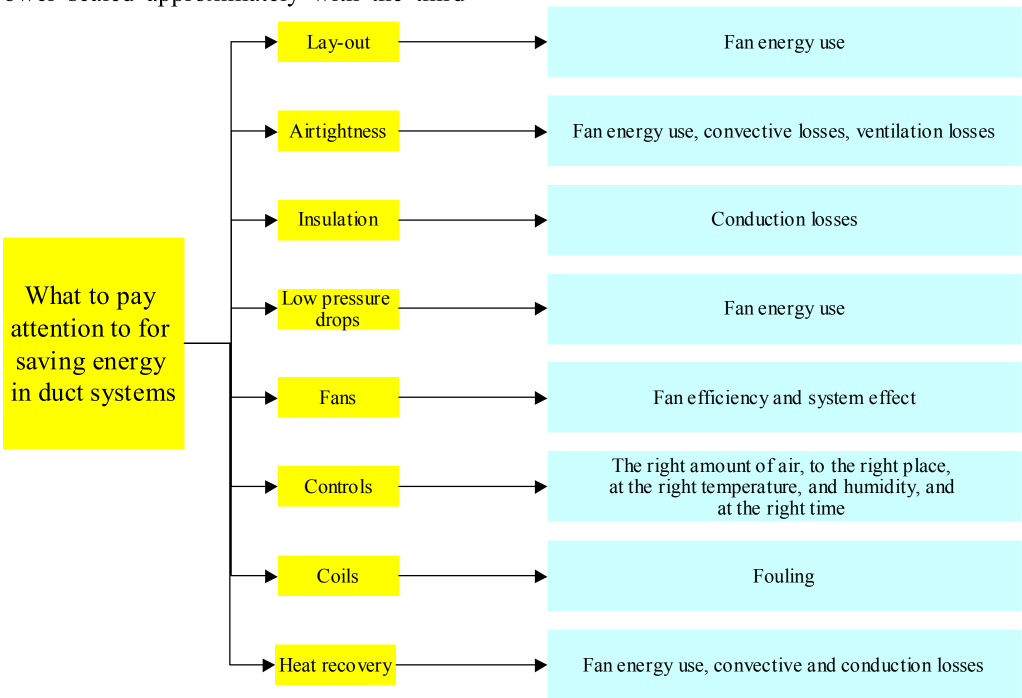


Figure 23 : Energy saving opportunities in duct systems.

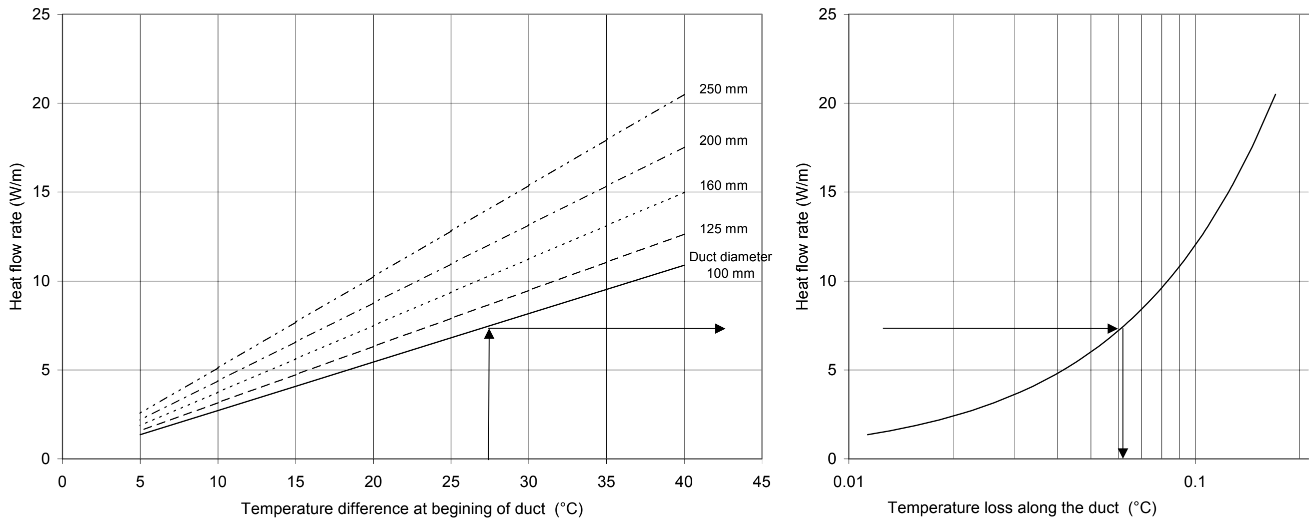


Figure 24 : Heat flow rate and temperature loss per unit length of duct for different duct diameters. Airflow rate = 0.1 m³/s: 60-mm thick insulation

Figure 25. Water-loop heat exchanger (left); cross flow heat exchanger (middle); rotary heat exchanger (right).

4.4 LOW PRESSURE DROPS

In a ductwork system, pressure can be viewed as energy created by the fan that can be reversibly converted into kinetic energy (airflow), or irreversibly dissipated by wall friction or turbulence effects (e.g., in a bend or sudden expansion). These losses, commonly called pressure drops or flow resistance, must be overcome by the fan to meet the desired flow rates at the air terminal devices. Pressure drops are expensive in that they are directly linked to the fan energy use. Therefore, the designer should perform pressure drop calculations and should try to minimise unnecessary flow resistance.

4.5 ENERGY-EFFICIENT FANS AND REDUCED SYSTEM EFFECT

The fan is the driving force of a mechanical duct system. Its power demand can vary drastically[4], typically from about 0.5W per l/s up to about 3 W per l/s depending on the fan itself, but also on the characteristics of the duct system in which it will be integrated, and the connection to that system. Therefore, it is important to use fans that are efficient in the range of operating conditions that are foreseen.

Also, to avoid significant departures from the manufacturer's performance data (system effect), the fan must be properly integrated in the system. This includes installing correctly sleeves to cut vibrations from the fan, but also avoiding singularities (e.g., bends or branches) close to the fan.

Figure 26 : Sleeve to cut fan vibrations

4.6 CONTROL OF AIRFLOWS, TEMPERATURE, AND HUMIDITY

Providing fresh air to a building implies an energy cost just by the fact that the air needs to be brought to indoor set-point conditions. Therefore, it is important to have the right amount of air delivered to the right place and at the right time, while minimising the distribution losses. When temperature and humidity control is associated to the system, it is further necessary to have the air delivered at the right temperature and humidity for obvious comfort and energy conservation reasons.

For this, adequate control devices and sensors should be used and tuned. These include timers, multiple-speed or variable-speed controllers, dampers, flow regulating registers, velocity sensors, temperature sensors, humidity sensors, etc. Regular maintenance is key to ensuring that there is no significant deviation when the system is operated.

4.7 COIL FOULING

Evidence shows that coils can be seriously fouled. Besides indoor air quality issues resulting from this fact, the resistance to the flow passage can be significantly increased. This unwanted increased pressure drop may result in deficiencies such as insufficient airflow rates and augmented fan energy use. A smaller effect is that the heat exchange between the coil and the air is affected as the dust accumulated can act as an added thermal resistance. Therefore, less energy is transferred from the coil to the air or vice versa.

To avoid these problems, protective filters should be installed upstream of the coils and regular maintenance of the filters and coils is necessary.

4.8 HEAT RECOVERY

Ventilation heat recovery consists in transferring some exhaust air stream energy to fulfil a specific task within the building such as pre-conditioning of fresh air (Figure 25). While this technique can be successfully implemented, there are some hidden losses that can seriously impact the energy benefits of such systems:

1. The fan (electric) energy use is increased (there are two fans and increased pressure drop);
2. The system must not be short-circuited, in particular, the building construction needs to be fairly airtight;
3. The conduction and convective losses in the supply and extract ducting (e.g., due to poor airtightness or poor insulation) must be limited.

Given these losses and the increased initial cost for these systems, heat recovery in balanced ventilation systems is in general not worthwhile in mild climates (< 2500 degree-days) from an energy stand-point. Note, however, that it may be useful from an air distribution point of view and for environmental reasons.

[4] See § 7.9.3. The value of 0.9 W per l/s (0.25 W per m³/h) is sometimes adopted as a reference value.

5.1 WHAT IS GOOD QUALITY DUCTWORK?

Many experts agree that better ductwork performance is needed in most European countries and that an improvement in the quality is highly desirable. However, in order to assess whether performances are better, one should define a reference framework for assessing the quality of ventilation systems.

In the ISO framework, 'Quality' is defined as: *'Totality of characteristics of an entity that bear on its ability to satisfy stated and implied needs'*
Within this concept, the customers and the society (through standards, regulations, etc.) have to define the requirements for quality (Figure 27). Once these requirements are defined, one can work out a concept of quality assurance.

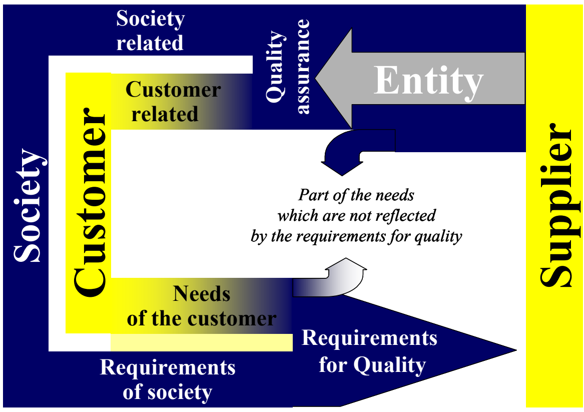


Figure 27: Overall scheme for assessing quality

In practice, one observes that many customers and societies have no or very limited requirements in relation to the performances of ductwork, e.g. ductwork airtightness, pressure losses, stiffness, maintainability, etc. There are very few stated needs and probably a lot of implied needs. Moreover – and partly linked to the lack of requirements – there is often no quality assurance. As a result, industry and installers are in many cases confronted with a market which pays little attention to a clear definition of the requirements and, moreover, without a coherent scheme for quality control.

As a result, many manufacturers and installers have limited motivation to develop advanced ductwork concepts and/or installation techniques. Of course, there are exceptions, e.g. the Swedish procedures in the framework of AMA [Ref. 41] and OVK (Obligatorisk Ventilation Kontroll) [Ref. 40].

It is important to stress that the ductwork market is confronted with various levels of performance and various types of needs. For instance :

- In the case of airtightness, classes A, B, C and D correspond to different levels of performances;
- The needs may vary from country to country and also vary in time. In Sweden, there is already a significant market for ductwork which :
  - is delivered with clean surfaces (see protection end covers in Figure 28);
  - is easy to maintain by including specific provisions for ductwork maintenance;
  - pays specific attention to sustainable aspects (e.g. by replacing the plastic coverings by wooden based coverings.

Figure 28: Attention in ductwork cleaning in Sweden

5.2 POSSIBLE SCHEMES FOR STIMULATING QUALITY

Given the fact that many customers are not aware of the importance of certain performances and given the fact that it is often not easy to evaluate if the requirements are met, it is probably inevitable to apply specific procedures for achieving minimum performance levels.

Basically, such approaches can be split up into 2 categories:

- Procedures which explicitly require minimum performances in relation to the ductwork performances;
- Procedures, which do not impose minimum requirements but which offer a framework that strongly stimulates the application of systems with good performances.

In practice, a mixture of approaches can be considered. Both approaches are further discussed in the following paragraphs through the example of airtightness.

5.3 PRACTICAL EXAMPLES

5.3.1 Minimum requirements for all applications

Such an approach has the advantage that one is sure that minimum performance levels are achieved (of course, on the condition that there is an appropriate control procedure). Examples are:

- Minimum requirements for ductwork airtightness;
- Minimum requirements concerning provisions for ductwork maintenance

The disadvantages are:

- It may be that other measures have a better cost-benefit;
- It is not possible to reward better performances than the minimum requirements.

In particular in the case of aspects related to the energy performance of buildings and systems, it may be better to count on indirect stimuli. This is discussed in the next paragraph.

5.3.2 Indirect stimuli by including ductwork performances in global assessment schemes

The energy related performances of ductwork are of course important but should always be evaluated in relation to other investments and costs for achieving improvements in energy efficiency. Such an approach is possible within the framework of so-called energy performance standards and regulations. Such standards and regulations determine for well-defined boundary conditions the total energy use of a building and impose a maximum value. All possible measures can be considered for achieving this requirement, e.g. better thermal insulation, better window performances, better heating, ventilation and cooling systems efficiency, renewable energies use, etc.

At present, several European member states are implementing or preparing such an approach as a basis for minimum legal performances.

As an example, in the case of the new French approach (Réglementation Thermique RT 2000) and the proposal for new approach in the Flemish region (Belgium), ductwork airtightness is an explicit part in the procedure for determining the normalised energy consumption of a building. Basically, the approach is as follows:

- If no information is available on the ductwork airtightness, one has to assume a default value. In the case of the French approach, this corresponds to a ductwork leakage rate corresponding to 15% of the nominal air flow rate (about 2.5 times worse than class A of the CEN standard);
- If measurement results are available, one can make use of these measured data (Flemish approach only).

As such, there is no absolute requirement on ductwork airtightness. However, if improved ductwork airtightness is economically more attractive than e.g. better thermal insulation or a more efficient boiler, it seems logical that the decision makers will give preference to better ductwork airtightness.

Within the framework of the SAVE ENPER-TEBUC project (www.enper.org), the issue of airtightness of buildings and ductwork is one of the aspects under consideration. A systematic inventory of all relevant aspects is part of the envisaged work.

5.3.3 Performance control after execution of the works"

At present, many countries have requirements in relation to energy performance of buildings and/or building and system components. In most cases, the proof of performance is only required at the moment of the building permit or in some cases even not at all. An alternative approach is to ask proof of compliance after the end of the work. Such an approach is very attractive in the case of ductwork airtightness since it is well known that the quality of execution is for most ductwork systems crucial.

5.3.4 Pragmatic approaches are important

The choice between direct requirements or indirect stimuli is important. However, the philosophy and approach for quality assurance is also very important. Attention has to be paid to the formal framework of quality assurance: Can the installers do it? How costly is the quality control? etc.

Let's take the ductwork airtightness as an example.

Within the framework of the Swedish AMA procedures, an interesting concept has been put into place:

- The HVAC contractors are obliged by the AMA requirements to include the cost of tightness testing in their contract price. The amount of ducts to be tested varies with the duct type; e.g. 10% of all circular ducts and 20% of all rectangular duct work have to be tested. Building owners decide which ducts should be included in the test and they are normally also present during the test. The contractors themselves can carry out the control measurements if they have the necessary knowledge and equipment, more often they engage specialised subcontractors to do the testing at the HVAC contractor's expense. Should the test show that the ducts are leaking more than required by the tightness class (B is standard for rectangular ducts and C for circular ducts) this results in requiring the leaking ducts are to be tightened and then once more tested until they are approved.

- If the ductwork is found to be leaking in excess of the requirement, the test is also increased to include testing of further ductwork (another 10% or 20% respectively). Should these also prove to be leaking too much, all ductwork has to be tested, tightened where needed and tested again. The method for testing and the protocols to be used to present the result is also presented in the HVAC AMA book.
- In principle, one has to test only a 10% or 20% fraction of the system, whereby the customer specifies the section to be tested (Figure 29). Only in case of non-compliance, more tests are thus needed.

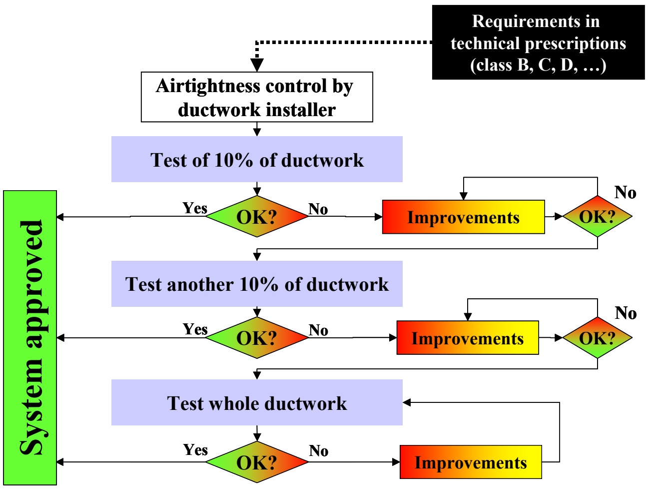


Figure 29 : Swedish approach in framework of AMA procedures

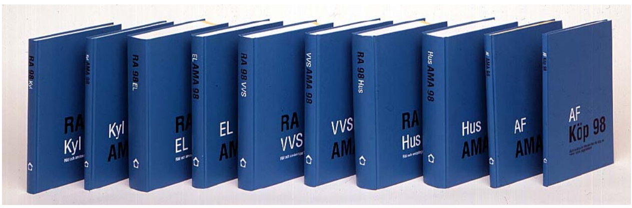


Figure 30 : The Swedish AMA covers all areas - construction, HVAC, electrical and refrigeration

6.1 COST COMPONENTS

The cost of an air distribution system can be divided into three major components:

- Capital or initial costs;
- Operating costs;
- Replacement costs (this item goes beyond the scope of this book).

Many parameters have to be considered when comparing the costs between two options, some of which are listed below:

Capital or initial costs:

- Cost for space;
- Cost factor for defining the requirements at the programme phase, including person-hours;
- Cost factor for designing the duct system, including person-hours, and calculation and design tools;
- Material cost for the ductwork, including packing, transport, and waste;
- Cost factor for installing the duct system, including:
  - labour;
  - tools, machines, huts, scaffolding, etc.;
  - building cost (e.g., wall penetrations that must be made);
  - insurance, fees, site cleaning, etc.;
  - site organisation, administration, profit;
  - inspection and supervision;
  - maintenance and operating manuals;
- Cost factor for commissioning the system, including testing and balancing, airtightness test, etc.

Operating costs

- Operating cost, including training of personnel, person-hours, heating and electricity energy use, service and maintenance, etc.

Replacement costs

- Replacement cost, including necessary building works, exchanges and repairs, rehabilitation, etc.

All these expenditures vary from one country to another, even from one city to another and especially from one time to another.

6.2 GLOBAL UNDERSTANDING OF POTENTIAL COST SAVINGS

The cost of a system should be evaluated globally, not sequentially.

Let's consider the case of an attempt to save money by ignoring access issues at the design phase. A direct cost consequence is that duct inspection and cleaning will be more expensive—e.g., the technicians will have to cut holes for and install access panels.

Let's consider the case of an attempt to save money by reducing or eliminating time/cost for pressure drop calculations and optimised fan selection. This will often result in inadequate airflow rates, leading to either insufficient air renewal in the occupied spaces or, conversely, excessive energy use as well as excessive air velocities and subsequent noise issues. These problems are easy to spot at commissioning, provided that it is performed. In that case, experience shows that the repairs will cost more than the savings that have been achieved. Note also that penalties may be applied to the contractors in addition to the obligation to fix the problem. If the problem is not brought to light at commissioning, premature rehabilitation, energy use, and productivity cost factors may very well equate the savings made during the design phase.

In sum, cost savings looked at sequentially can be extremely misleading. The decision makers must have a global understanding of the underlying issues associated with potential cost savings on specific items.

6.3 AN INTERESTING APPROACH THROUGH LIFE CYCLE COSTING

Different options should not be compared on an initial cost basis alone. For example, the ductwork insulation or the ductwork airtightness should be considered if they have an impact on energy use, thus on operating costs. Life Cycle Costing is a useful tool for such comparisons as it brings the different cost components together.

Life Cycle Costing allows one to express a stream of expenditure over a number of years in terms of its Net Present Value (i.e., it is brought back to its value in year 0). For instance, capital costs and energy (operating) costs can be combined to allow fair comparisons between different options.

As an example, calculations were carried out in the case described in Figure 31. The cost performance of a leaky (3 Class A) and a tight system (Class D) are compared in Figure 32. The results are based on the figures presented in Table 3. Figure 32 clearly shows the key role of the ductwork airtightness. The calculation has been done according to the method presented in § 7.2

Normalized cost of the system	120 EUR/m^2 of duct surface area
Cost for heating energy	0.03 EUR/kWh
Cost for electric (fan) energy	0.105 EUR/kWh
Additional initial cost of tight system	10 %
Fractional on-time	0.75 (6570 hours per year)
Discount rate	5 %
Inflation rate for energy	1 %

Table 3. Input parameters set arbitrarily for Life Cycle Cost calculation example shown in Figure 31 and Figure 32. Beware that these figures can only be used locally in space and time for a specific ductwork system.

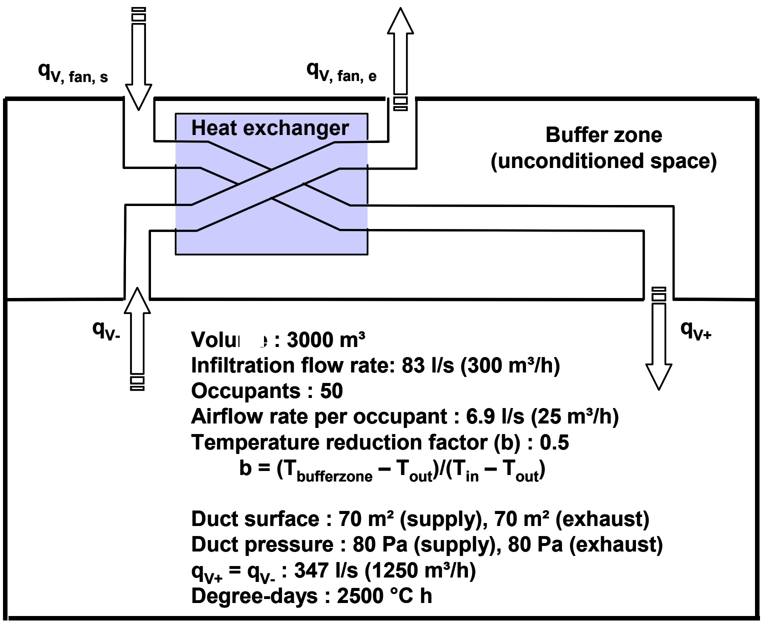


Figure 31. Schematic diagram of the office building used in the LCC calculations . It is equipped with a balanced ventilation system with heat recovery. The fan airflow rate is adjusted to match the required airflows at the air terminal devices.

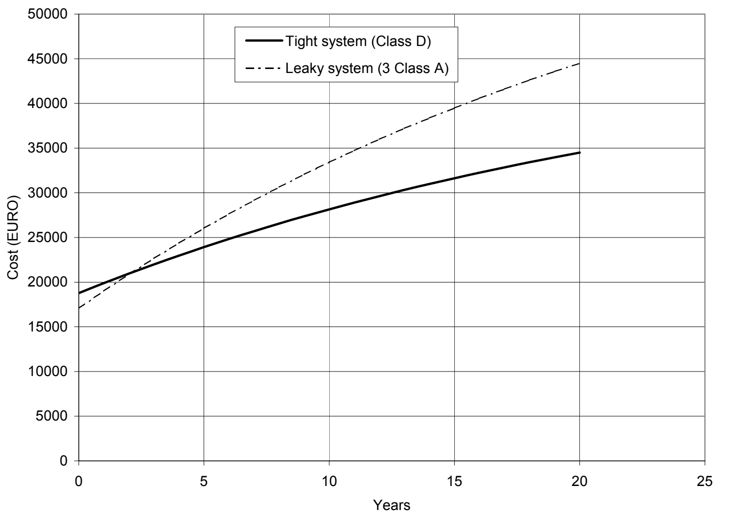


Figure 32: Comparisons of costs (Net Present Values) of a leaky (3 Class A) and an airtight (Class D) duct system. Calculations are based on the system described in Figure 31 and the parameters shown in Table 3. In that case, the pay-back period is about 2 years.

6.4 WHAT ARE THE BARRIERS TO DESIGN, INSTALL, AND USE BETTER DUCTWORK ?

6.4.1 Traditions, knowledge, and know-how

In many European countries, shifting to higher quality ductwork would imply changes in:

- The design methods, which imply a drastically different approach to the design process with subsequent cost, staffing and training issues;
- The manufacturing processes, which imply major investments in machine-tools as well as staffing and training issues;
- The installation methods to adapt to the changes in design methods and products;
- The TAB process (see § 6.4.4), nearly nonexistent in most cases;
- The maintenance, poorly performed nowadays; and
- The overall care for ductwork systems in the building construction process.

However, today's traditions and lack of knowledge and know-how for achieving better ductwork systems appear to be major barriers to any change in that direction.

6.4.2 Conflicts of interest in cost minimization

Cost minimization performed independently at various stages of the system construction can be extremely misleading. A classical example of such bias is a building where the investors during the construction process are neither the future manager nor the future occupants. These investors may not pay enough attention to issues such as indoor environment and energy use and authorize budget cuts that will be detrimental to both.

6.4.3 The owner ignores or underestimates the global impact of cost reductions

The owner may not understand that higher quality ductwork results in better performances, therefore potentially a better indoor environment, lower energy use, greater renting and selling value, etc. Very few owners view good air distribution system design as an investment.

6.4.4 Testing, Adjusting, and Balancing must be properly done

One of the major barriers to a global approach is that, in many European countries, commissioning is rarely done. Besides, if it is performed, it rarely results in requirements on flow balancing or air velocities for instance; rather, it focuses on safety issues such as compliance with fire safety regulations.

6.4.5 There are no incentives for doing things well

Building quality ductwork is a delicate task that requires time and skilled designers and installers. However, tight costs devoted to air distribution systems combined to little risk of penalties due to poor TAB, have encouraged design offices and installation companies to cut design time or personnel training budgets.

6.5 WHAT ARE THE BENEFITS TO DESIGN, INSTALL, AND USE BETTER DUCTWORK ?

6.5.1 For the owner

Better ductwork installations need less maintenance and use less energy, which results in reduced operating costs. It increases the overall building quality, which therefore rents and sells better.

6.5.2 For the designer

Good ductwork design reduces the risk of unpleasant surprises at commissioning that may result in penalties applied to the designer and/or the installer. It will also positively contribute to the designer's reputation.

6.5.3 For the installer

Well designed ductwork and quality products are often easier to install. A good ductwork installation reduces the risk of non-compliant installations that may result in penalties and additional work for the installer.

6.5.4 For the occupants

Quality air distribution ductworks provide better comfort to the occupants. It does not induce health problems unlike poor installations sometimes proved to be unhealthy. Finally, companies may benefit from greater productivity of their staff.

6.6 IN SUMMARY

Quality air distribution systems *can* result in lower costs. In particular, significant savings can arise from increased system lifetime, lower maintenance costs, or increased occupants' productivity. On the other hand, initially cheap low quality ductwork may prove to be very expensive in the long term. To draw adequate conclusions, decision makers must have a global understanding of potential cost reductions on specific items.

7.1 LAY OUT

7.1.1 One main system or several sub-systems?

The first logical step during the design of the ventilation and air-handling systems for a building is to decide whether the supply and extract of air should be handled by one common system for the whole building or if several systems would be better.

The following items influence this question:

- The size of the building and the airflow needed – the larger, the better reason to use several systems. In a large low-rise building the ductwork will be large, costly and difficult to accommodate if all air be supplied from one spot.
- The number of occupants – have they different demands on operation time (e.g. offices and stores do not have the same working hours so energy and costs could be saved if the system could be run according to the individual needs and not at full speed because one tenant needs it).
- Do the users have different requirements on air quality and thermal comfort? This would probably result in different technical solutions being easier to handle with individual systems. If the users or tenants will cover their own costs it will also be easier to split the cost between them if they are served on an individual basis.
- Fire zones and other safety aspects. It is often easier to design safe ventilation systems for individual fire zones than a common system that connects to several (see § 7.6).

7.1.2 Location of fans and air handling units

There are several aspects that should be considered when the location of fans and air handling units is decided:

- Try to avoid locating them near noise-sensitive areas such as conference rooms etc. (see § 7.8).
- Locate them near the areas they serve to reduce the length of feeding ductwork. This will reduce both costs and energy use and save space.
- Air handling units, AHU's, and supply fans should be located near to suitable air intakes (see § 7.1.3).
- Fans and units need regular maintenance (see § 11) to work properly and will have to be replaced when they are worn out. Plan the location to facilitate this job. Avoid locations that are difficult to reach, e.g. attic spaces or roofs (especially in cold climate and on high rise buildings). Consider carefully how this work is going to be done and what it requires. (see § 7.1.5). Do not forget that these rooms are workrooms for the maintenance personnel and should be designed and equipped as such.

Figure 33 : Large roof mounted air handling unit lifted by crane to its location

7.1.3 Location of air intakes and exhausts

The air intakes for the supply air should be located where the quality of the ambient air is good.

It is better to locate them:

- High up on the backyard side of the building than towards the street with its traffic exhausts.
- On the North façade instead of sunlit fronts.
- Away from exhausts from the same building or neighbouring buildings. Consider the predominant wind directions and the distance between intakes and outlets.
- Away from cooling towers and evaporative coolers (The first reported case of Legionella was in 1976 in the United States of America where former legionnaires of the American Army were affected by an epidemic of pneumonia during one of their congresses. The cause of the epidemic was the presence of the bacteria Legionella Pneumophila in the small water droplets spread by the air conditioning system).

The location of the exhausts is the other side of the coin. Locate them where they won't cause any problems for yourself or your neighbours.

7.1.4 Location of shafts

Study the different floors and how the supply and extract airflow is distributed. Try to find locations of the shafts as central as possible. The more symmetrical the distribution of air is in relation to the risers in the shafts the lower the cost of the ductwork will be and the less space for them will be needed.

A symmetrical "tree-structure" of the riser in the shaft and its connected ducts on the floors will reduce the pressure drop and thus energy use and will enhance the air distribution.

In larger buildings divided into several fire zones it is often an advantage to separate the supply and extract ducts in separate shafts. The shafts are then considered as separate fire zones on condition that the shaft walls are of approved performance (see § 7.6).

For structural reasons the shafts are often located adjacent to the lift shafts of the building.
In oblong buildings with lifts at both ends it might be a good idea to locate supply risers in one end and the extract risers in the other.

Observe that the shafts have to be accessible from each floor, both during installation and later on for inspection and alterations. In larger buildings with several ducts the shafts are sometimes provided with inspection doors at each floor, grating joists and lighting in the shafts.

7.1.5 Space planning – Access and space requirements

Very early during the design phase the size and location of plant rooms (see § 7.1.2) and shafts (see § 7.1.4) have to be decided.

The space planning has to include the following activities. The equipment, units, ductwork etc., has to have ample space to be (see Figure 90 and 4 next ones):

- Transported into the building which might require guy derricks, hoists, transport doors and openings
- Mounted which requires space for tools and personnel. Ductwork installations require free space for connecting the different duct parts where the demand depends on the type of ducts, circular or rectangular and whether the ducts are to be insulated on the outside (see § 8.1).
- Tested and commissioned (see § 10).
- Operated and maintained (see § 11).
- Repaired
- Substituted for new equipment when worn out or obsolete. The life span of technical equipment is much shorter than that of the building itself. Prepare for that ! (see also § 7.2).

It could come handy to have some ideas of the space requirements before the detailed design has started. The following diagrams could be used as first means of assistance and rules of thumb.

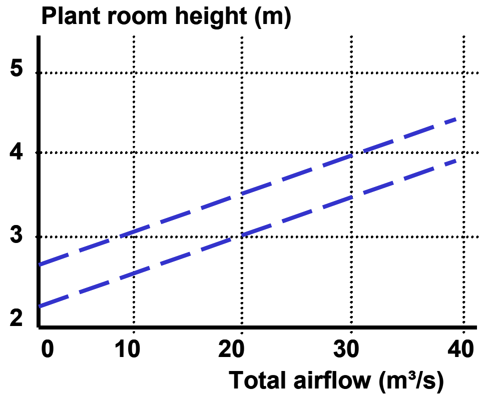


Figure 34 : Estimated room height for air handling installations

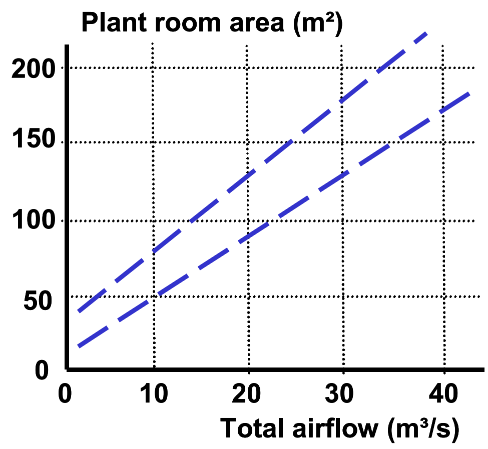


Figure 35 : Estimated plant room area for air handling installations

7.1.6 Symmetrical design

The sizing of ductwork installations is described in other chapters (see § 7.3 and § 8).

One aspect that is sometimes overlooked is the advantage of using a symmetrical design of the ductwork. When the total airflow into a large room is to be supplied equally through a number of supply air registers, the design shown in the example below results in the same duct pressure drop through all the registers. With this design the air passes through the same duct length and through the same number of bends on its way from the main duct to each of the registers.

Using a symmetrical design, with “clusters”, where possible will facilitate the adjustment of the airflow; the pressure drop being the same means that each register should be adjusted to the same position. There is no need for any control dampers except maybe between separate clusters.

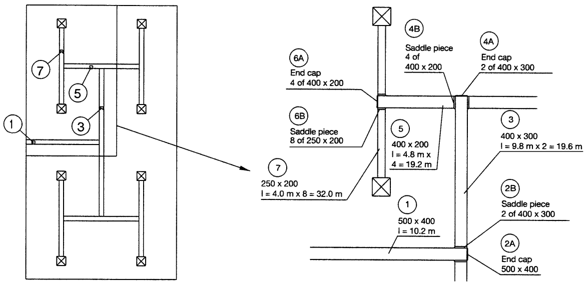


Figure 36 : Symmetrical ductwork where the supply air (entering at 1) passes through identical duct components on its way to the registers. The same principle is shown with round ducts in Figure 38.

Figure 37 : Symmetrical ducts in a warehouse

Figure 38 : Symmetrical ducts (blue) in a restaurant

This also leads to a higher degree of standardization and probably thus to reduced costs and installation time. The installation will probably also be more flexible to future changes of the airflow – if the airflow in the main duct is changed, it will result in an similar distribution of the airflow through the registers. No new airflow balancing of the registers will thus be necessary.

The ductwork installation, as shown above and in one of the case studies (see § 12.5) in this book, is easy to install and will probably lead to a more cost-effective installation.

If the registers are connected in parallel to the same duct the static pressure in the duct will vary and the registers will have to be individually adjusted with dampers to deliver the same airflow as shown below.

Figure 39 : Registers installed in parallel in a duct have to be provided with individual dampers, and perhaps also, as here, with silencers to reduce the noise from the dampers. Ducts (yellow) in a restaurant.

One important space-influencing factor is where supply and exhaust ducts have to cross. This typically happens with ductwork located at office corridor ceilings with office rooms on both sides of the corridor. As this space is normally used also for other building installations, the installations have to be carefully planned and coordinated - also regarding the time and order for the different contractors. A detailed drawing designating the space for each contractor is recommended (see § 9.2.3).

When ducts are installed in a false ceiling space the hangers for the ducts and for the false ceiling have to be integrated. As the work is normally split between two different contractors the installation work has to be planned in advance.

Another question is of course whether the false ceiling is really necessary (see § 3.2) or if the ducts may be visible.

7.1.7 Marking the installations

To facilitate the operation and maintenance of the installations (see § 11) it is necessary to have main equipment marked with designations and numbers that will be found in the operation and maintenance manuals. The maintenance personnel might not be familiar with the building or the installations and a proper marking aids them to be able to perform a correct job.

To identify the ducts e.g. in a shaft they should be marked with signs or nametapes showing e.g.:

- Content, e.g. supply air
- System designation
- Served room, zone or part of the building
- Arrow showing airflow direction

Vital equipment, e.g. fire dampers, shall be marked and the sign placed well visible. If the equipment itself is not visible – e.g. hidden above a false ceiling – the sign shall be placed on the wall underneath the damper – not on the surface of the false ceiling.

Figure 40 : Arrows showing flow direction and type of air (red for supply and yellow for extract air).

7.1.8 Make the installations adaptable (or easy to change)

It is often worth while to make the installations adaptable to future changes in demand. New tenants or changes in activities and enterprises often lead to other requirements on the building installations. How symmetrical ductwork might be one solution was discussed above (see § 7.1.6).

Well-planned and ample plant rooms for fans and air handling units is one prerequisite for adaptability but the limiting factor is often the duct installations not being able to handle an increased airflow due to noise or other aspects.

By designing duct installations for low air velocities the possibility to satisfy future demands on higher airflow will increase.

Demands on comfort cooling from the tenants in this office building resulted in the installation of an AHU comprising desiccant cooling instead of the former unit. The ductwork in the building could be retained.

The installations have a shorter time span than the building itself (see § 7.1.5 and 7.2). Be careful when using technical solutions where the installations are integrated with the building structure. This could result in costly and difficult renovations when the ductwork installations have to be replaced for some reason. "Clean" and not combined materials also facilitate increased demands on environmentally acceptable solutions requiring recycling and reclaiming of demolition waste.

7.2 COST – ECONOMICAL ASPECTS

Duct costs vary from country to country, from time to time, and can thus only be expressed here as relative and not actual costs. One interesting comparison is between circular and rectangular ducts and some of the differing cost aspects for these two alternatives is discussed (see § 8.2).

Cost minimization is an important boundary condition for ductwork design. When choosing between different layouts of a duct system, all able to fulfill the primary functions required, the alternative using least resources, based on the lifetime performance, should be chosen. Provided that the price of different resources as energy, material, and building space is adequate, this choice can be based on cost minimization.

Ventilation systems often account for the lion's share of a building's energy use. In another chapter (§ 7.4.2.2) it is e.g. shown that the pressure drop in air filters accounts for a significant portion of the total pressure drop in a ventilation system. If several alternatives are available then one should select filters based on energy efficiency without compromising filtration requirements. For economical reasons it can be advisable not to run the filters until the pressure drop has reached their maximum nominal values provided by the manufacturers but change them earlier. The recommendation to calculate the Life Cycle Cost (LCC) for actual alternatives should also be used when selecting among different ductwork alternatives.

The ductwork in a building will probably be used for at least twenty years (see § 7.1.5). The investment cost, the cost for used building space and the annual energy and power costs (electricity) during the useful life or utilisation time of the ductwork are converted to a net present value in the LCC calculation.

$$NPV = CC + OC \times \sum_{k=1}^{n} \left(\frac{1+j}{1+i} \right)^{k} + RC \times \sum_{p} \left(\frac{1+j}{1+i} \right)^{n_p}$$

where:

NPV = the Net Present Value (currency);
CC = the capital cost (currency);
OC = the operating cost (currency);
RC = the replacement cost (currency);
i = the discount rate (-);
j = the inflation rate (-);
n = the number of years over which the analysis is performed (-);
n_p = a year during which a replacement cost is foreseen.

Note that different discount and inflation rates can be applied to individual components of cost (e.g. energy cost, maintenance cost, etc.).

The reader may refer to ASHRAE (1999) for further details on LCC calculations.

A corresponding procedure is adopted for future maintenance costs, e.g. internal cleaning of ducts. The alternative with the lowest LCC cost should be chosen as being “best buy”.

The investment cost for the ductwork comprises of costs for

- material;
- manufacturing;
- transportation;
- insulation (including recycling costs);
- building space;
- installation of the ducts;
- and cleaning and maintenance.

The cost for building space is probably the most difficult factor to consider in the calculation. The cost depends on how the saved space for a less space consuming alternative could be used and what profit that could be gained by doing so. In a high rise building with vertical ducts installed in shafts, a smaller space need by an alternative could increase the rental income considerably as it adds up on each floor. One of the presented case studies shows an interesting example on this (see § 12.2).

Figure 41 : Installation of vertical ducts in a high rise building in a space saving manner.

The same is the case if the space needed for the ductwork would influence the necessary height between the floors. The extra space needed per floor times the number of floors could add up to a missed floor in a high-rise building. One way of reducing this space need might be to refrain from using false ceiling at least locally as discussed elsewhere in this book (see § 3.2). Another of the case studies illustrates this.

For a given existing duct, an airflow rate change will influence:

- the air velocity
- the pressure loss (varies typically as $v^{1.8}$ even though v^2 is often used[5]);
- the fan power (varies typically as $v^{2.8}$ even though v^3 is often used)[6];
- the pressure distribution in the ductwork;
- the quality of air distribution;
- the noise generation;
- the costs for ducts, insulation, heat losses, space, installation, maintenance, and more.

When the air flow rates and the lay out of the duct system have been chosen, the next step is to size the ducts, that is to decide the diameters (or equivalent diameters) of different parts of the ductwork.

For a given airflow rate the air velocity in the duct (v) influences:

- the duct diameter (D) to be chosen (D varies as $v^{-0.5}$ at constant airflow);
- the pressure loss (varies typically as $v^{2.4}$);
- the fan power (varies typically as $v^{2.4}$);
- the pressure distribution in the ductwork;
- the quality of air distribution;
- the noise generation;
- the costs for ducts, insulation, heat losses, space, installation, maintenance, and more.

Duct sizing can be treated as an economical cost-minimizing problem as all costs increase for larger duct diameters except the fan energy cost, which decreases. This optimization is much influenced by the fan energy demand that rapidly increases when smaller ducts are chosen. For Swedish conditions, “economical velocities” have been shown to be in the range 7-4 m/s. In practice, noise generation often is a limiting factor resulting in velocities lower than the “economical” in ducts close to the served rooms.

Control of the air distribution is easier when duct air velocities are low. Flow energy losses are then small which gives more uniform pressures in the system and bigger authority to dampers and air terminal devices. Low air velocities also mean bigger flexibility, as e.g. additions to the duct system are easier to handle and there is a margin for airflow rate increase. Low air velocities also decrease the risk for noise problems.

Good function of the duct systems main object, air distribution, is the priority. Duct cost, noise generation, etc. are very important but have the character of boundary conditions. From this aspect cost minimization is only feasible when all function criteria

[5] The pressure loss caused by friction is proportional to the dynamic pressure, which in turn is proportional to the velocity squared, that is $\Delta p \propto v^2$. However, the friction factor decreases with increasing velocity (compare the Moody chart - Figure 42) which results in $\Delta p \propto v^{1.8}$

[6] The fan power is proportional to the product of flow rate (which is proportional to v) and Δp

are met. The function criteria should have been adapted to the budget frame in an earlier stage of the project

Historically, common sizing methods in "low velocity system" are:

- **Equal Friction**. This method gives higher velocities for the larger duct size for the fan. Typical friction value is *1 Pa/m.*
- **Choice of velocity**: different in different parts of the system (values normally in the range 6-2 m/s, the higher values closer to the fan. When space is expensive, as in high rise buildings and ships, the velocities are higher.)
  This method can be regarded as a variation of the equal friction method, where consideration has been taken to noise generation aspects. Based on literature studies and Swedish experiences, the following suggestions can be given:

	Air velocity (m/s)	
	Dwellings	Offices, schools
Main ducts	4	6
Branch ducts	3	4.5
Duct with air terminal device	1.5	2

Table 4 : Duct velocity recommendations. In offices, higher velocities can be used for ducts in fan rooms and shafts.

- **T-method.** This method represents here a class of ductwork cost minimizing methods taking into account the actual costs, which apply to the specific building being designed. It is a method intended for use with computers. As cost for different types of ducts and for electrical energy can vary rather much, such methods have a potential to save energy, especially in uncommon applications, where standard methods, developed with experiences from normal systems, are not applicable.

When making the cost minimization, or developing simplified rules as those mentioned above, it is very difficult to take all relevant factors into consideration. A fourth alternative is the "constant diameter method" which typically gives high costs as estimated traditionally. But a constant diameter duct system has many advantages, which are appreciated today, as simple installation logistics and high flexibility (it is difficult to reverse the flow distribution in a system with small diameters in one end and big in the other!). Thus the use of “constant diameter” seems to increase, especially in the part of the systems that are visible.

7.3 DUCT AIR FLOW

The airflow in ventilation air ducts is stationary, or can be treated as stationary because flow variations are slow. The driving force is a pressure difference caused by temperature differences, wind pressure, or a fan. As the pressure variations in a ventilation system are small in comparison with the atmospheric pressure the airflow is treated as incompressible (because it is simpler) when making pressure loss calculations. (In reality, air is of course compressible and behaves nearly as an ideal gas. This means that the expansion process associated with the pressure losses in duct air flow is isothermal while the compression process at the fan causes a temperature increase).

A force has to be applied in the flow direction to sustain the flow and overcome the pressure losses. This causes the pressure to decrease along the duct. These losses are divided into flow friction losses and component losses, e.g. in bends and T-junctions. Both types of losses are associated with losses of momentum. Duct friction losses are caused by high velocity air in the middle of the duct which looses momentum when it is brought into the low velocity region around the perimeter of the duct by the turbulence, and the need to continuously accelerate the air which is instead transported into the high velocity region. Component losses are often associated with local acceleration of air (e.g. due to contraction phenomena) and the following loss of momentum when the air is slowed down. To minimize losses it is thus essential to design the ductwork so the flow is disturbed as little as possible.

7.3.1 Pressure losses

Duct air flow is associated with pressure decrease in the flow direction.

The pressure losses are due to flow friction and local flow disturbances in components. Both types of losses are caused by local velocity changes:

- Flow friction corresponds to the force needed to accelerate air leaving the low-speed region along the duct perimeter and entering the high-speed region in the central part of the duct;
- Component losses correspond to the force used for local increase of mean air speed in the ductwork.

To minimize pressure losses the flow shall be as smooth and even as possible:

- Avoid abrupt area changes, sharp bends with no vanes, and similar;
- Avoid duct components closer than 5 duct diameters from each other.

The largest local mean air velocity in a ductwork often is in a fan outlet connection to the duct. This is the most important place to have smooth flow conditions, as pressure losses can be large.

As the pressure losses depend on velocity, they are normalized with the dynamic pressure. For a part of a straight circular duct of constant diameter D and length L, the pressure loss due to friction between section 1 and section 2 is (λ_f : is the friction factor):

$$\Delta p_{12} = \lambda_f \frac{L}{D} \cdot \underbrace{\frac{\rho v^2}{2}}_{\text{dynamic pressure}}$$

v (m/s) is the mean velocity defined as the ratio of volumetric fluid flow rate q_V (m^3/s) and duct flow area A (m^2).
For a circular duct:

$$v = \frac{4 q_V}{\pi D^2}$$

D = duct diameter (m)

The corresponding force acting on a volume of air in a duct with square area A (m²) is $\Delta p_{12} \cdot A$ (N). For the passage from section 1 to section 2 (distance L m) the air needs t seconds. Thus $L = v \cdot t$.

The displacement work is:

$$\Delta p_{12} \cdot A \cdot L = \Delta p_{12} \cdot A \cdot v \cdot t = \Delta p_{12} \cdot q_V \cdot t$$

The friction factor λ_f is a function of Reynolds number Re (the product of mean duct air velocity v (m/s), duct inner diameter D (m), and the inverse value of the kinetic viscosity ν (m^2/s) of the air) and the duct relative roughness k/D (where k is the mean roughness (m)). If these values are known, the friction factor can be found in a Moody chart, see Figure 42.

According to Miller (1972) the Moody chart can be approximated with the formula

$$\lambda_f = \frac{0.25}{\left[\log\left(\frac{k}{3.7D} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2}$$

In order to make pressure drop calculations in rectangular ducts easier, an "equivalent diameter D_e" has been defined. This is the diameter of a round duct which has the same pressure loss for friction as the rectangular duct at the same air flow rate:

$$D_e = \frac{1.30(ab)^{0.625}}{(a+b)^{0.25}}$$

where a and b are the side lengths of the rectangular duct. Friction data for circular ducts can then be used also for rectangular ducts with aspect ratios a/b <8.

Beside friction, pressure losses due to flow disturbance also occur in *bends, T-junctions and other components*. This is illustrated by Figure 43 below.

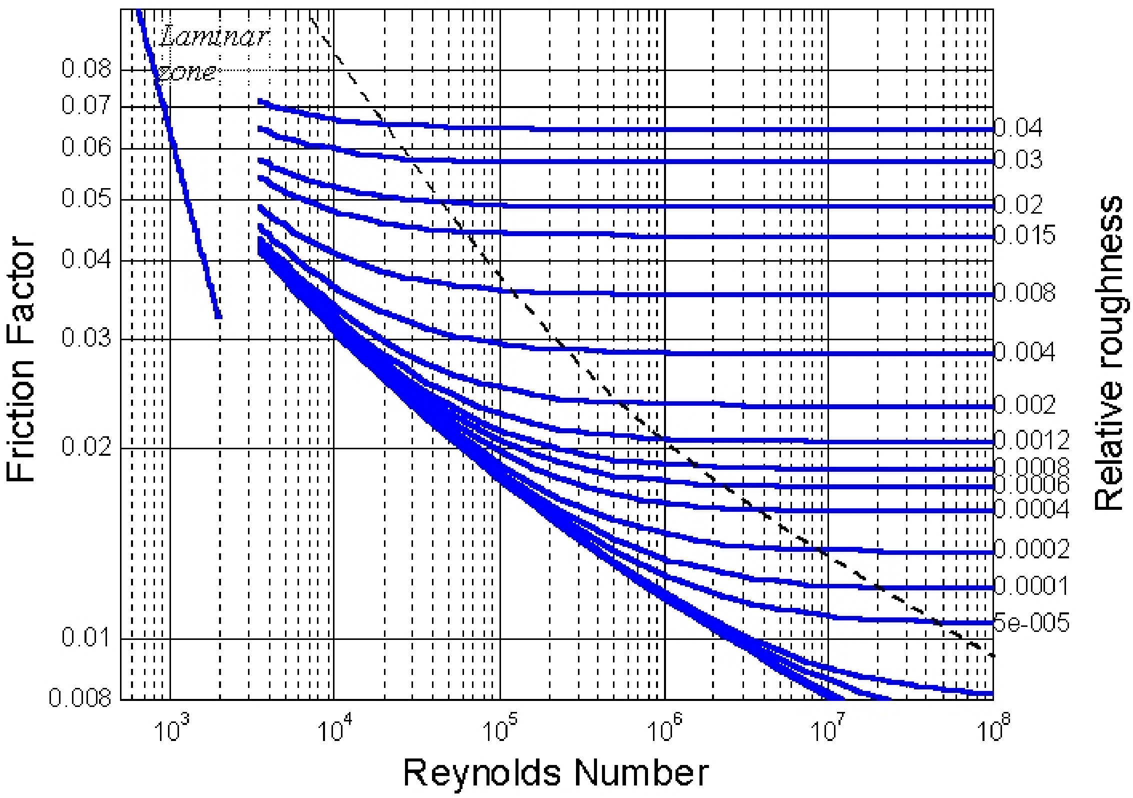


Figure 42 : Moody chart

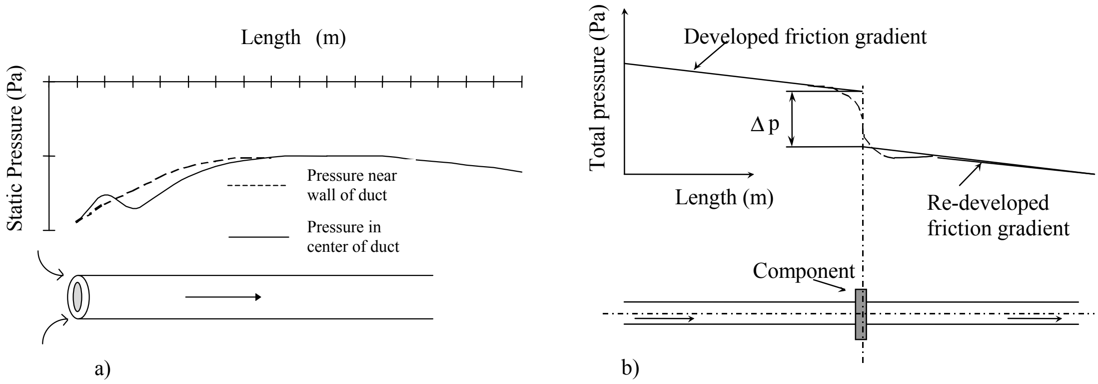


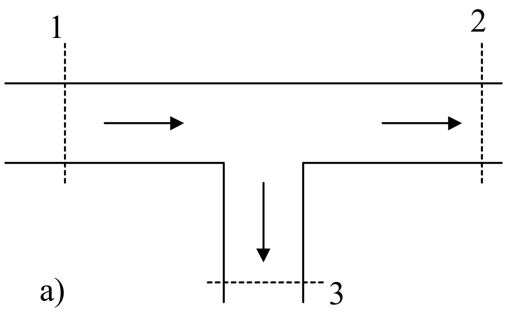
Figure 43: Pressure gradients a) Static pressure measured with a Prandtl static probe in the centre of a duct, downstream of an exhaust terminal device. b) Definition of component pressure drop. After Miller (1978). The graph illustrates the case that airflow rate and duct diameter is constant as the slopes of the friction lines are the same in front of and behind the obstacle. .

As is shown in Figure 43b, the loss coefficient definition is based on the extrapolated pressure difference in the plane of the component. This is to allow for the customary calculation of duct friction losses, based on the total duct length. In Figure 43b the pressure difference Δp could be interpreted as a difference in static pressure. However, please note that the dynamic pressures before and after the components are equal (the friction gradient is the same as are duct diameter and flow rate). The loss coefficient ζ_{12} is always based on the difference in total pressure, i.e. the sum of static and dynamic pressure:

$$\Delta p = (p_1 + \rho \frac{v_1^2}{2}) - (p_2 + \rho \frac{v_2^2}{2})$$

$$\Delta p_{12} = \zeta_{12} \cdot \rho \frac{v_1^2}{2}$$

Pressure loss coefficients for T-junctions need special attention as the flow rate changes. The loss coefficient is always based on the mean velocity in the leg of the T-junction with the total flow, leg 1 in Figure 44a and Figure 44b.



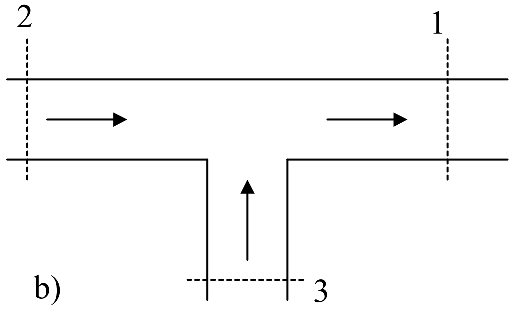


Figure 44 : Flow in dividing and combining T-junctions.

Of special interest is the case with a sudden area increase of the duct resulting in a velocity decrease and increase in static pressure. The net effect is a ”total pressure” loss (the loss of dynamic pressure is bigger than the increase of static pressure). A corresponding effect can be achieved in the main duct after a T-junction, where air has been extracted. If the diameter of the main duct is not reduced, the velocity will decrease and dynamic pressure will transform to static pressure. In this way static pressure can be kept more constant along the duct, which makes flow balancing much easier. The corresponding duct sizing method (“static regain”) has the disadvantage of high air velocities in part of the duct system.

For pressure loss coefficients see handbooks as ASHRAE Handbook, Eurovent, national handbooks and catalogues.

7.3.2 Driving forces

The forces sustaining the airflow in the ducts are :

- Thermal forces;
- Wind forces;
- Fan forces.

Thermal and wind forces are natural forces and fan force is a mechanical one. Using the natural forces can save energy, normally electrical energy.

The thermal force depends on the density difference between surrounding air (normally outdoor air) and transported air. The gravitational force acting on a column of air of 1 m^2 square area and with a height of H m, that is a volume of 1·H m^3 and a mass of 1·H·ρ (kg) (where ρ is the density in kg/m^3), is 1·H·ρ·g (N). This corresponds to a pressure difference of H·ρ·g (N/m² or Pa). This pressure difference acts between the ventilation air intake and exhaust. If it is colder outside than inside the density of outdoor air is bigger and the pressure difference acts upward on the lighter air.

$$\Delta p_T = H \cdot g \cdot (\rho_o - \rho_i)$$

ρ_o : density of outdoor air (kg/m^3)
ρ_i : density of indoor air (kg/m^3)

Note that ρ_i shall be the mean density of indoor air, in proportion to the corresponding vertical distance. This is of importance as air heaters may be located at a different level than the intake, and there may be heat recovery of exhaust air.

The wind force creates an overpressure on the wind side and underpressure on the leeward side (see Figure 21), and often also on the sides parallel with the wind direction. These pressure differences can be estimated as a function of the wind speed (v_w):

$$\Delta p_w = C_w \cdot \rho \frac{v_w^2}{2}$$

Many solutions exist that actively use the wind speed, especially on the exhaust side. Examples are hoods, which rotates so the opening always is on the leeward side, nozzle shaped and disc formed covers above the exhaust opening creating an under pressure independent of wind direction, and more (Figure 45).

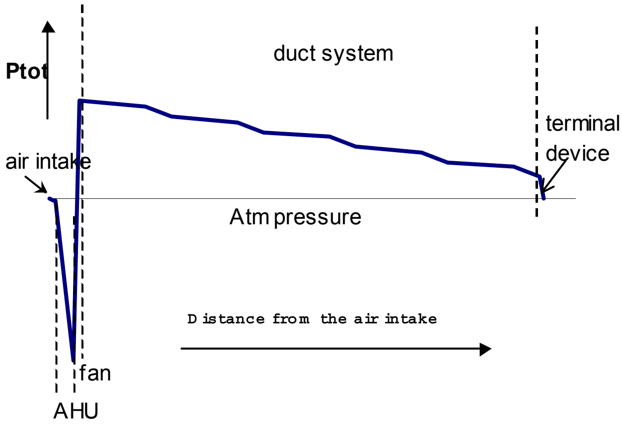


Figure 45 : The pressure distribution in a supply duct system

The fan increases the pressure. This is defined in analogy with the component pressure loss (but in this case it is an increase):

$$\Delta p_{fan} = (p_1 + \rho \frac{v_1^2}{2}) - (p_2 + \rho \frac{v_2^2}{2})$$

Δp_{fan} is the sum of all the losses. The energy to sustain the flow between locations 1 and 2 in a duct has been shown above to be $\Delta p_{12} \cdot q_V \cdot t$ (Nm). The work the fan adds to an air flow of q_V (m^3/s) during a time t seconds is in consequence:

$$W = \Delta p_{fan} \cdot q_V \cdot t$$

If the total efficiency of the fan is η the corresponding electrical energy is E (Ws):

$$E = \frac{\Delta p_{fan} \, q_V \, t}{\eta}$$

7.3.3 The fan curve

The fan curve is a graph of the increase of total pressure the fan is able to create at different air flow rates. Different fans have different characteristics.

Figure 46 shows typical fan curves for (from top) centrifugal fan with forward curved impeller, centrifugal fan with straight impeller, centrifugal fan with backward curved impeller, and axial fan. Normally, the highest efficiency of the centrifugal fans has the one with backward curved impeller and lowest the one with forward curved impeller.

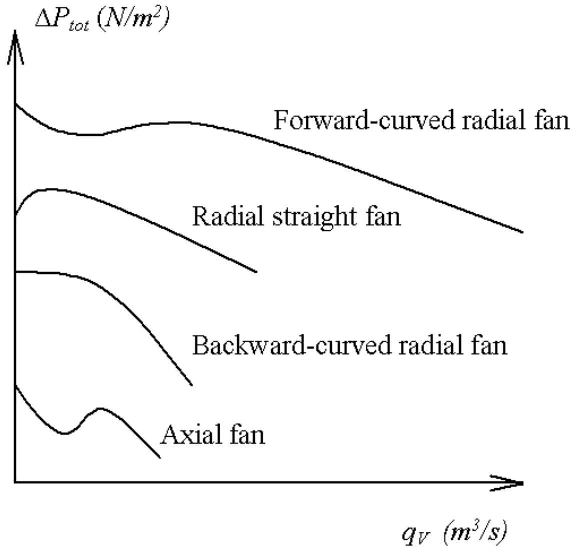


Figure 46: Examples of fan curves for different types of fans

The fan imposes both dynamic and static pressure to the airflow. The total pressure is the sum:

$$\Delta p_{tot} = \Delta p_s + \Delta p_d$$

It is common to express the relation between the dynamic and total pressure as

$$L = 10\sqrt{\frac{\Delta p_d}{\Delta p_t}}$$

L is a dimensionless number.
L = 10 means that the fan only creates dynamic pressure, i.e. movement; in that case, the fan is not connected to a duct. L < 2 and L > 7 should be avoided. Often the highest efficiency occurs for L = 2 to 3 for a centrifugal fan and L = 5 for a radial fan (Figure 47).

7.3.4 System Curves

The system curve is a graph of the total pressure loss of a duct system (or a supply duct, room and exhaust duct combination if there is only one driving force) as a function of the volumetric flow rate. Duct friction typically varies as $q_V^{1.8}$. (Compare the Moody chart, Figure 42.)

Systems often have components where pressure loss varies almost proportional to the flow as some filters and rotating heat exchangers. This indicates that the flow partly is laminar due to narrow flow passages. It is thus necessary to add all the pressure losses at various flow rates in order to make a system curve (and not just assume that the pressure loss varies as a power law function of the flow rate) if a particular system shall be studied.

The system curve is constructed from the sum of pressure losses at different flow rates. However, due to interactive behaviour of the flow in different components the real pressure loss for the system may differ from this sum. This is called the "*system effect*" and usually means that the actual pressure need is somewhat bigger than the calculated. A big such influence often occurs at the fan connection. Therefore, be sure that the fan data are measured with the same type of connection as is used in the system being designed.

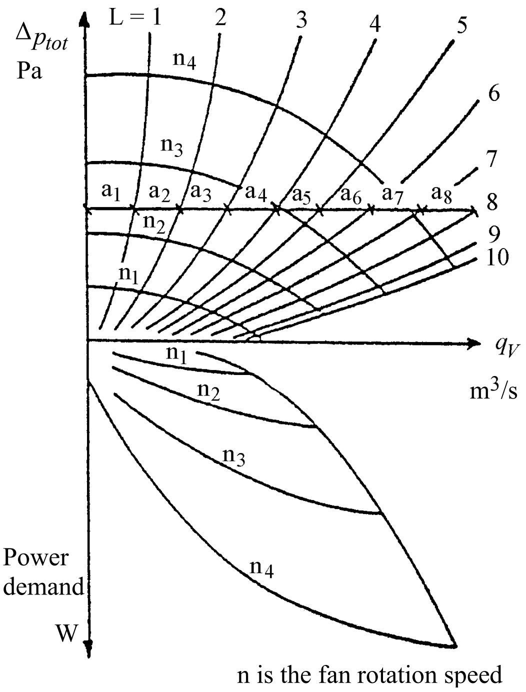


Figure 47: Fan graph with curves for different rotation speeds n, working lines 1-10, and power demand.

7.3.5 The working point for a fan

The working point is at the intersection between the fan and system curve, see Figure 48.

The figure shows two fan curves, one (whole line) at a rotation speed n and another for a lower rotation speed n_1. There are also two system curves, one lower (whole line) and one higher where additional pressure losses have been imposed. The point 1 is the original working point, 1' the working point after reduction of rotating speed to n_1, and 1'' the working point with the original rotation speed n but with additional pressure loss in the duct system.

Thermal or wind induced forces create a pressure independent of the airflow. Their equivalent to the fan curve is a straight line, parallel to the x-axis. The lines move up or down depending on temperature or wind speed. This pressure difference typically is small compared to those created by fans. “Natural” ventilation systems thus must be equipped with larger ducts than mechanical systems.

Example of fan calculations:

What effect will the following conditions have on the fan’s operating point ? (Figure 49)

1. A hole in the ductwork;
2. Clogged filters;
3. Exhaust opening is on the windward side;
4. A device that needs a pressure Δp_m to open.

Answers :

1. The air will always follow the path of least resistance. The hole in the ductwork will decrease the resulting resistance of the duct system. In this case, the system characteristic curve will shift down and the airflow rate through the fan will increase (point A in Figure 49). Note however that the flow rate through the terminal devices will decrease.
2. Insufficient filter cleaning will lead to higher filter resistance. The airflow rate will decrease and the system characteristic curve will shift up (point B in Figure 49).
3. The exhaust opening on the windward side of the building (where a local over pressure is created) increases the flow resistance in the duct system. The system curve will shift upward in the graph. As the pressure increase is independent of the duct airflow, the upward move will be as illustrated in Figure 50. The fan curve will not change and the flow will decrease somewhat as the working point will shift to the left in the graph.
4. Devices like some VAV boxes do not open until the pressure has raised a certain value like Δp_m in Figure 50. This case thus is similar to case 3.

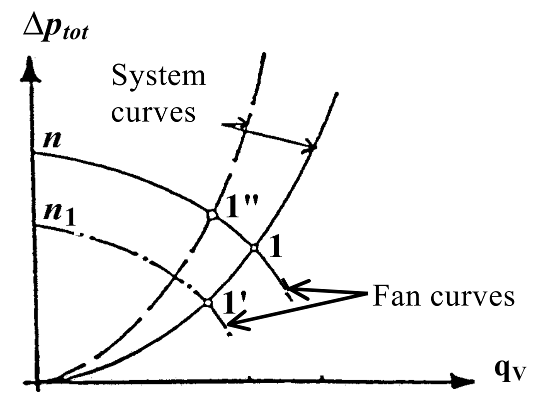


Figure 48: Illustration of the fan working point

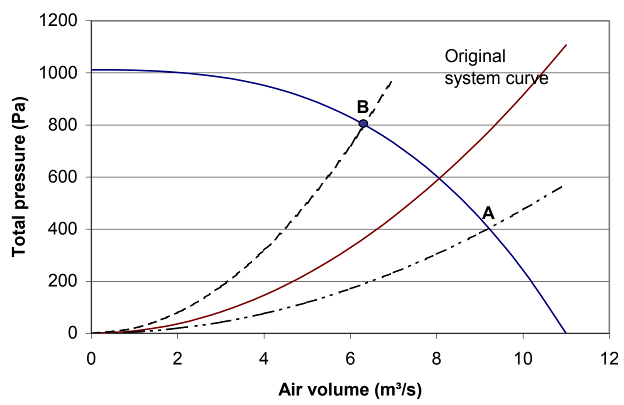


Figure 49 : Illustration of working points for fans

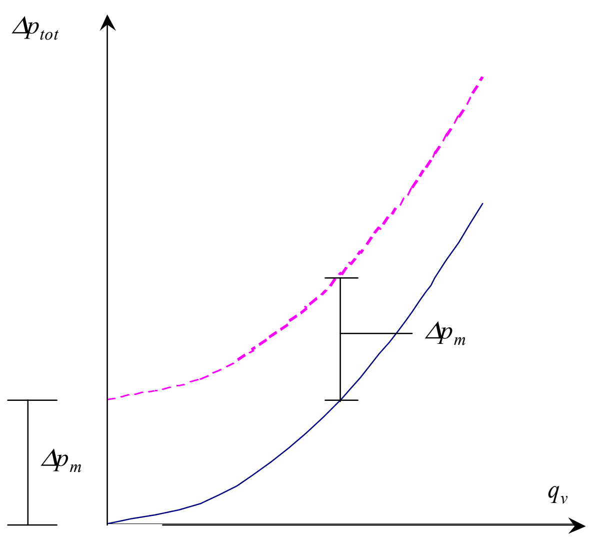


Figure 50: System curve when there is an initial resistance, which has to be created before flow can begin.

7.4 HYGIENE

Supply air ducts distribute ventilation air to the building. It is thus essential that they do not pollute the air. Such pollution can be caused by materials in the duct like oil residues from the manufacturing, rubber seals, or lining. Care must be taken when manufacturing the ducts so production methods and materials that do not cause such pollution should be used. Deposits of particles or dirt in the duct can also cause pollution. If water is added to such deposits microbial growth will probably occur.

Also return air ductwork should be clean, to prevent flow decrease caused by fouling.[7] If return air is used, it is of course still more important to keep the return ducts clean. (see § 7.4.6)

Figure 51 : Large ducts protected with end covers

It is most important that the ducts are protected from dirt during transport to the building site, during installation, and before the system is used. If such protection is not possible or feasible, the ducts have to be cleaned before they are used. Checking of duct cleanness should always be a part of the commissioning process.

When in use the air is cleaned by a filter that also protects the duct. It is important that the filter does not break, or that dirty air cannot pass beside the filter or leak into the duct downstream of the filter.

The duct has to be equipped with inspection and cleaning openings. As this probably increases duct leakage, unnecessary openings should be avoided.

7.4.1 Air intake

As pointed out in § 7.1.3, the air intake has to be located where the air is as clean as possible. It should not be close to air exhaust openings, if possible the distance should be at least 10 m. Of course locations close to other sources of pollution (like chimneys, cooling towers, roads with traffic, garages, parking lots, and similar) also cause pollution of the air. To avoid the highest concentration of particles from cars, the intake should be located more than 3 m above the road.

Important for duct hygiene is that water (rain or snow) not is brought in with the intake air. The grille protecting the intake must be big enough to result in a low air velocity (front air velocity <3 m/s) to achieve this. An important function of the grille is to protect the intake from birds and other animals. To achieve this the grille is often supplemented by a net. The net grid size should not be too small in order to avoid blocking by leaves etc. In Norway a grid size of 5-12 mm is recommended. It is most important that the grille and net are well maintained. If the intake is located so it is difficult to inspect and clean it, and if there is risk for blocking it with leaves, ice or similar, the grille should be easy to open. When the risk of ice on the grille is high, a heated grille may be considered.

Interior lining should be avoided in the intake duct because of the risk of water penetrating through the intake. When there is risk for condensation, insulation and vapour barriers as appropriate should be installed on the outside of the duct. The duct between intake and air handling unit shall be as short as possible. There should also be possibilities for inspection, draining and cleaning. The drain must not be directly connected to the sewage system (because of the danger of ejecting polluted air).

7.4.2 Air Handling Unit

The air-handling unit (AHU) could consist of the following parts:

- Outdoor air damper
- Filter
- Exhaust air heat exchanger or if return air is used, a mixing box
- Heater
- Cooler
- Humidifier
- Fan

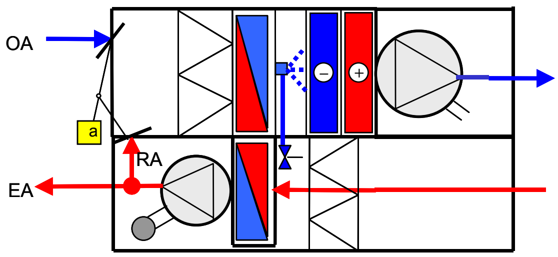


Figure 52 : To reduce the energy used for heating/cooling the AHU should either be equipped with a heat exchanger or – if the extract air has an acceptable quality – use return air. The shown unit has both possibilities!

[7] and to prevent pollution of air that flows backwards into the building by mistake. This risk should be eliminated when designing the system.

7.4.2.1 Outdoor air damper

The outdoor air damper can easily be fouled which deteriorates the function, it could e.g. cause air leakage because of incomplete closing of the damper. Fouling decreases if high air velocities in the damper are avoided. It should be designed and installed so it is easy to inspect and clean. It is important from an energy point of view that it is tight when closed. When the system is not in use the closed damper should also prevent tendencies of backward flow in the supply duct, which could cause fouling of the parts of the duct then not being protected by a filter.

The outdoor air damper is often located close to the filter in the AHU. It is then important that the damper has the same area as the filter, otherwise the full filter area will not be used as the air approaches the filter in a jet flow, hitting only a part of the filter area.

7.4.2.2 Filter

The filter should have a large area resulting in low air velocity. It should have a pressure-drop measuring device to check the degree of fouling of the filter. A large pressure drop indicates that it is time for filter change.

Fouled filters steal fan energy, emit dust during start-up of the system, and increase the risk for filter damage. They can also cause smell penetrating into the building.

The space around the AHU should allow easy filter changing.

It is important that the filter does not allow any unfiltered air to bypass it. This could happen if the filter is damaged or if air leaks around the filter frame or between the filter frame and the AHU casing. Control and, if necessary, sealing is vital for function and hygiene, see Table 6.

It is most important to prevent water from penetrating the filter. The filter should also if possible be protected from high relative air humidity (RH >80-90%). If this is not possible (for instance if it is installed too close to the air intake), the filtration should take place in two steps. The second filter should then be installed where it will not be exposed to high RH thus effectively preventing the growth of micro-organisms and particles.

Filters are classified in classes G (G1-G4) and F (F5-F9). The higher the number the better the arrestance (G) and dust spot efficiency (F-filters).

When to use what ?

- G1 and G2 are efficient for fibrous and coarse industrial dust
- G3 and G4 also take coarser atmospheric particles
- F5 and F6 also protects against finer atmospheric dusts and somewhat reduces "blackening" of the protected equipment
- F7 and the best filters of class F6 (dust spot efficiency >75%) keep ductwork and ventilation equipment clean
- F8 reduces tobacco smoke and bacteria
- F9 are mainly used for very high demands like optical industries, operation theatres in hospitals, etc.

Filtering in two steps or more can be used either to prevent moisture problems or to prolong the lifetime of the better filter. The latter should be regarded as an economic problem. To reduce the energy use, the pressure drop over the filters should be kept as low as possible. Use of higher quality and/or dirty filters increases the energy use. It is therefore advisable to replace filters earlier than at their nominal end pressure drop (250 Pa for filters class G and 450 Pa for filters class F according to EN 779 [Ref 29]). These pressure drops are high compared to other pressure drops in the system.

Tightness

It is important that the air filters are properly installed and that the tightness and condition of the filters must be checked regularly by visual inspections of the installation. No visual leakage or traces of leakage should be accepted.

Eurovent 4/10:1996 - In Situ Fractional Efficiency Determination of General Ventilation Filters [Ref 33] describes a method of measuring the performance of general ventilation air-cleaning devices in an installation. This method makes it possible to compare laboratory tests and check the air filter properties in real life. Eurovent 4/10 is a recommendation or guideline when testing an installation in situ and covers the measurement of air flow, pressure loss and fractional efficiency.

Acceptable filter bypass leakage is defined in the EN 1886:1998 [Ref 28] according to Table 5. The norm defines different leakage rates in percentage depending on the filter class.

Filter class	G1-4	F5	F6	F7	F8	F9
Total leakage in % of nominal air flow	-	6	4	2	1	0.5

***Table 5:* Acceptable total leakage, 400 Pa test pressure. EN 1886:1998.**

Outdoor Air Quality	Indoor Air Quality			
	IDA 1 (High)	IDA 2 (Medium)	IDA 3 (Acceptable)	IDA 4 (Low)
ODA 1 (pure air)	F8	F7	F6	F6
ODA 2 (dust)	F6/F8	G4/F7	G4/F6	G4/F6
ODA 3 (gases)	F6/F8	F7	F6	F6
ODA 4 (dust + gases)	F6/F8	G4/F7	G4/F6	G4/F6
ODA 5 (very high conc.)	F6/GF*/F9	F6/GF*/F8	G4/F6	G4/F6

** GF = Gas filter (carbon filter) and/or chemical filter*

Table 6: Recommended filter classes according to prEN 13779

7.4.2.3 Exhaust air heat exchanger

Heat exchangers (see Figure 25) for heat recovery between exhaust and supply air are rotary (regenerative), or cross flow (direct plate exchangers - recuperative). If the supply and exhaust ducts cannot be located beside each other, water-loop heat exchangers connected with piping are often used.

Besides fouling, leaking of return air into the supply side is a frequent problem. This is particularly the case with rotary wheel exchangers, but happens also with plate heat exchangers, especially if they have been exposed to frost. To avoid such leakage, pressure should be somewhat higher on the supply side than on the exhaust side. Recovery systems should be easy to inspect and clean and also possible to disinfect. Filters should protect the equipment also on the exhaust side, for plate heat exchangers to protect from fouling, for rotating heat exchangers also because particles otherwise can be transported over to the supply air.

It is important that condensed water can be taken care of in the warmer section of the airflow. Need for defrosting must also be analyzed.

7.4.2.4 Air heaters and air coolers

As already discussed for heat recovery systems, heating and cooling coils should be protected from dirt. Air coolers often operate below the dew point of the air. Cooling coils must thus be provided with drainage designed in such a way that there is no risk for ejection of polluted air from the sewage system. Cooling coils should be provided with a drip-plate below the coil, and a droplet separator downstream. Coolers should not have filters or silencers directly downstream. The equipment should be easy to inspect and clean.

To avoid too high relative air humidity downstream of the cooling coil, this must be shut off before the other parts of the AHU (except the humidifier) when closing down the system.

7.4.2.5 Humidifiers

The humidifier should be designed so it is easy to inspect, clean, and disinfect. It should be provided with a drip-plate, drainage, and a droplet separator.

Material like plastic or stainless steel, not promoting microbial growth should be preferred for hygienic reasons (risks of Legionella, see § 7.1.3). Steam or direct water humidifiers are safer than humidifiers circulating water. Scheduled cleaning of the humidifier is also necessary for the same reason.

The humidifier shall be controlled so the relative air humidity, RH, in the system, especially at the filter, does not exceed 90%.

To avoid humidity downstream of the humidifier, this should be shut off before the other parts of the AHU when the system is closed down.

7.4.2.6 Fans

The fan should be possible to inspect and clean. Especially free-sucking belt driven fans can emit particles to the supply air. Big belts are better than small in this aspect. The fan should have a smooth start to avoid emission of particles from the belts to the supply air.

When a high quality filter is used as the second stage it should be located downstream of the fan to avoid risk of leakage of polluted air into the system.

7.4.3 Sound absorbers

Like all other parts of the system, silencers shall be accessible to inspection and cleaning. Porous sound absorbing materials should be possible to clean without this causing any deterioration of the absorption properties. Duct-mounted sound attenuators should be dismountable for cleaning or exchange. Mineral wool and glass fibre should be covered with perforated steel plate to reduce the risk of erosion by the passing air.

7.4.4 Supply air ducts

The ductwork should be possible to clean, but too many inspection openings should be avoided to minimize cost and leakage. The ducts should be inspected at regular intervals.

If there is a risk of condensation at the ducts outside or inside, they should be insulated and provided with a moisture barrier. Inside insulation should be avoided, especially if there is any risk of water, through penetration or condensation.

7.4.5 Extract air ducts

If return air is used, it is important for the air quality that the extract air ducts are clean. Heat recovery equipment in AHUs should also be protected from fouling, often by a filter located directly upstream of the unit. Severe fouling can also result in decreased airflow and unbalance in the duct system. Exhaust air ductwork should therefore be easy to inspect and clean. Although it is not normal practice today, filters, located close to, or combined with, the air terminal devices could also protect the ductwork. The increased fan energy use due to the filter pressure drop must of course be considered before such decisions are made.

7.4.6 Duct cleaning

7.4.6.1 Why?

There are three main reasons for cleaning ducts:

- the ducts are blocked by pollutants to such a degree that the function is deteriorated, the pressure drop has increased and the airflow has dropped, or,
- the inside of the ducts has been covered by inflammable pollutants that can be ignited and cause a fire or explosion, or
- the ducts contain annoying contaminants or contaminants creating a health hazard if they are released to the room where they might hurt occupants.

Figure 53 : Clean-out and inspection openings on vertical duct (left) and horizontal ducts.

7.4.6.2 Cleaning necessary for keeping the function of the duct system

A risk for deteriorated function as consequence of blocked ducts has been found in extract air ducts, e.g. from bathrooms in dwelling houses.

These extract registers are normally connected to ducts with small dimensions. Ducts with a diameter of 80-mm do not stand for any considerable additional build-up with contaminants on the inside before the area is choked to such a degree that the airflow becomes insufficient.

This is true for extract registers in bathrooms in particular, as the extract air is humid and also often contaminated with textile fibres from towels and drying laundry. When the vapour condenses on the inside of the duct wall the surface becomes moist and the fibres then will stick to it. But this is something that primarily happens near the duct inlet, on the first half metre, and can easily be taken care of from the room if the register is taken down.

In other cases the contaminants may enter the duct system in a more unplanned way. They could e.g. be the result of broken supply air filters, or created by air that is bypassing the filters through leaks or, after the plant has been in operation for a long time, been built up by the contaminants that are not caught in the filters but passing through. Cleaning of ducts should here form a part of the preventive maintenance.

7.4.6.3 Duct cleaning to prevent fire and explosion

Ducts transporting inflammable or explosive pollutants are to be cleaned regularly as part of the national fire codes.

There are several examples when this is applicable for ducts. Extraction from spray-paint booths, from stoves, roasting-ovens and deep-fry pans in restaurant kitchens and from bakery ovens are some examples of systems where the prime solution is to prevent the contaminants to enter the duct, e.g. by using a grease filter above the stove.

When designing and installing these types of ducts, special care should be taken. Location of clean-out openings and other devices that will facilitate the cleaning e.g. wires inside the ducts, should be designed according to the national bylaws. Duct and insulation material and safety space between a combustible part of the building and the fire insulation on the duct has to chosen correctly (Fire insulation is discussed in § 7.5.2).

7.4.6.4 Duct cleaning for health and comfort reasons

This is the newest of the three reasons and has been discussed during the last two decades as one way of preventing buildings to be stricken by the sick building syndrome.

Shall the ducts be cleaned due to health and comfort reasons? The problems would then normally be limited to the supply ducts as return air for hygienic reasons is not used as much today as it used to be. If return air is used in spite of this, then e.g. tobacco smoke and smells must not be brought back with the supply air and the return air must also be part of the inspection and duct cleaning scheme.

It is self-evident that the air-handling system should not be allowed to release contaminants to the supply air from dirty ducts. Should that be a risk, cleaning the ducts must prevent it.

This risk could apply if the supply air filters are of poor quality (as discussed in § 7.4.2.2) permitting contaminants to enter the system. If the ducts are exposed to microbial growth, e.g. mould in internal duct insulation (discussed above) or if the supply air is mixed with return air this could also result in an increased risk.

The needs and reasons for duct cleaning presented above are all due to contaminants entering the ducts during operation. Table 8 summarises common and important reasons for cleaning ductwork.

Contamination during manufacture, transport and installation is another problem. Keeping the ducts clean by covering the duct openings with lids is one alternative that is more and more frequently used. Should this be required it is necessary to state it clearly in the building specification e.g. as one of the following alternatives:

Level of protection	During manufacture	During transport	During storing at site	During installation
0	No	No	No	Yes, but only vertical ducts
1	No	No	Yes	Yes
2	Yes	Yes	Yes	Yes

Table 7 : Level of protection by covering duct ends

7.4.6.5 Duct cleaning methods

Methods used for cleaning include dry cleaning, wet cleaning, disinfecting, encapsulation and duct lining removal as discussed in chapter 11.3.2.

The long term effectiveness of duct cleaning is not well documented. Methods to evaluate duct cleanliness are not well developed and range from simple hand wiping of a small surface area to the use of contact microbial growth plates.

7.5 INSULATION

Ducts are insulated for three different main reasons:

- thermal insulation to create a thermal barrier between the inside and the outside of the duct
- fire insulation to prevent the spreading of fire through the duct wall
- acoustical cladding or lining to absorb noise inside the duct.

Sometimes two of these reasons, e.g. requirements for both thermal and fire insulation, might coincide. Then the most cost-effective solution might be to combine the two demands by choosing insulation that fulfils both requirements in the same solution. Which of the two requirements is the strongest differs from case to case. Normally the demand to conserve energy requires thicker insulation than that of fire protection.

Duct insulation for all three purposes is typically fire resistant and made of mineral wool or glass fibre.

7.5.1 Thermal insulation with and without vapour barrier

Used as thermal insulation, for energy conservation, the insulating material can be applied either to the outside or inside of the duct. Application on the outside of the duct wall is the normal installation mode when the purpose is to prevent heated supply air from being cooled down.

If the purpose is the opposite – the air in the duct is chilled and should not be heated – it gets a little more complicated. If the temperature of the duct wall, due to the air in the duct, is lower than the dew point of the surrounding air condensation could occur on the outside of the duct wall. To prevent this, insulation fixed to the outside of the wall, which might be preferable from a hygienic point of view (see § 7.4.4), will have to be protected by a vapour barrier.

When there is risk for condensation, insulation and vapour barriers as appropriate should be installed on the outside of the duct, i.e. on the moist side of the wall where the partial water vapour pressure in the air has the highest value.

It is extremely important that the vapour barrier, e.g. plastic foil or galvanised steel sheet, be completely tight. Otherwise the water vapour will enter the insulation material through leak openings, condense inside the material and wet the insulating material (and probably also corrode the duct wall). An insulation material looses most of its insulating capability when wet.

If acceptable from a hygienic point, the insulation can instead be located on the inside of the duct wall. The metal duct wall then serves as the necessary external vapour barrier.

When insulation material is applied on the inside of the duct, it is important to choose a material that can be cleaned with normal duct cleaning methods (duct cleaning is described in § 7.4.6). It is also vital that the material does not release any fibres to the air – erodes – at the actual air velocity in the duct. This may be achieved by using long fibre insulation material or by covering it with plastic foil and/or perforated steel sheet.

What ducts should be cleaned?	Why should they be cleaned?		
	Function	Fire hazard	Health
Extract air ducts in dwellings, offices and schools	x	-	-
Return air ducts in dwellings, offices and schools	x	-	x
Supply air ducts in dwellings, offices and schools*	-	-	-
Supply air ducts in offices and schools with return air	x	-	x
Extract ducts in industries	x	-	-
Cleaning due to fire hazard as required by law	-	x	-

* *valid when outside air is well filtered, without leakage which by-passes the filter, fouling should be checked regularly.*

Table 8 : Reasons for cleaning air ducts

The risk of getting the material wet might also apply if the material is installed on the inside of the duct. The intake duct bringing outside air to the air-handling unit is often thermally insulated on the inside to prevent air in the fan room to condense on the duct wall. (Its temperature is quite low in wintertime, the air passing through the duct having not yet been heated in the air handling unit). Nor has it been cleaned by the filters. This has sometimes led to an unwanted phenomenon, raindrops and snowflakes wet the insulation material and dust, earth and seeds brought in by the air create excellent conditions for microbial growth in the duct. If the intake duct is not externally insulated and provided with a vapour barrier, one has the choice between two bad alternatives; the most acceptable one is to accept the condensation on the outside but not the health hazard with microbial growth. Whenever there is risk of water being brought in with the air into the duct, internal insulation should thus be avoided.

To minimize the risk of having raindrops or snowflakes entering the plant with the supply air the intake grille should be large enough to keep the air velocity through it below 3 m/s (see § 7.4.1).

The duct between intake and air handling units should be as short as possible (VDI 6022 [Ref 39]). There should be possibilities for draining and cleaning (see § 7.4.1). The drain should not be directly connected to the sewage system (because of the danger of ejecting polluted air). The duct should be provided with an inspection opening.

7.5.2 Fire insulation

Fire insulation should always be installed on the outside of the duct to protect the duct and its gaskets etc., from melting. When ducts are passing through firewalls or other fire partitions, insulation is especially important to prevent fire from breaking through the duct wall.

The fire requirements on ducts and the classes used for defining these requirements were discussed in § 1.6. The requirements are not yet common in different countries in Europe and there is not yet any EN covering this. Circular ducts are in some countries approved with a thinner layer of outside fire insulation than the equivalent rectangular ducts. Where for example 140-mm mineral wool net matting is required for a rectangular duct, 100-mm is considered sufficient for a circular duct.
As stated in chapter 1.6, the ductwork could present a fire hazard in a building when the ducts are run through fire classed walls. Even though there are different building code requirements in different countries they all have one thing in common – the duct penetrating the wall must not lead to a reduction of fire safety. The technical solution chosen should thus be compared to the case of the wall without the duct. Likewise should the duct hangers be able to withstand the strain from the fire without falling down.

7.5.3 Acoustical absorption in ducts

Absorbent material inside ducts is a very efficient sound attenuator on the assumption that the material is located in the sound path. Located in duct bends the material will be hit by the direct sound wave and also be able to absorb sound energy from the reflections both upstream and downstream of the bend.

Another efficient location is inside the duct that is connected to the fan outlet. Here the sound is very turbulent before it has been straightened up by reflections against the duct walls. Absorption cladding of the inside of this part of the ductwork is therefore also very efficient.

Using inside insulation for this purpose, the same considerations as described for internal thermal insulation above apply (see § 7.5.1). The material should not deteriorate due to erosion and particle release due to high air velocities and it should be possible to clean the material with normal cleaning procedures.

Perforated steel sheet may be used to protect the absorption surface from eroding. This does not decrease the absorption capability of the surface when using a perforation with a free area down to 20% (i.e. 80% of the material is covered by the steel sheet). This is due to the fact that the sound deflects towards the open holes in the surface.

7.6 FIRE

7.6.1 General

There are many boundary conditions regarding air ducts. One of the most important is also related to fire: the duct system should not spread fire or smoke in the building. This gives restraints regarding duct system lay out, duct material, and fire insulation of the ducts. Another primary function of ductwork can be to transport smoke out of the building in case of fire, or assist in pressurization of escape routes.

The ductwork is thus important for fire safety from the following points of view:

- Fire spread;
- Smoke spread;
- Smoke exhaust;
- Pressurization of escape routes.

The building is normally divided into several "fire cells", designed not to allow a fire in one cell to spread to other cells. A good solution then is to have separate duct systems, one system for each cell. When this is not possible the passage through cell dividing firewalls has to be designed to prevent the fire from spreading. This is achieved by using fireproof materials in the ducts and by tightening with extra fire resistant insulation round the ducts at and close to the passage through the wall, to prevent leakage of hot gases and heat conduction along the duct.

Ducts shall not burn or be so hot that building material, equipment or furniture outside their fire cell ignites. When there is a risk, a safety distance from such materials should be kept and/or sufficient insulation should cover the duct. Note that radiation tends to dominate the heat transfer. A hot gas inside the duct is the most dangerous case. To stop such flow, dampers controlled by fire sensors are installed in the duct system.

Fire insulation is discussed in § 7.5.2.

Besides sealing and refinishing the duct hole in the fire wall as described above, the most important precaution is achieved by blocking the duct with fire dampers (see § 7.6.3) to control and prevent smoke spreading. These dampers can be used in different ways to enhance fire safety:

- To close the ducts supplying the building with air when the air is polluted by smoke;
- To bring the smoke more directly out of the building and prevent smoke polluted exhaust air from passing e.g. heat recovery units;
- To open special duct systems for extracting smoke, a technical solution that is sometimes used;
- To close overflow openings or ducts between two fire cells.

The fire damper system is normally controlled by smoke detectors in the ducts and in the building. The location of the sensors is important and should be studied carefully. If a sensor is located in a main duct, the smoke from the room with the fire will be diluted by extract air from the other rooms connected to the same duct. The sensor will then have to have a sensibility that can cope with this low concentration level. To evacuate the people out of the building has of course highest priority, especially in high rise buildings. Smoke-free escape routes can e.g. be achieved by extracting smoke out of the top of stair shafts. A more advanced method is to pressurize the escape route so air only can leak out and no smoke-polluted air can leak in. This can be achieved with special fan and duct systems or with redirecting airflow in the normal duct system. In both cases it is a problem that the equipment is not in normal use and thus may not be reliable when needed. Systems of this kind therefore have to be tested regularly; a requirement that should be included in the operation manuals and documented.

All countries have their own fire codes covering these and other fire resistance measures. Even though there is an ongoing European standardization of these matters there are still many requirements that are regulated in national codes. Check these carefully before finalizing the design.

7.6.2 Escape routes

Escape routes have to be protected from smoke. This can be achieved by pressurization, i.e. by keeping the fire room at a lower and escape routes at a higher pressure than the surrounding building[8].)

Pressurization can be achieved by:

- Using the normal ventilation system with changed flows and flow directions;
- Using special fire pressurization systems.

A limiting factor for vertical escape routes like stairwell shafts is the pressure gradient imposed by the temperature difference between indoors and outdoors. If the temperature indoors is 23°C higher than outdoors, the inside pressure will increase with 1 Pa/m. Especially when the shaft is pressurized, this can result in high overpressures in the upper parts, which can make it difficult to open the doors (especially as the doors for safety reasons should open towards the escape stairwell).

[8] See e.g. BS 5588:Part 4:1978 [Ref 20].

7.6.3 Fire dampers

There are several different types of fire dampers (see also § 1.6):

- for protection against fire (I-class tested);
- for protection against the spread of smoke (E-class tested);
- for protection against the spread of both fire and smoke (EI-class tested).

They should tighten also at high temperatures which put requirements on the design and materials. A test code is NT FIRE 010 [Ref]. See also BS 476:Part 20:1987 [Ref 21] and EN 13053 [Ref 24].

They shall be tested regularly (see § 1.6) and need thus to be provided with a damper motor to open the damper after it has been released. These damper motors should be factory installed as an integrated and factory-tested component of the fire damper.

Older fire dampers installed before the 1960's – and still found in buildings from that time - are of a rather primitive type compared to those used today. The damper blade comprised of a double steel sheet cover insulated with mineral wool of a thickness intended for the fire class (see § 1.6). The blade was hinged at its upper side and kept open by a lock combination comprising of a fusible alloy (melting at ca. 70^{o} C) and a nitrated string (ignited by flames). Had it been released and closed, the damper had to be reopened manually and provided with a new lock. These dampers are difficult to check and it happened that they did not function because they were stuck in open position due to corrosion.

7.7 STRENGTH

7.7.1 General

Ductwork has to fulfil the following strength requirements:

- on mechanical strength;
- on corrosion sustainability;
- on rigidity to vibrations.

Ductwork has also to be installed with hangers withstanding the load of the ductwork under different conditions.

Many of these requirements will be covered by European norms at present being discussed before ratification. In the meanwhile most of it is covered by national or trade standards.

7.7.2 Mechanical strength

Ducts are exposed to either internal positive pressure (supply air ducts) or negative pressure (extract air ducts).

7.7.2.1 Rectangular ducts

Rectangular ducts and components shall have dimensions according to EN 1505 [Ref 26] and fulfil strength and tightness requirements according to prEN 1507 [Ref 32]. This would result in the following minimum thickness for welted steel sheet ducts:

Side length	$L < 250$	$250 \leq L < 500$	$L \geq 500$
Thickness	0.5	0.6	0.9

Table 9 : The larger the duct, the thicker the steel

If the duct is corrugated or has a similar rigidity the thickness can be reduced to 0.7 mm if satisfactory documentation can be submitted.

Ducts shall not generate noise or vibrations. The inner radii on bends and branch ducts should be 100-mm or be equipped with guide vanes.

The distance between the hangers on rectangular ducts should be (NS 3420 [Ref 38]):

Duct perimeter (m)	None	R 15	R 30
	t_{isol} = 0 mm	t_{isol} = 40 mm	t_{isol} = 70 mm
3.6	2.4	2.4	2.4
4.0	2.4	2.4	2.2
4.2	2.4	2.4	2.1
4.4	2.4	2.4	2.0
4.8	2.4	2.4	1.8
5.0	2.4	2.4	1.7
5.2	2.4	2.4	1.7
5.6	2.4	2.4	1.5
6.0	2.4	2.3	1.4
6.4	2.2	2.1	1.3

Measures are in meter unless otherwise stated in the table. "R"-values stand for fire strength class at given insulation thickness (see § 1.6).

Table 10 : Distance between duct hangers.

7.7.2.2 Circular ducts

Circular ducts and components should meet the requirements in EN 1506 [Ref 27] and circular duct should fulfil strength and tightness requirements according to prEN 12237 [Ref 31].

The distance between the hangers on circular ducts should be (NS 3420 [Ref 38]):

Duct diameter mm	None	R 15	R 30
	t_{isol} = 0 mm	t_{isol} = 30 mm	t_{isol} = 50 mm
400	3.0	3.0	3.0
500	3.0	3.0	2.8
630	3.0	3.0	2.1
800	3.0	2.8	1.6
1000	3.0	2.1	1.2
1250	2.8	1.7	1.0

Measures are in meters unless otherwise stated in the table. "R"-values stand for fire strength class at given insulation thickness (see § 1.6).

Table 11 : **Single hanger in one point**

Duct diameter mm	None	R 15	R 30
	t_{isol} = 0 mm	t_{isol} = 30 mm	t_{isol} = 50 mm
400	3.0	3.0	3.0
500	3.0	3.0	3.0
630	3.0	3.0	3.0
800	3.0	3.0	3.0
1000	3.0	3.0	2.5
1250	3.0	3.0	2.0

Measures are in meters unless otherwise stated in the table. "R"-values stand for fire strength class at given insulation thickness (see § 1.6).

Table 12 : Double hangers, i.e. one on each side of the duct

7.7.2.3 Flexible ducts

Flexible ducts are ducts that can be formed by hand without changing their cross-section form.

Flexible ducts shall fulfil the requirements in EN 13180 [Ref 25].

7.8 ACOUSTICS

An important boundary condition is acoustics. Noise, or private conversations in rooms, should not be transmitted through the ductwork. Nor should noise be generated in the ducts and transmitted to the rooms. Noise generation is often governing the choice of air velocity in the ducts, resulting in velocities lower than economically optimal (see § 7.2).

The noise abatement program starts already during the first design phase. A combination of common sense and basic knowledge will be a good start to prevent future problems, e.g. do not locate fan rooms for larger fans and air handling units above or next to noise sensitive areas (like hotel rooms or offices).

To prevent the fan noise from disturbing neighboring rooms, well sound-insulated walls, doors and slabs are required. The airborne noise easily passes through tiny cracks and narrow openings. Pipes, cables and ducts running through the walls have to carefully tighten around the perimeter; fan room doors have to be provided with tightening rubber seals. If the fans are located further away from these sensitive areas the problem is easier to solve.

Select a fan that has a high efficiency, which normally means that the fan is less noisy than less efficient fans (see § 7.3.5). Check that the fan is well balanced and prevent the vibrations from the fan to transfer to the building structure where it otherwise might result in noise being released elsewhere in the building – structure borne noise must be stopped already at the source. Figure 54 shows different noise paths from a fan.

Structure borne noise is a common cause for problems and can only be prevented at the source of the vibration, i.e. at the fan. It has thus to be installed on accurately dimensioned vibration isolators. Vibration bridges between the fan and the building structure have to be cut off. The duct connections on in- and outlet sides of the fan have to be soft, as also the cable to the fan motor and, if applicable, the drain pipe from the fan casing to the gutter – neither of these must prevent the fan from moving freely.

Figure 55 describes schematically how a noise calculation for a ventilation system is normally made. Before starting this task, acceptable noise levels in the different rooms in the building will have be to decided upon. The chosen noise level values for the different rooms should be set according to the intended use of the rooms. This decision should be taken together with the architect early during the design process as it could influence also other acoustic factors than the dampening of ventilation noise e.g. the design of walls, doors, slabs and suitable reverberation time values.

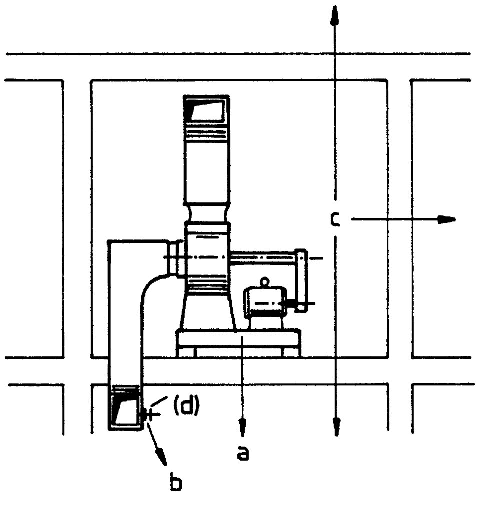


Figure 54 : The noise from the fan can spread in different ways and directions: Vibrations can result in structure borne noise (a) - Air borne noise carried through the ductwork (b) - Airborne noise in the fan room spreading to adjacent rooms (c), and noise emitted from other ductwork components such as dampers, registers etc (d).

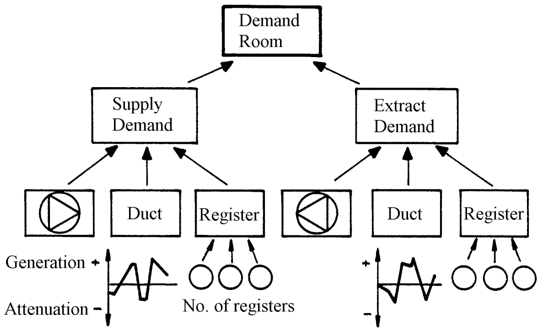


Figure 55 : The ventilation noise calculation has to be split up in several steps as described in the text below

The noise calculation is normally limited to one or a few rooms in the building. The rooms chosen are those with the highest requirements, i.e. those hardest to satisfy and/or those located nearest to the fans, i.e. where the fan noise is the highest and thus where the most fan noise attenuation is needed.

When these rooms have been chosen for the calculation the next step will be to specify the acceptable noise level from the ventilation system to the room. This ventilation noise level is normally lower than the one previously specified for the room as such as there are other sources of noise also adding to the room noise level. The ventilation system is one of several sources, other are e.g. traffic noise from the outside and noise from activities in the building.

This next step in the calculation is thus to decide what level can be accepted in addition from the ventilation system – "Requirement Room" in the figure. It should normally lie at least 3 dB lower than the room level thus allowing for other sources to add the same amount of noise to the room (see Table 13).

The following step is a further split up – the ventilation system normally comprises both a supply side and an extract side and they both have fans, ductwork and registers that create noise. The sum of the two sides must thus not exceed the previously set target. If both sides are allowed to supply the same amount of noise to the room this would mean that they should have target values that are another 3 dB lower as the sum of two equal noise sources is 3 dB higher than the value for one of them (Table 13). Or, as the supply side probably generates more noise due to its higher total pressure drop, it could be allowed to be a bit noisier at the room.

Examples:
Allowed noise level from ventilation: 40 dB

1. Supply side: 37 dB; Extract side: 37 dB
   $10 \cdot \log (10^{37/10} + 10^{37/10}) = 40$ dB
2. Supply side: 38 dB; Extract side: 36 dB
   $10 \cdot \log (10^{38/10} + 10^{36/10}) = 40$ dB

Each side, supply and extract, has to be calculated separately as they are built up in different ways. Thus the division goes on. There are three main noise sources in each system:

- Fan;
- Ductwork;
- Registers.

Noise can be created as well as dampened in the *duct system*. It is important to keep the air velocities low near ventilated rooms. As the fan noise has been dampened passing through the ductwork secondary noise sources like duct bends or dampers might disturb more. The third main noise source in the ventilation system is the air terminal device. Check data from the manufacturers and chose the best alternative. Several registers in the same room add together logarithmically:

Total noise level = Noise from one device + 10 log n
where n = the number of devices

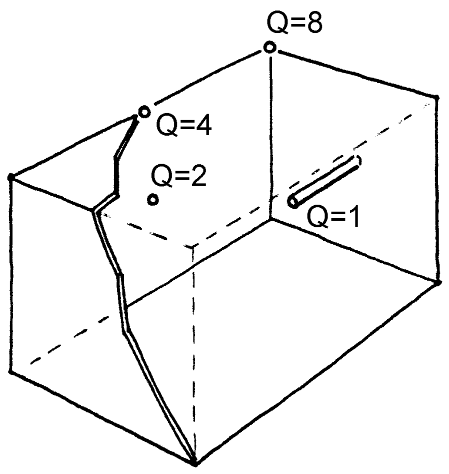
Number of devices	2	3	4	5	6	8	10	20
Add dB	3	5	6	7	8	9	10	13

Table 13 : Number of dB's to be added to the level of one source to get the total sound level value.

Example:
The noise level from one supply outlet is: 30 dB
With 4 similar outlets the level will be: 30 + 6 = 36 dB
($30 + 10 \cdot \log 4 = 36$ dB)

The location of the registers is also important. Walls and ceiling will reflect the noise from the register (like a megaphone). If the terminal device is located in a corner of the room it is surrounded by three reflecting surfaces. Near the register this will result in a higher noise level in the room than if it is located on the wall at the ceiling (2 reflecting surfaces) or in the middle of the ceiling (one reflecting surface). Each additional surface increases the direct noise with 3 dB at the same distance from the register.

The noise emanating from the fan will be reduced as it passes through the duct system. This dampening of the noise is achieved in many ways. First the sound energy transmitted into the duct at the fan will probably be split up into several branch ducts in the same way the air is split up. The table above can be used as a rough tool to calculate this. If the air – and thus the noise – is split up into two equal parts (each will thus get ½, i.e. 50%) the noise reduction into each of the two branch ducts will be 3 dB (see the first column "2" = 3 dB). A split up into three equal ducts reduces the noise with 5 dB. Ten equal parts = 10 dB reduction and 1/20 (i.e. 5 %) of the total airflow into each = 13 dB noise reduction. The rules of calculating noise are often fairly simple but they are mostly based on logarithms.



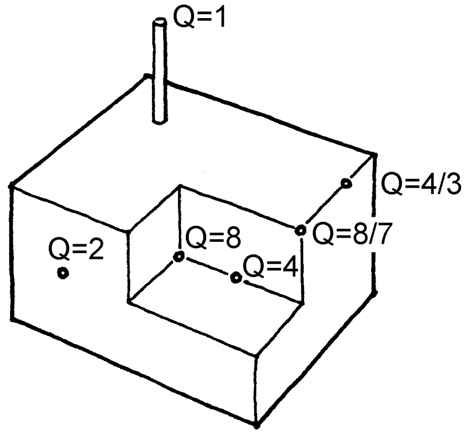


Figure 56 : The noise from a source will be influenced by the surrounding surfaces. The directivity factor Q equals 1 for full sphere and 8 for 1/8 sphere. Near the source each doubling of Q will result in a 3 dB noise level increase: $\Delta L = 10 \cdot \log Q$.

Sound (noise is defined as unwanted sound, like fan noise) is defined as pressure propagation (or transmission) through an elastic medium (normally air). When this pressure wave reaches an obstacle, e.g. a wall in a room, part of the sound energy will be absorbed as the sound is reflected back into the room. If the wall material is soft and porous the air molecules will partly enter the material where part of the kinetic energy is transformed into heat due to friction losses in the material (similar to the pressure drop when air is passing through a filter). But also a smooth but slightly elastic wall (a windowpane, a duct wall) will be brought into movement by the sound kinetic energy. The movement of this membrane transforms part of the kinetic energy into heat in the material itself and at its edges. The third noise absorbing principle is the cavity or Helmholtz absorber that could be described as a bottle set into a wall with the bottleneck facing the room. The sound wave will move the air in the bottleneck in accordance with the oscillating pressure. The air in the bottle volume being compressed and decompressed respectively will slow this movement down resulting in efficient noise attenuation at a frequency that can be calculated as a function of the geometric properties of the absorber.

Silencers are typically made as soft walls in the duct. In rectangular duct systems extra walls are often introduced in the damper (baffles), in circular ducts the most common is to use the perimeter wall only. The sound absorbing material often is mineral wool or a corresponding material. The geometric design of the silencer and the type of damping material chosen affect the damping ability of absorption silencers. The straight variants may consist of an outer sheath made from ventilation duct, and an inner sheath made of perforated sheet steel. The space between them is filled with mineral wool of varying density, depending on application. A fiber cloth is inserted between the perforated sheet metal and the mineral wool. Its purpose is to prevent fibers from entering the duct air flow and to make cleaning possible.

Silencers with baffles have parts that block the duct system to a greater or lesser extent, and thus obstruct or prevent cleaning of the duct system.

A bibliography “Ventilation and Acoustics” was published by AIVC (1997). [Ref 4]

7.9 ENERGY USE

The energy impact of ventilation is usually itemized as ventilation losses, distribution losses, and fan energy use:

- Ventilation losses are due to the difference of enthalpy between the incoming and outgoing airstreams (outside air getting into the building has to be brought to the temperature and humidity set-point);
- Distribution losses are energy losses that may occur as the air is transported—e.g., air that leaks out of a duct;
- The fan uses energy.

7.9.1 Ventilation losses

The specific enthalpy of air is:

$$h = \underbrace{c_{pa}\,\theta + x\,c_{pw}\,\theta}_{\text{sensible heat}} + \underbrace{x\,L_0}_{\text{latent heat}}$$

where the symbols used in this equation are defined in the nomenclature. (See § 14.3)

7.9.2 Distribution losses

Distribution losses include:

- pressure drops (See § 4.4 and § 7.3.1);
- leakage losses (See § 4.2 and § 7.10);
- conduction losses (See § 4.3 and § 7.5.1);
- and heat recovery losses (See § 4.8).

The steady-state temperature distribution of the air flowing through a duct located in an environment maintained at a constant temperature is given by:

$$T_f - T_{cont} = (T_i - T_{cont}) \exp\left(- \frac{U\ A}{\rho_a\ c_{pa}\ q_V} \right) = B\ (T_i - T_{cont})$$

where:

- T_f is the air temperature at the duct end (K);
- T_i is the air temperature at the duct entrance (K) ;
- T_{cont} is the air temperature of the duct surroundings (K) ;
- A is the duct surface area (m^2) ;
- U is the U-value (thermal transmittance) of the duct ($W\ m^{-2}\ K^{-1}$) ;
- B is the transmission losses fraction (-);

and the other symbols are defined in the nomenclature (See § 14.3).

The heat flux (Φ) lost through the duct shell is:

$$\Phi = U\ A \frac{(T_f - T_{cont}) - (T_i - T_{cont})}{\ln\left(\frac{T_f - T_{cont}}{T_i - T_{cont}} \right)} = U\ A\ \Delta T_{lm}$$

where the quantity ΔT_{lm} is called logarithmic temperature difference.

More details regarding conduction losses through a cylindrical duct are available on the CD-ROM.

Heat recovery units allow some energy to be recovered from outgoing air streams. The effectiveness is defined as:

$$\varepsilon = \frac{\text{Actual transfer of energy}}{\text{Maximum possible energy transfer}}$$

For sensible heat energy transfer, referring to the figure below, this equation becomes:

$$\varepsilon = \frac{q_{m,s}\ c_p\ (T_2 - T_1)}{q_{m,\min}\ c_p\ (T_3 - T_1)}$$

where:

- $q_{m,s}$ is the mass flow rate of supply (kg/s)
- $q_{m,e}$ is the mass flow rate of exhaust (kg/s)
- $q_{m,min}$ is the smaller of $q_{m,s}$ and $q_{m,e}$ (kg/s)

and the other symbols are defined in the nomenclature (See § 14.3).

Typical sensible energy recovery effectiveness of air-to-air heat recovery units range from about 50% up to about 80% (Table 14). Water-loop heat exchangers (see Figure 25) have relatively low efficiencies (40 to 60%). Heat recovery can be successfully implemented, however, one should pay attention to hidden losses that can seriously impact the energy benefits of such systems (see § 4.8).

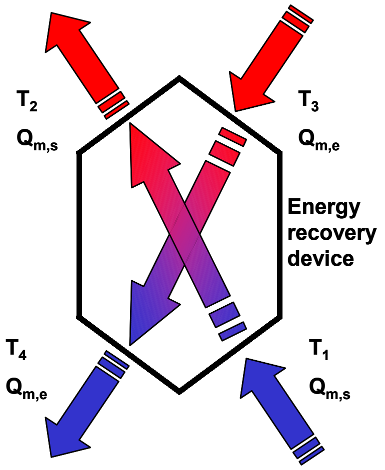


Figure 57. Schematic diagram of energy recovery principle. Subscript s and e denote the supply and extract sides, respectively.

Type of heat exchanger	Class A (%)	Class B (%)
Rotary air-to-air heat exchanger	70	80
Fixed-plate cross flow heat exchanger	50	60
Fixed-pipe heat exchanger (*)	50	60
Heat exchanger with two-phase medium (**)	45	55

(*) Heat exchanger where one of the airstreams passes through the inside of the pipes and the other on the outside of the pipes.
(**) i.e., heat pipe heat exchanger.

Table 14. Minimum temperature effectiveness (sensible energy recovery efficiency) as defined in AMA (1998) [Ref 41]

7.9.3 Fan energy use

The fan power demand can be calculated as follows:

$$P_{fan} = \frac{q_V\ \Delta p_{fan}}{\eta}$$

where:

- P_{fan} is the fan power demand (W)
- q_V is the airflow created by the fan (m^3/s)
- Δp_{fan} is the total pressure difference across the fan (Pa)
- η is the global fan efficiency (-)

The French building code (RT 2000) [Ref 22] proposes reference values between 0.2 and 0.6 for the global fan efficiency (Table 15-Table 16).
Typically, the fan power demand lies between 0.5 to 3 W to provide each l/s of air to a space[9]. A commonly used fan law is that the power increases with the cube of the airflow rate (see § 7.2).

[9] The value of 0.9 W per L/s (0.25 W per m^3/h) is sometimes adopted as a reference value.

$$P_{fan} \propto q_V^3$$

This law is true only when the flow conditions stay similar as the fan speed changes. In particular, caution should be exercised when regulating devices are used.

	Total pressure drop (Pa)	
Building type	Supply	Extract
Residential	200	150
Non-residential	500	450

Table 15 Reference pressure drop across the fan defined in the French building code (RT 2000).

Case 1. Non-residential supply	> 10000 m^3/h	Between 2000 and 10000 m^3/h	< 2000 m^3/h
Case 2. Residential supply, all buildings extract	> 15000 m^3/h	Between 3000 and 15000 m^3/h	< 3000 m^3/h
Global fan efficiency (-)	0.6	Linear	0.2

Table 16 Reference global fan efficiencies defined in the French building code (RT 2000).

7.10 AIRTIGHTNESS

Duct leakage is detrimental to energy efficiency, comfort effectiveness, indoor air quality, and sometimes even to health. A ductwork airtightness limit should be required:

- to minimize the cost and the energy penalty due to an over-sized or inefficient plant;
- to ease the flow balancing process;
- to have control over the leakage noise; and
- to limit the in/ex filtration to unconditioned spaces (with potentially large effects on energy use, power demand, indoor air quality, and comfort-effectiveness).

A duct system will never be "completely tight". Its leakage is generally classified based on the leakage flow rate at some reference pressure normalised by the duct surface area.

7.10.1 EUROVENT Leakage Class

This classification is based on maximum values of the leakage coefficient per m^2 of duct surface area ($l/(s\ m^2\ Pa^{0.65})$).

$$K = \frac{q_V}{A\ \Delta p_{ref}^{\ 0.65}}$$

where:

q_V is the leakage volume flow rate (m^3/s)

A is the duct surface area (m^2)

Δp_{ref} is the reference pressure at which the tightness test is performed (Pa)

Note that the flow exponent arbitrarily set to 0.65 actually varies considerably (Carrié *et al.*, 1999) [Ref 2].

Eurovent 2/2 leakage classes (*) $l/(s\ m^2\ Pa^{0.65})$	Leakage at 100 Pa l/s per m^2	Leakage at 400 Pa l/s per m^2	ASHRAE Leakage Class (in SI units) $ml/(s\ m^2\ Pa^{0.65})$
Class A: $K < K_A = 0.027$	0.54	1.33	27.0
Class B: $K < K_B = 0.009$	0.18	0.44	9.0
Class C: $K < K_C = 0.003$	0.06	0.15	3.0
Class D: $K < K_D = 0.001$	0.02	0.05	1.0

(*) Note that leakage Class D is not defined in Eurovent 2/2 but is used in some European countries.

Table 17. Eurovent 2/2 leakage classes.

7.10.2 ASHRAE Leakage Class

This classification is based on the leakage flow in cfm per 100 ft^2 of duct surface area at one inch of water, generally termed C_L. Its definition differs in SI units since 2001. It is simply 1000 times the leakage coefficient K defined above.

7.10.3 Effective Leakage Area

The Effective Leakage Area (ELA) concept is commonly employed to characterise the leakiness of a building envelope. The equation linking the pressure differential to the leakage flow rate is arranged as follows:

$$q_V = C_d\ ELA_{ref} \sqrt{\frac{2\ \Delta p_{ref}}{\rho_a}} \left(\frac{\Delta p}{\Delta p_{ref}}\right)^n$$

where:

C_d is the discharge coefficient (-)
perfect nozzle : C_d=1
perfect sharp-edged orifice : $C_d \approx 0.6$

ELA_{ref} is the effective leakage area (m^2)

Δp_{ref} is a reference pressure difference across the leaks (Pa)

and the other symbols are defined in the nomenclature (See § 14.3).

The physical meaning of the Effective Leakage Area is that, at the reference pressure difference, the flow rate passing through the leaks would be the same as that leaking through an orifice of this same area under the same pressure difference. The reference pressure difference is set according to the typical duct pressures.

For duct leakage applications, the discharge coefficient is usually set to 1 and the reference pressure should be close to the ductwork operating pressure.

7.10.4 Leakage flow rate

The true leakage flow rate is very difficult to measure. However, it can be approximated with the previous equations if one knows the leakage class and the operating pressure. The percentage of the airflow generated by the system that passes through the leaks is an interesting performance indicator. It is often recommended that the leakage flow rate does not exceed 6%, but higher demands are encouraged.

Example: Take a tightness class C ductwork with a duct surface area of 200 m^2. The operating pressure is 90 Pa. Therefore, an estimate of the leakage flow rate is:

$$Q_{vl} = K\ A\ \Delta p_{op}^{0.65} = 0.003 \times 200 \times (90)^{0.65} = 112 \text{ l/s.}$$

7.10.5 Technical solutions

Conventional sealing techniques include the use of tape and/or sealing compound (Figure 58). Pre-fitted gaskets, commonly used in Scandinavia, are rarely used in other European countries (Figure 59). Components equipped with pre-fitted sealing devices are more expensive to buy than conventional solutions; however, these components are much easier to install. Therefore, the significant savings that are achieved on labour cost can result in a lower ductwork system cost when the installation cost is included. Besides, these solutions provide better guarantee towards good airtightness which may reduce operating costs as well. Clip systems are an interesting option if the ducts need to be dismantled during the ductwork system's life (Figure 60).

7.10.6 Status in existing buildings

43 leakage tests in France and 21 in Belgium are reported in the SAVE-DUCT handbook [Ref 2]. The results show that the airtightness is on average more than 3 times worse than the class A upper limit (Figure 61). Conversely, leakage tests performed in Swedish buildings at commissioning show that class B or class C compliant ductwork can be obtained on a regular basis (Figure 62).

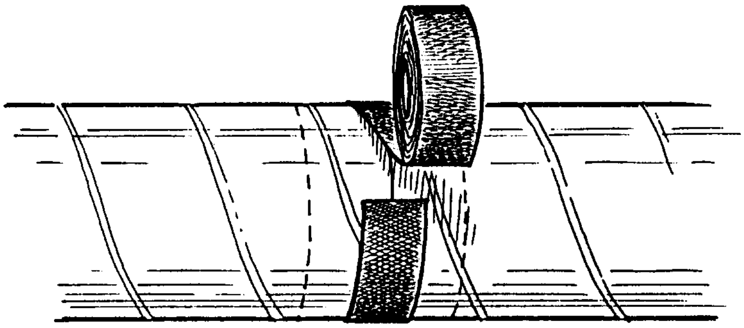


Figure 58. Self-vulcanising sealing tape applied around the duct with overlap.

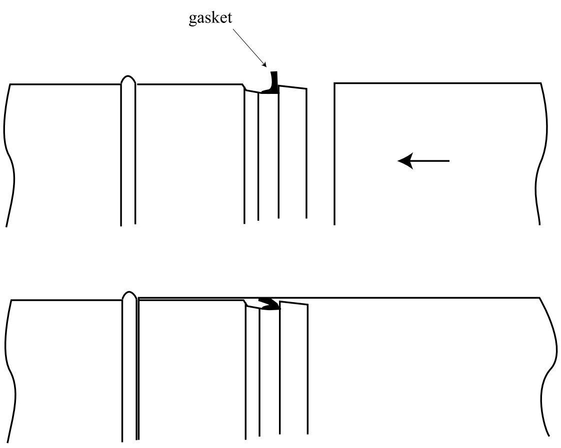


Figure 59. Pre-fitted sealing gaskets for circular ducts. Airtight rivets or plate-screws may be necessary to ensure the mechanical stability of the joint.

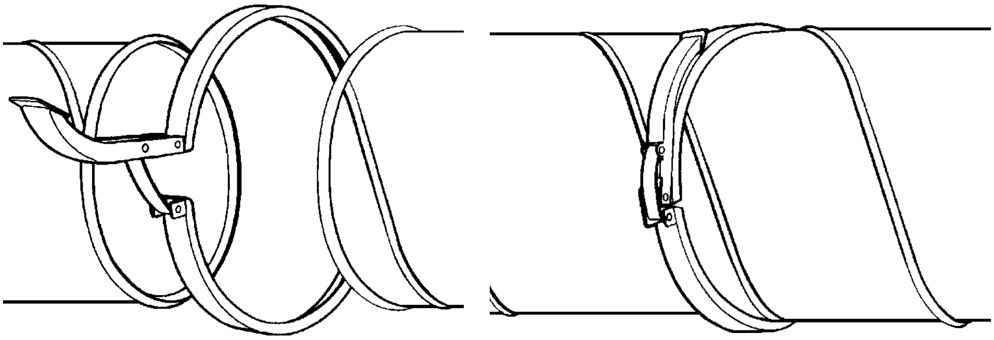


Figure 60. The clips ensure good airtightness and the mechanical stability of the joint. These systems are mainly used for non permanent ductwork or ductwork which has to be cleaned regularly.

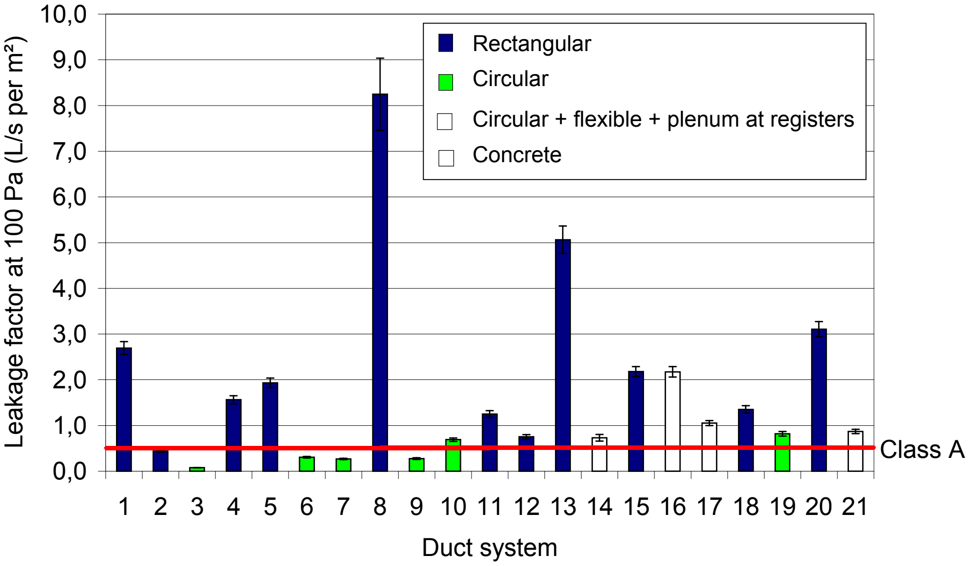


Figure 61. Leakage flow at 100 Pa divided by duct surface area (leakage factor) for systems investigated in Belgium during the SAVE-DUCT project (Carrié et al., 1999).

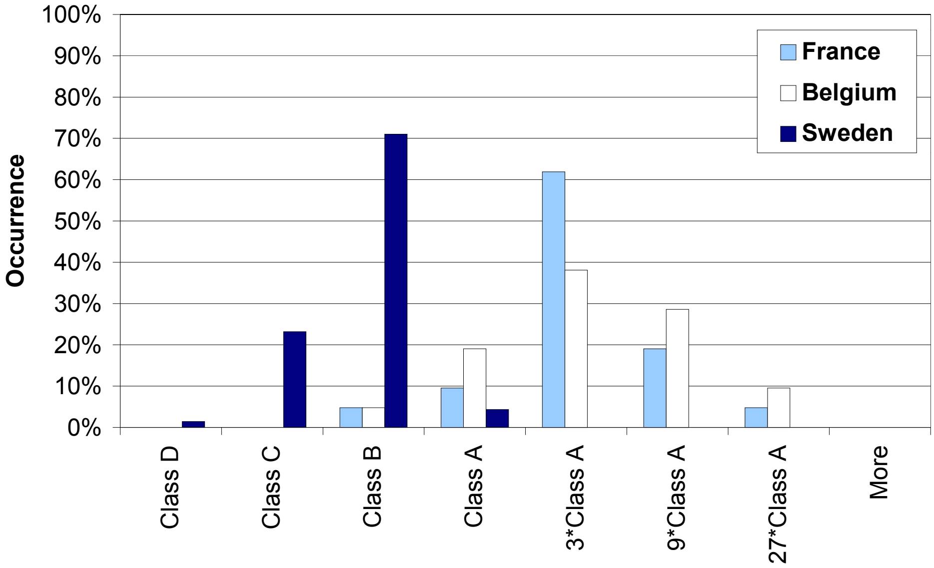


Figure 62. Occurrence of the different tightness classes. Based on 21 systems in Belgium, 21 in France, and 69 in Sweden. Each stack represents the relative number of systems that comply with the specified tightness class.

8.1 SPACE DEMAND FOR DUCTWORK

As described under chapter 8.2, circular ducts are normally most cost-effective when compared to rectangular ducts. ASHRAE Fundamentals [Ref 9] also recommends that circular ducts should be used whenever feasible. Rectangular ducts were most frequently used earlier and still are in many countries. Normally the best solution is to use the two types in combination, e.g. rectangular ducts as plenum ducts nearest the air handling units where the airflow is high and the duct dimensions consequently large. Further downstream the distribution ducts, being circular, are connected to the plenum duct.

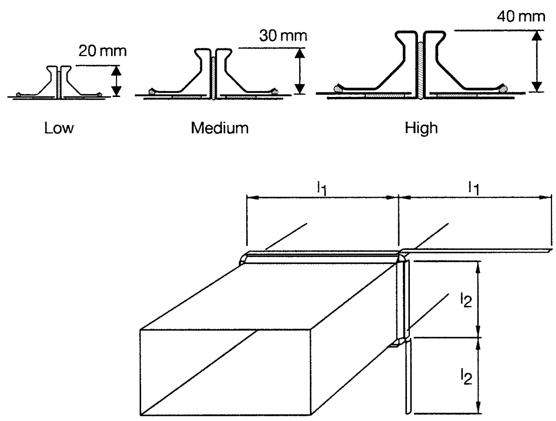


Figure 63 : Slip joints on rectangular ducts add to the space requirement. At installation free space has to be available for the joint connection.

When considering the space demand for the ductwork, it is important not just to check the cross-section of the ducts but also on how they are connected. The slip joints normally used on a rectangular duct are space consuming compared to joints used on circular ducts.

The slip joints on a rectangular duct also require a space on either side of the duct for pushing on the slip joints. This sometimes fools the inexperienced designer who finds the logical solution for a rectangular duct shaft to be a rectangular duct.

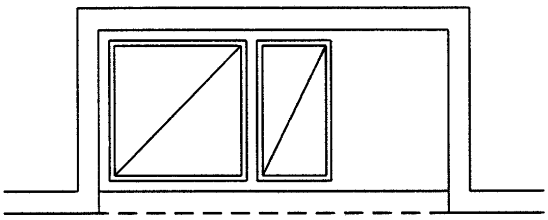


Figure 64 : Slip joints make it difficult to install these ducts in the shaft.

The space that is required for installing a circular duct is thus often less than for a rectangular duct with similar pressure drop. The slip joints on rectangular ducts protrude normally between 20 and 40 mm on all sides of the duct. As these slip joints cover the duct width, they require an available space of the same order on either side of the duct. Often when the duct is installed above the false ceiling in a corridor or in a duct shaft and the ducts are only accessible from one side; severe problems arise due to the inwards facing joint sections.

One reason for using rectangular ducts is that they can use the available space in a more efficient way than circular ducts, especially if the side ratio of the space is big. For such cases an alternative could however be to use several circular ducts in parallel.

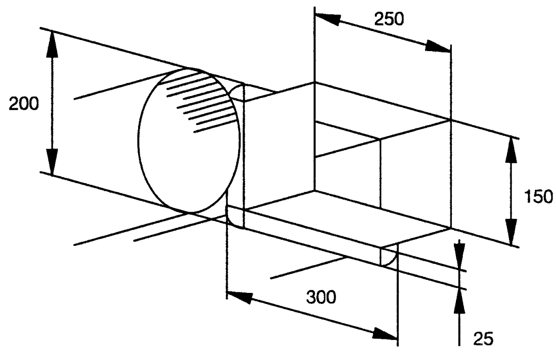


Figure 65 : Same space and same free duct area

A rectangular duct, 250 x 150 mm can, without any increase in pressure drop, be replaced by a duct of 200 mm diameter within the same space. The cost is normally less for the circular alternative.

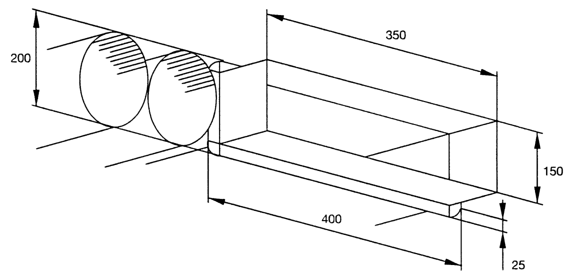


Figure 66 : A flat rectangular duct can often be replaced by several parallel round ducts

Several circular ducts, without any need for extra space, can often replace a flat rectangular duct (Figure 67). Also here the installed cost is normally less than for the rectangular duct. The use of two or more ducts instead of one rectangular will probably also give advantages of better airflow control, simplified air balancing and more flexible zone sectioning.

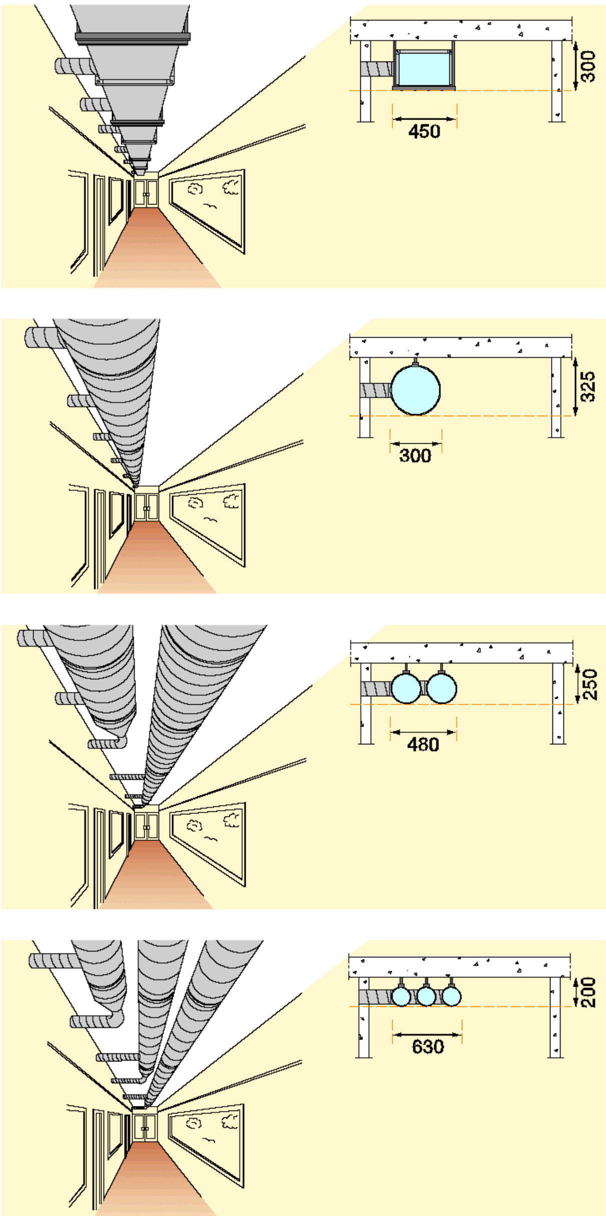


Figure 67 : Space demand for rectangular or circular duct(s)

8.2 COSTS

Traditionally, ventilation and air-conditioning ducts have been manufactured with rectangular cross sections. The rectangular ducts can easily be adapted to restricted ceiling voids and plant rooms, however often at the cost of efficient airflow design and possible cost savings.

The use of circular ducts seems to be increasing, and Evans and Tsal (1996) [Ref 12] give the recommendation that circular ducts normally are most cost-effective. Also ASHRAE Fundamentals (2001) [Ref 9] recommend that circular ducts should be used whenever feasible.

Even though it is possible to make rectangular ducts as tight as circular ducts, the cost for doing so is higher. Thus the total energy use for rectangular ducts is larger than for circular, as both friction and leakage normally increases. As the investment cost is about the same for one rectangular duct and several circular ducts, the latter can be a good alternative when the space is cramped (Jagemar 1991) [Ref 15].

Circular ducts are easier to manufacture, make tight, and handle than rectangular ducts, and are thus normally less expensive. Also, for transporting the same airflow at the same pressure loss (that is, with the same equivalent diameter), the sheet metal perimeter area of a square duct is 13% larger than that of a circular duct. For a rectangular duct with side ratio 1:2, the perimeter is 20% longer. It is 41% longer for a side ratio 1:4 and 51% for a side ration 1:5.

For the same cross sectional area the circular duct is not only less material consuming due to its shorter perimeter and simpler connections. The steel gauge can also be reduced for the smaller and most frequently used duct dimensions due to the more rigid construction of a spiral wound circular duct. The strength of ducts of different dimensions is discussed in § 7.7. The complete weight of a typical system comprising a normal combination of straight ducts, bends and diffusers, is normally between 30 and 40% higher for a rectangular system than for a circular duct system (Figure 68).

All these costs tend to increase with duct size or diameter. As circular ducts and their components are manufactured in standardized sizes – in diameters following a mathematical series of $1:2^{1/3}$ – this is often more cost effective than using rectangular ducts that are "tailor-made" in a high number possible combinations of height and width (see Table 18). Also the length of a piece of rectangular ductwork has to be measured and manufactured to fit the requirement and cannot be changed on site.

"Time is money" is an often-used expression that is applicable also to the building process. As circular ducts and fittings normally are stock items and can be delivered quickly it facilitates fast track building programs. The alternative dimensions for rectangular ducts and components are, as said, practically infinite and thus too many to permit any batch production.

This leads to another cost aspect; circular ducts can be used anywhere in the building where the diameter fits. They are delivered in longer lengths than the rectangular ducts reducing the number of necessary joints. If planned accordingly circular ducts of up to 6-m length can be used while rectangular ducts normally are limited to 2.4-m length due to the size of steel sheet used.

The weight and bulk of a circular duct system is less than that of a rectangular, this influences the cost level and makes it easier to install.

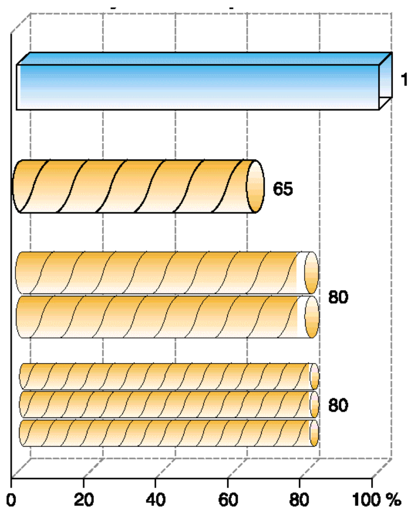


Figure 68 : Weight of ducts comparison

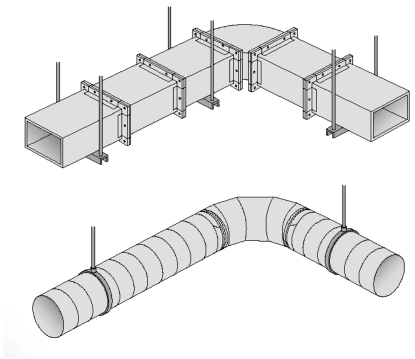


Figure 69: Hangers and joints for rectangular and circular ducts

The cost for installing the ducts is thus also normally different with an advantage for the circular ducts. While two people are normally required for the rectangular ducts, one worker can in most cases install circular duct systems up to 200 mm diameter single handed.

The duct hangers are often of a simpler design than for the rectangular duct. The needed space between the hangers is often larger for a circular duct resulting in a reduced number and a cost and installation time that normally is some 20% less (Figure 69).

9.1 MANUFACTURE OF DUCTS

9.1.1 From manual to industrial manufacturing

There is a large difference in the manufacture of ducts – from very manual and time-consuming methods requiring high skill from the workers to large-scale industrial manufacturing. One great step from the first to the second phase came with the introduction of machines for the manufacture of spiral-wound circular ducts in the middle of the 1960's. Before that circular ducts were practically not used at all.

Figure 70 : Manually made duct (1910). Today neither the skill, the money nor the time is there.

Another important change came with the introduction and large-scale application of standardised dimensions for ducts as described in § 9.1.3.

An increased awareness of the importance of tight ducts in many countries starting in the middle of the early 1970's resulted in improved and tighter joints on rectangular ducts. Many manufacturers introduced their own systems often based on the use of slip joints with compressed rubber seals increasing the tightness and reducing the need of mastics and tape. Higher duct tightness requirements were followed by demands on tightness control. In step with improved construction solutions, the demands were raised until today in many countries where the standard requirements described in chapter 7.10, vary from Class A to D depending on where the ducts are installed.

9.1.2 Manufacturing of rectangular ducts

Despite standard dimensions of heights and widths (Table 18) there is such a large number of possible combinations for straight ducts – and even more for bends – that there is no possibility to stock manufactured ducts. They are always manufactured on order. The length of straight ducts is restricted to a maximum of 2.4 m by the standard size of the galvanised sheet metal plates.

The normal way to join the different duct parts is by using transverse standing drive slips where the two duct pieces are pressed together compressing an intermediate rubber seal. The larger the size of the duct the larger the standing slip joint needed is (see § 8.1). To align the ducts the four corners of the ducts are often provided with holes for bolts simplifying the drive slips mounting.

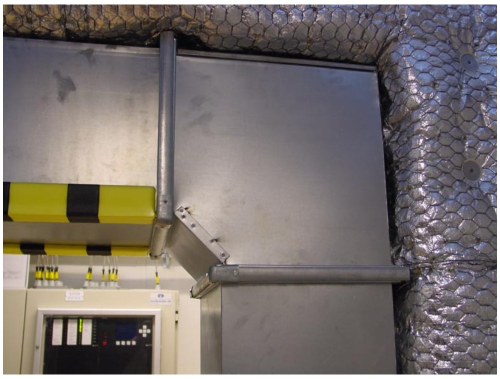


Figure 71 : Slip joints on a rectangular bend

Large widths or heights need to be stiffened to counteract any pulsation due to varying internal air pressure in the duct. This could otherwise result in annoying noises from the moving duct wall. This stiffening is done during the manufacture either by cross-bending the duct sides diagonally or by using sheet metal with crosswise indented grooves.

Figure 72 : Cross-bent duct sides to increase stability.

9.1.3 Manufacturing of circular ducts

All circular metal ducts used today are manufactured from steel or aluminium bands on rolls. The machines used are basically of the same type. The band is rolled together to a standard diameter circular duct with stringent and standardised measurement deviations.

Side lengths mm	100	150	200	250	300	400	500	600	800	1000	1200
200	0.020 149	0.030 186	0.040 218								
250	0.025 165	0.038 206	0.050 241	0.063 273							
300	0.030 180	0.045 224	0.060 262	0.075 296	0.090 327						
400	0.040 205	0.060 255	0.080 299	0.10 337	0.12 373	0.16 456					
500		0.075 283	0.10 331	0.13 374	0.15 413	0.20 483	0.25 545				
600		0.090 307	0.12 359	0.15 406	0.18 448	0.24 524	0.30 592	0.36 654			
800			0.16 410	0.20 463	0.24 511	0.32 598	0.40 675	0.48 745	0.64 872		
1000				0.25 512	0.30 566	0.40 662	0.50 747	0.60 825	0.80 965	1.00 1090	
1200					0.36 614	0.48 719	0.60 812	0.72 896	0.96 1049	1.20 1184	1.44 1308
1400						0.56 771	0.70 871	0.84 962	1.12 1125	1.40 1270	1.68 1403
1600						0.64 819	0.80 925	0.96 1022	1.28 1195	1.60 1350	1.92 1491
1800							0.90 976	1.08 1078	1.44 1261	1.80 1424	2.16 1573
2000							1.00 1024	1.20 1131	1.60 1323	2.00 1494	2.40 1650

Table 18 : Cross-sectional area (m²) and equivalent diameter (m) of standard rectangular ducts according to EN 1505 [Ref 26]

Circular ducts are manufactured in a limited number of sizes. The standardised diameters follow a mathematical series with a constant diameter increase of $1:2^{1/3}$ (i.e. approximately of 27%). The following diameters are standardised in Europe (Table 19 - diameters not following the series are sometimes used in some countries, these diameters are shown within brackets).

63	80	100	125	160	200
250	315	(355)	400	(450)	500
(560)	630	(710)	800	(900)	1000
(1120)	1250	(1400)	1600		

Table 19 : Standardised diameters for circular ducts in Europe (mm)

The length of a straight duct is virtually limited only by transport restrictions. A standard length is thus 3.0-m but in some cases also 6.0-m lengths have been manufactured, transported and installed. Using large duct lengths speeds up the installation and reduces the number of required joints.

Using intermediate fittings provided with none, one or two rubber sealing gaskets normally joins the straight ducts. The duct components are also provided with the same type of sealing joints. To prevent the ducts from loosening the joints are fixed with either tight rivets or special screws.

A normal ductwork system comprises a large number of duct components, described in chapter 2.2, along with the straight ducts. These duct components are for example bends, T-branches, X-branches, dampers and reducers to name but a few. As these follow the standard dimensions described above, they are normally manufactured on stock with short delivery times.

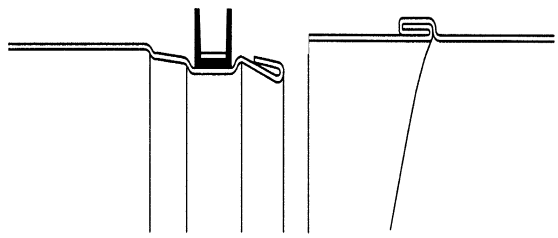


Figure 73 : Double sealing gasket. Due to larger tolerance range between duct and fitting with increasing duct diameters, the gasket size increases in steps with the duct diameter.

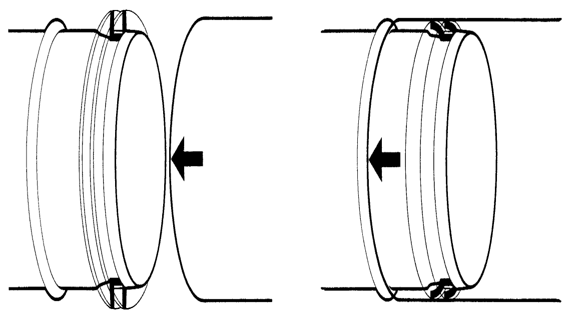


Figure 74 : When the duct is pushed onto the fitting (or vice versa) the gasket is compressed and tightens the space between the two.

Figure 75 : Truck arriving at site with duct components.

9.1.4 Manufacturing of flat oval ducts

One disadvantage of using circular ducts is that they cannot be flattened when the space is scarce. This is one strong reason for using rectangular ducts even though there might be a possibility to use several circular ducts in parallel as described in chapter 8.1

A compromise used in some countries is the flat oval duct. It is manufactured as a circular duct as described above but is then pressed or stretched in a special tool to become “flat oval”. This is to be primarily used instead of flat rectangular ducts in narrow spaces.

The requirements for a flat oval duct – being manufactured as a circular one – follows generally those for a circular duct. Flat oval ducts should only be used for positive pressure applications unless special designs are used to prevent the duct from being too flat.

One disadvantage with flat oval, as opposed to circular, ducts is however the more complex joint systems and duct components. The latter are also required in a large number of width and height combinations making prefabrication of ducts and components unfeasible.

9.2 INSTALLATION OF DUCTS

9.2.1 Common duct installation problems

Ducts, whether rectangular or circular, are large in comparison to other building installation systems such as cables and pipes. They have large turning radii and are thus difficult to move around if should come in collision course with other installations. To prevent the very common problem of colliding installations, e.g. in corridor false ceiling space, these space critical parts of the building, coveted by all designers and contractors, should be studied in advance and in detail. Sections showing the permissible installation area for each installation and contractor should be clearly stated. Anyone that is leaving a designated area and is moving into a neighbour’s should be obliged to redo the job by moving back.

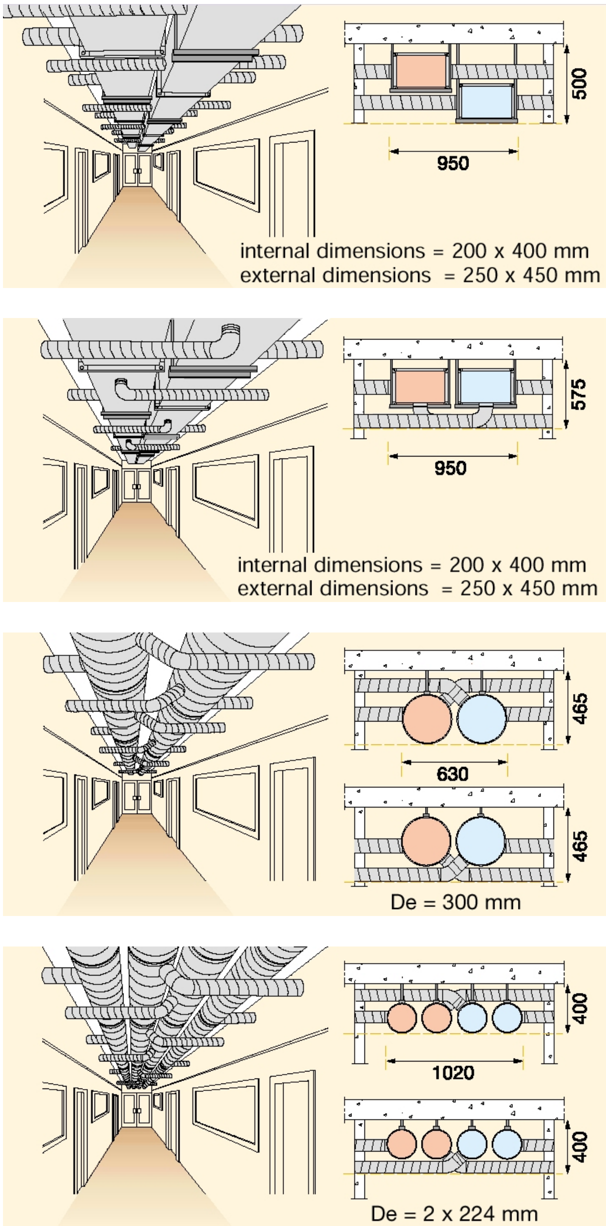
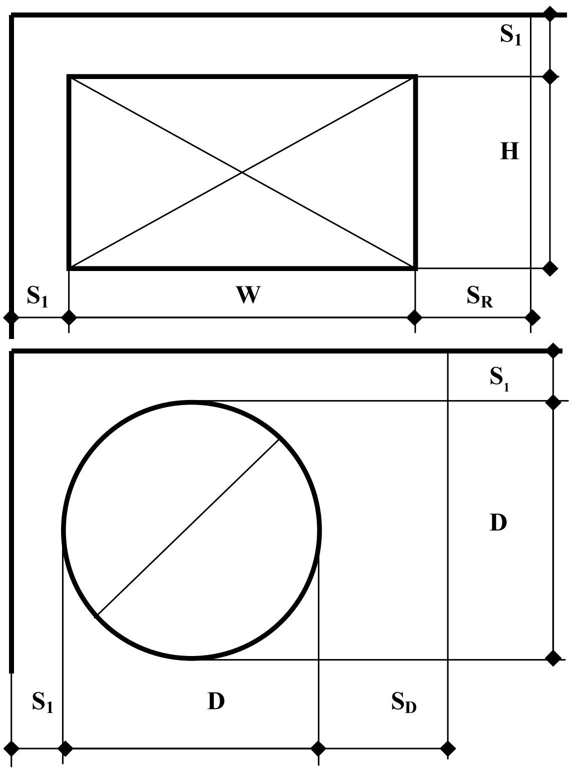


Figure 76 : Four possible alternatives starting with rectangular ducts followed by circular ducts.

Ducts serving rooms on both sides of a corridor often lead to a tricky space-planning problem. The space is often also required to serve other purposes than ventilation: cable trays, lighting, sprinkler tubes, and often hangers for the false ceiling. Figure 76 shows four possible solutions for typical duct installations where orange represents the supply duct(s) and blue the extract one(s).

As seen, the height needed for the ducts differs and could be a crucial factor if the free room height in the corridor is limited.

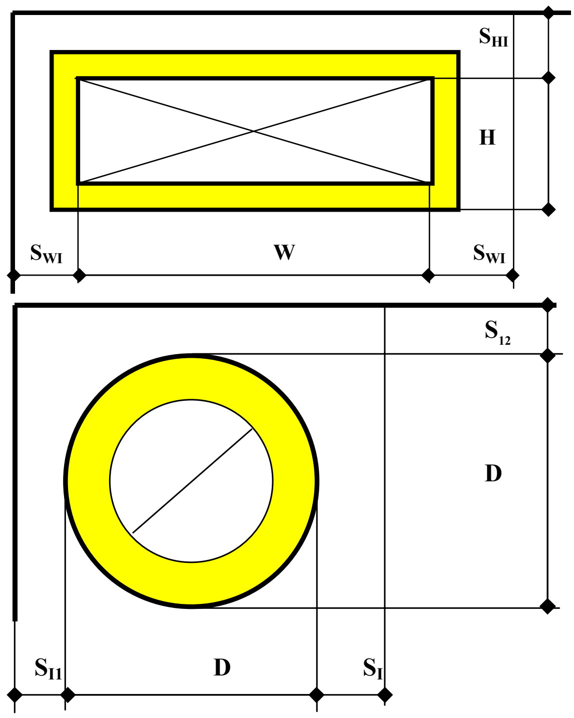


Duct size (mm)				
Circular **D**	Rectangular **W** or **H**		Minimum	Recommended
≤160	≤150	S_1	≥50	≥100
>160	>150	S_1	≥100	
≤800		S_D	≥400	
>800		S_D	≥400	**D**/2
	W≤800	S_R	≥400	
	W>800	S_R	≥400	**W**/2

Figure 77 : Installation space for uninsulated ducts

This detailed planning is troublesome but is well worthwhile. It prevents the first installer from using the main part of the available space and leaving only an inadequate remaining space for colleagues. It speeds up the installation process and prevents heated arguments on site.

When designing critical areas in this detail it is necessary to take the installation methods used and the space requirements that follow into consideration. A typical illustration is the way an externally insulated duct is installed. After the duct is installed – requiring e.g. proper space for slip joints if the duct is of rectangular shape and space for duct hangers – the insulation contractor will arrive to start work. Ample space to put on and fasten the insulation material has to be found. If the ducts are installed too close to the ceiling, walls or other installations, high standard duct insulation will be difficult to ensure.



Duct size (mm)		**Circular ducts**		**Rectangular ducts**	
Circular **D**[10]	Rectangular **W** or **H**	S_{I1} mm	S_{I2} mm	S_{WI} mm	S_{HI} mm
≤160		≥100	≥50		
>160≤300		≥200	≥100		
>300≤500		≥300	≥100		
>500≤800		≥400	≥100		
>800		≥500	≥150		
	W,H≤700			≥400	≥400
	700< **W,H**≤1200			≥600	≥400
	W,H>1200			≥600	≥600

Figure 78 : Installation space for ducts insulated with 100 mm

[10] NB: D is here the gross measure including the 100 thick insulation

9.2.2 Installation of rectangular ducts

Even though the ductwork is shown to scale on the drawings, the manufacture has to be based on site measured dimensions, at least for the last part of the duct that has to fit in into the remaining space. Should a piece of rectangular duct be incorrectly measured that part often goes to scrap as it is normally impossible to use it somewhere else in the building due to the large variety of rectangular duct dimensions.

The ducts should, on site delivery, be protected from rain, dust and snow especially if the are internally insulated. As described in chapter 7.4 there is an increased awareness of dirty ducts being one important reason for creating SBS conditions. By protecting the ducts and components from pollutant during transport, storing and installation the risk is at least diminished.

Larger sized ducts are heavy and normally require two fitters (and sometimes a fork lift truck) for the installation work. The work starts with installing the duct hangers, one on each side of the duct width, that are fixed to the ceiling. In industrial buildings, ware houses and stores the ducts are often fixed to a wall using brackets.

These brackets should be heavy-duty and securely fixed to the wall. It has happened that these rectangular ducts have been used as a platform when replacing faulty lamps high up on the wall. It was easier to do it this way than to get a ladder or a wheeled scaffold – but much more dangerous! In Sweden several serious, even fatal, accidents due to this misbehaviour has lead to a special requirement: Ducts (or pipe bridges or cable ladders) that are installed so that they might be mistakenly used as platforms should be dimensioned for an extra force of 1 kN" (corresponding to weight of ca 100 kg).

When the ducts are installed there has to be enough space for connecting the ducts with the drive slips that are hammered on to the upstanding joint flanges from the side of the duct. As these slips have to have the same width or height as the duct itself there has to be an accordingly free space available during the installation. This is sometimes forgotten, it seems to be a good idea to fill a rectangular shaft with a rectangular duct of the same size. It looks good on the drawing but is unfortunately not possible to achieve in reality (see § 8.1).

9.2.3 Installation of circular ducts

Compared to rectangular ducts for the same air velocity circular ducts are less heavy. This follows from the fact that less material is used for the duct itself (the perimeter is shorter for a circle than for a quadrangle or rectangle with the same cross-area) and for the joints. The less weight enables a single fitter to install larger ducts than is the case for rectangular ones. Even quite large diameter ducts can be installed single-handed by using a fork lift truck for lifting and holding the duct while being connected and fixed to the hangers.

Duct hangers for a circular duct are often less material consuming. They can either consist of straps on both sides of the duct diameter or a single hanger similar to the ones used for pipes.

Figure 79 : Installation of ductwork from a movable platform.

Figure 80 : Bracket-hanger for circular duct.

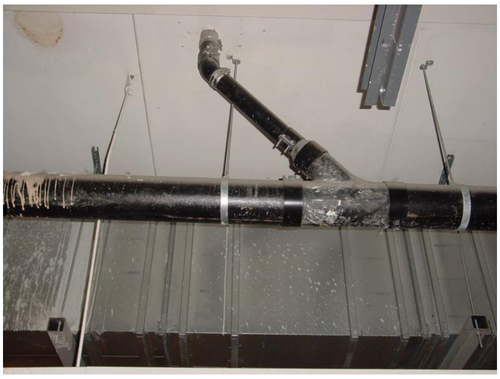


Figure 81 : A rectangular duct has to be supported on both sides with hangers – compare with the pipe.

A circular bend – contrary to a rectangular one – can be turned in any direction, to each side, up or down or in any arbitrary direction. This is an example of how a small number of components can be used in a large number of ways and how a component not fitted in one place can be used somewhere else. It simplifies the work on site as the ducts and components are prefabricated and not tailor-made.

Externally insulating a circular duct is relatively easy as the insulation material is formed around the circular shape of the duct without being stretched at any corners, as is the case with a rectangular duct. On the other hand insulating ducts internally is not possible on circular ducts but is easily done on rectangular ducts (even if it is not that common today as it used to be earlier due to an increased concern about cleaning ducts on the inside – see § 7.4.6).

The normally less space requirement of a circular duct is often especially valuable when installing ducts in shafts of high rise buildings. One of the case studies (see § 12.2) shows an interesting solution. In a very cramped space in a vertical concrete shaft it has been possible to install twenty parallel circular ducts, one for each floor of the building. The space saving duct installation enables a larger part of the area on each floor to be let and thus increases the income for the building owner in the years to come.

10.1 QUALITY CONTROL

There are different commissioning procedures. Different customs and practices and different standard contracts will influence the process.

The important common item is that a commissioning procedure takes place before the building is put into operation and the liabilities of the parts being involved in the building process expire. The building will probably stand for at least half a century and its building installations, though having a shorter life span, are also expected to last for some twenty years. It is at this time, before the building is ready for occupation, vital to control that it has a probable chance to fulfil the expectations of the building owner, and of the future tenants on a healthy building with good thermal comfort.

When it comes to the commissioning of ventilation duct systems there are, regardless of different national customs, however some common quality matters that should always be included among the necessary quality control checks:

- As-built drawings;
- Cleanliness control;
- Airflow and Flow balancing;
- Tightness control;
- Thermal and acoustic insulation;
- Fulfilling of fire safety requirements;
- Duct hangers vs. duct requirements;
- Marking of ducts.

Another common requirement should be that applied measurement methods should be well documented and have as small a method error as possible and that the instruments being used have adequate precision, are calibrated regularly and that the use of both methods and instruments are well known by the personnel involved.

The results of the different controls should be accounted for in written form using standard protocols signed by the person in charge. These documents should be filed, as they will prove valuable in the future for function controls and before reconstruction.

10.2 AS-BUILT DRAWINGS

Normally the contractor and the building proprietor should have agreed on larger changes of the original design beforehand. The designer should be involved in this decision process, as the change might be contrary to the intended function. In this case the decided alteration will normally be added as a revision to the original drawing.

Very often the outcome of the building process does not however exactly corresponds to the design shown on the original drawings. The reasons can be numerous, e.g. unforeseen collisions between different installations and/or building components. It is important that these changes are shown clearly on a set of drawings and that these are filed for future use. Often these divergences are hard to detect once the constructions are hidden behind walls or above false ceilings.

Changes being made during the building process might negatively influence the performance of the ductwork installations. The noise generated by the duct components might be higher and the noise attenuation lower than originally anticipated. The pressure drop in branches can be higher influencing the future operation costs and making the flow balancing more difficult. The possibility to install correct insulation might have diminished thus jeopardising the fire safety of the building.

The contractor (who ought to know where he has made alterations) should show these changes on a set of the design drawings kept on site during the construction and handed over to the building proprietor prior to the flow balancing start up. These changes should be transferred to the design drawings being filed as “As-built drawings”.

10.3 CLEANLINESS CONTROL

In chapter 7.4.6 the motives for requiring clean ducts, the cleanliness maintenance methods during the installation and the cleaning methods have been described. A spot-check control of the internal cleanliness of the ductwork should be made prior to the other ductwork checks.

This spot-check should also determine the future possibility to clean the ductwork. Are the ducts provided with necessary and correctly located inspection openings? Are they accounted for in the drawings? Is the location clearly marked in case they are otherwise hard to find?

10.4 AIRFLOW BALANCING

It should be a common rule that the airflow to the different rooms in the building is carefully adjusted and controlled as part of the commissioning of the building and its installations. In some countries this seems to be more the regular case than in other countries.

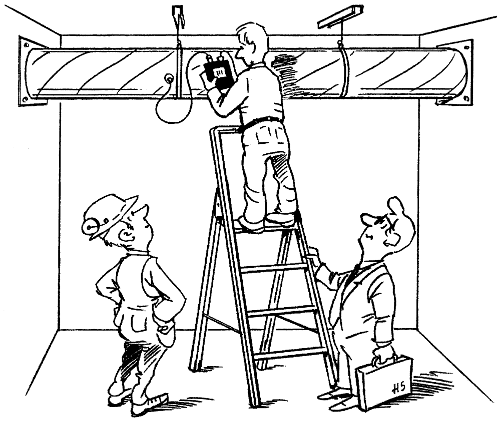


Figure 82 : Airflow measuring in a duct

In order to achieve this it is important that the duct system is planned and installed in such a way that the balancing and the measuring of airflow is possible and that this work can be done accurately at minimum cost.

Two major methods are used for the balancing of airflow:

- the Proportionality method;
- the Pre-set method.

10.4.1 The proportionality method

10.4.1.1 General

Air balancing according to the proportionality method is done by adjusting dampers and registers in the system so that every register delivers the same proportion of its designed airflow. The work is done as a systematic step-by-step method where every step is depending on the previous one. It is not necessary to measure the absolute value of the airflow. The method is instead based on relative data such as air velocity and pressure. When finally the fan speed has been adjusted all registers in the system should deliver the designed airflow.

The proportionality method uses the principle that the relation between the different airflow in branch ducts will remain the same even if the airflow in the main duct is changed. This means that the airflow in the branch ducts will be reduced by 20% if the airflow in the main duct is lowered by 20% using an adjustment damper in the main duct.

The same relation is valid for all registers in the system. This principle is used a systematic adjustment of the airflow. It means that the relation or the quotient between measured airflow and designed airflow for the different air registers and branch ducts gradually will be adjusted to the correct values. During the adjustment work there is no need to make any measurement of the absolute airflow; instead it is an advantage to make relative measurements.

10.4.1.2 Prerequisites

The total pressure drop in a duct comprises friction resistance and pressure drop over obstacles (see § 7.3.1). The pressure drop across obstacles will normally vary with the square of the air velocity in the duct.

Certain duct components, such as T-junctions, will not always follow this rule completely, which could be disadvantageous if the flow is largely changed. The friction pressure drop will normally vary with the square of the air speed (see § 7.3.1). At large changes of the airflow deviations from this quadratic relation can be obtained. This means that at big (>50%) changes of the airflow the prerequisites of the proportionality method will not be fulfilled. To cover oneself against unfavourable flow conditions it is therefore recommended that the flow deviation in the subsystem to be adjusted is not higher than ± 30%. At higher deviations the branch ducts should first be roughly adjusted.

10.4.1.3 Advantages with the method

Most supply and extract air installations, regardless of type and size, can be adjusted wholly or partly with the proportionality method. The method can be combined with the pre-set method (see § 10.4.2). This pre-setting could e.g. be done for groups of registers while the dampers in the branch ducts leading to the groups are adjusted according to the proportionality method.

10.4.1.4 Description of the method

The adjusting of the airflow of the registers always starts with having all dampers and registers fully open. The register that is located at the largest distance downstream is denominated as the reference register R.

The starting point of the adjustment is the register that has the lowest relation between measured and designed airflow, i.e. $Q_{measured}/Q_{designed}$. Should any other register than “R” in the group have a lower quota, this register will be designated the Index register, I. The reference register is adjusted so that its quota becomes equal to the quota of the index register. The damper of the index register shall be fully open after the adjustment.

The procedure continues with adjusting the registers against the reference register by adjusting the dampers in the registers so that the airflow relations, or quota, will be the same for the registers.

The same procedure will be used at adjustment of duct branches and main ducts.

10.4.2 The pre-set method.

The pre-set method requires that:

- A careful pressure drop calculation for the ductwork installation is available. The calculation is based on reliable data from the manufacturers;

- The set values for all dampers and registers have been calculated and noted on the drawings;
- All ductwork components have been installed according to the building specification;
- The actual installation corresponds to the design drawing and to the one calculated (otherwise a new calculation based on the as-built drawings has to be made).

Once this has been checked the pre-set adjustment method is fast and accurate. All dampers and registers are set according to the values shown on the drawings and in the building specification.

The measurement of the airflow at the registers will now correspond to the design values and verify that the calculation has been correct and that the adjustment of dampers and registers has been made correctly. Should this not be the case the work has to be restarted checking the items listed above.

Even though this method is theoretically perfect and - in the best of worlds - fast, reliable and cost effective it is in practice rather seldom used except for small and easily controllable systems. In reality there are too many alterations between the designed installation and the one actually installed to make it possible to base the adjustment only on software.

10.4.3 Comparison between the methods

Comparison shows that the proportionality method really is based on the actual installation and not on the contemplated design forming basis for the pre-set method. Even though the proportionality method is time consuming, costly and requires skilled personnel, it is the most used method today.

10.4.4 Ways to simplify the adjustment work

It is an advantage both for the adjusting and for the energy use of the plant if the ductwork design is made with parallel distribution paths rather than distributing the air to registers in series. The shorter the transport distance is between the fan and the registers, the lower the transport energy normally needed and the easier the adjustment.

Installing dampers in a symmetrical ductwork – as shown in one of the case studies, see § 12.3 - is an extremely simplified method. The distance between the main duct and each register is built up in the same manner, with the same amount of elbows and the same duct lengths (see § 7.1.6).

The distance between the first and the last register installed in the same duct should be as short as possible to prevent too high throttling in the register dampers which could lead to adjustment and noise problems. The duct should instead be split up in branch ducts and connection ducts, see Figure 83.

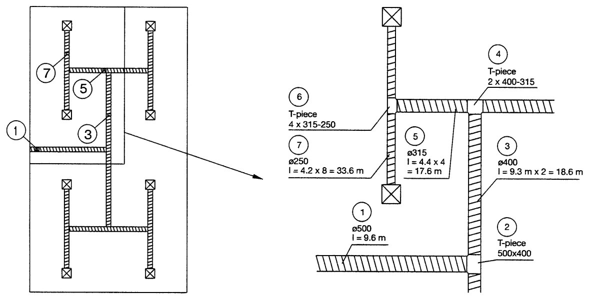
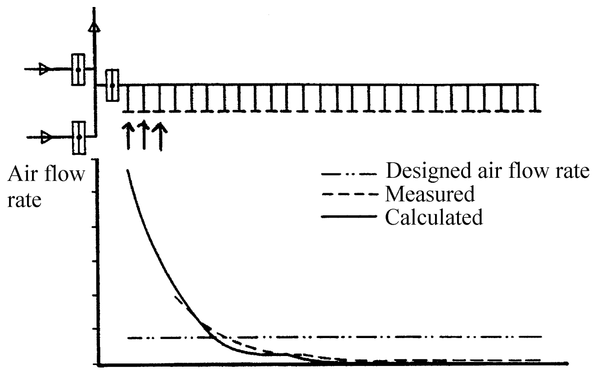


Figure 83 : Symmetrical ductwork where the supply air (entering at 1) passes through identical duct components on its way to the registers.



-.- = design airflow
--- = pre measurement before adjustment
__ = calculated air distribution
flow in liters/second

Figure 84 : Example on calculated and actual airflow distribution on a branch duct with 26 connected extract air registers. Each register comprises an adjustment damper. This example is showing a real installation before reconstruction!

Figure 85 and Figure 86, where the symmetrical principle has been used, show the same branch duct as in Figure 84. The split up of registers in groups makes the airflow adjustment possible.

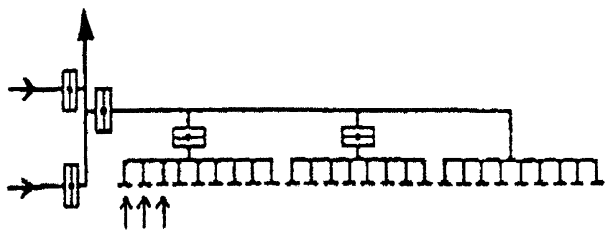


Figure 85 Now it is possible to adjust the airflow. The registers are combined in smaller groups, each with its adjusting damper.

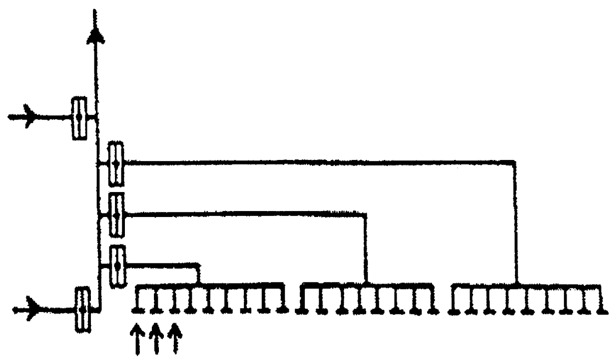


Figure 86 The same system once more solved with an alternative location of the adjusting dampers.

10.4.5 Airflow measurements

When you can measure what you are talking about and express in numbers, then you know something about it. [Lord Kelvin, 1824-1907]

10.4.5.1 Vital for the function

Probably the most important quality criterion for an air handling system is its ability to supply and extract the correct airflow. The airflow will change during the life span of the installation due to wear and tear in the long run and due to clogging filters in the short run. It is thus vital that the installation is built in such a way that the airflow can be measured accurately and be cost-effective at the commissioning and also at regular intervals in the future.

10.4.5.2 Measurement methods

The airflow measurement should be based on measure methods and instruments with known accuracy. In the Nordic countries such methods have been described in detail in a handbook recommended by the Nordic Ventilation Group [Ref 16]. The work started already thirty years ago and has been regularly updated; the latest edition is from 1998. The methods described have one factor in common, they have been tested and they have a known and recognised low method error (less than 10%) if applied in the correct manner described in the book.

The following methods in different applications are described and recommended in the latest edition:

A – Measurement in duct

- Prandtl pipe traverse in circular duct
- Prandtl pipe traverse in rectangular duct
- fixed installed measurement units without dampers
- fixed installed measurement units with dampers
- hot-thread anemometer in circular duct
- hot-thread anemometer in rectangular duct
- tracer gas measurement
- measuring of total airflow at fan inlet

B – Measurement at exhaust registers and air inlets

- point measurement with hot-thread anemometer at rectangular air intakes
- pressure drop measurement with probe
- pressure drop measurement with probe
- pressure drop measurement with fixed installed measurement unit
- measurement with anemometer
- measurement of center velocity in circular extract air openings
- measurement with impeller anemometer on air intakes

C – Measurement at supply air registers

- measurement of reference pressure at plenum box inlet
- measurement of reference pressure inside plenum box with one pressure outlet
- measurement of reference pressure inside plenum box with two pressure outlets
- direct measurement method with connection sleeve
- indirect measurement method with connection sleeve
- measurement with zero pressure difference (help fan)
- the bag method

10.4.5.3 Measurement accuracy

Every measurement always has an error, an accuracy that can vary and that should be expressed as calculated or an estimated deviation from the value shown on the measurement instrument. This measurement error comprises of three different types of errors:

m_1 = instrument error, due to hysteresis that is not possible to compensate for. The manufacturer should give information about this type of instrument inaccuracy. The accuracy of a measurement instrument is often related to the price of the instrument.

m_2 = method error, due e.g. to the chosen direction of the measurement probe and the distance between the probe and e.g. the surface of the air register. It is important that this type of method error is known and that the measurement is carried out under the same conditions. Different methods have different method errors and the method chosen should take this into account. Common for the different methods listed in chapter 10.4.5.2 is that the method error, when the method is applied as described in the manual, is less than 10% with the best ones being the bag method (normally 3%) and the Prandl pipe used in rectangular ducts (normally 4%).

m_3 = reading error, due e.g. to the difficulty to optimally read the value of the instrument. Scale and type of instrument, analog or digital, is of importance.

For instruments with analog scale the error can be estimated to 1/3 of the steps of the scale. If the deflection is pulsating an additional error, estimated to 1/8 of the amplitude, has to be added.

These three parts form the probable error of the measured value:

$$m_m = (m_1^2 + m_2^2 + m_3^2)^{1/2}\ \%$$

The result of the measurements should be accounted for in a signed protocol. This document has a value during the commissioning to show that the ventilation system is fulfilling the requirements stated. But it has also a value in the future; it provides a valuable tool for control of the function of the system. A very common cause for the sick building syndrome is that the airflow is not correct or not in balance with the emissions emitted into the room air.

The protocol should include many details:

- All data describing the plant, project, reference number, date for the measuring;
- System measured and location of the probe or instrument;
- Instruments used, their number or other designation that will enable an identification in case of a dispute;
- The measured data;
- Notes of factors that may have had an influence on the measured result (e.g. stack effects due to outside/indoor temperatures, wind effect – these factors are described in § 3.3 and § 7.3.2);
- Calculated probable measurement error, i.e. what is the ± deviation of the stated value;
- Signature by the one responsible for the given values.

To facilitate the checking of the airflow in the future in a simple manner – otherwise it will probably not be done – it is a good rule to have the location of the measurement probes in the ducts marked in a easily readable way.

10.4.6 Conclusion

The methods may vary from building to building but the important conclusion is: make the systems possible to adjust and measure; Check that the set airflow requirements are achieved. Correct airflow is the most vital prerequisite for a well functioning ventilation system.

10.5 TIGHTNESS CONTROL

The importance of having tight ducts in the installation is described in chapter 4.2.

Spot-check control of the ductwork tightness is a vital part of the commissioning procedure. It is by stating quality requirements in the building specification and by controlling the actual quality at the commissioning stage that the quality can be improved.

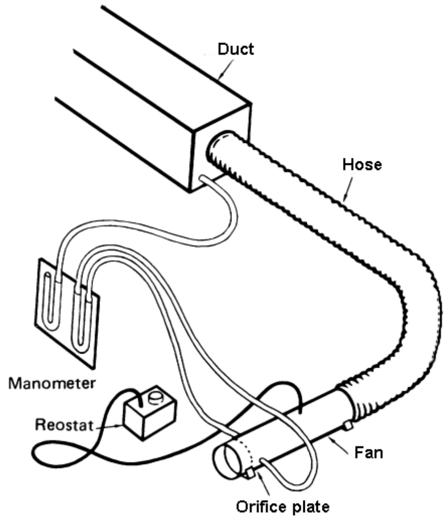


Figure 87 : Typical equipment used for tightness testing of ductwork.

An interesting example of this is described in chapter 7.10 where the tightness in a previous European project showed that ducts in Sweden were 25-50 times tighter than those installed in Belgium and France. One important difference between the countries is that tight ducts have been required in the Swedish contract conditions for ventilation systems (VVS AMA [Ref 41]) since 1968 with the demands regularly raised concurrently with technology advances.

Also note that the installed quality has been spot-checked under the supervision of the consultant as part of the contractor's commitment. In case the installation is found to be leaking more than required the installation has to be tightened and re-measured before accepted (see § 5.3.4).

11.1 MAINTENANCE – WHY?

11.1.1 Plan for a long installation life span …

The life span of a technical installation is often compared with the shape of a bath tube (Figure 88):

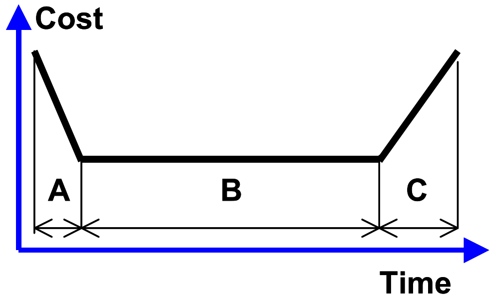


Figure 88 : Life span of a technical installation

There are high costs at both ends. By following the annual costs for maintaining an installation, replacement can be planned well in advance.

When the installation is new, and the operation has just started, there is a need for checking that it is working as expected. Minor alterations and repairs have to be made during the first period. These costs are normally carried by the contractor as part of a guarantee. These actions normally lead to a better and more trouble-free operation of the installation and the adjustment costs decrease – *part A of the curve*. Then follows a hopefully long period – some decades – *part B of the curve* during which the plant has to be maintained according to plans but few repairs are needed.

During this period the amount and cost of maintenance work can be planned and cost-estimated based on experience from similar installations. The aim of the maintenance work during this period is to regularly raise the function up to the original level whenever needed (Figure 89). How this is done should be described in maintenance manuals tailor-made for the actual installation.

In house or hired personnel will carry out maintenance depending on complexity. Often the choice is a combination of in-house responsibility for ordinary and simple jobs and hired personnel from a contractor to do work requiring special equipment and more expertise.

Examples of regularly needed maintenance actions could be duct cleaning or filter exchange. The first is based on inspections the latter on pressure drop measurements for example.

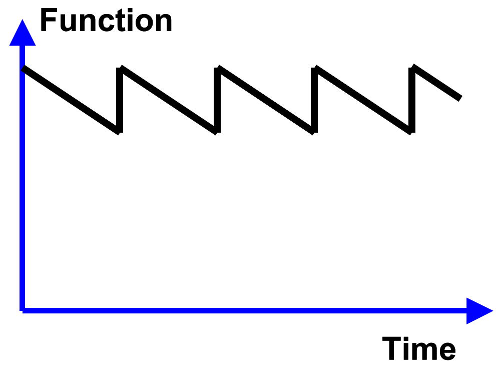


Figure 89 : Function raise up of a technical installation thanks to maintenance

11.1.2 … but it will not last forever

When the installation becomes older wear and tear takes its toll and age begins to tell. The costs for necessary maintenance measures now increases and repairs become more frequent – *part C of the curve*. By keeping a good control of the maintenance and repair costs the exchange of a worn out piece of equipment can be made as a planned part of the preventive maintenance and not as an unplanned calamity. The work can then also be made at a specific time, e.g. during vacation periods, when the disturbance to the use of the building is as low as possible.

11.1.3 Corrosion protection is vital

Choosing the right duct material is most vital when it comes to extending the life span of the ductwork. This item is discussed in chapter 11.1.4. If the ductwork is installed in corrosive environments standard material – zinc-coated steel – is often not good enough.

The following table shows the speed with which the zinc coat is corroded in different environments. A common problem for building installations occurs when condensation water is dripping down from a cold surface on to a galvanized duct or other zinc-coated surface. This should be prevented e.g. with adequate thermal insulation and vapour barrier on the cold surface or by relocating one of the two. The reason for the aggressiveness is that the condensation water, like distilled water, is salt-free.

Environment	Approximate corrosion speed (μm/year)
Indoors	<0.5
Alpland	<1
Countryside, inland	0.5 – 1.5
Sea-coastal regions	
Towns	1 – 3
Countryside	0.5 - 2
Industrial areas	2 – 10
Sea water	
North Sea	12 – 46
Baltic Sea	ca. 10
Fresh water	
Hard	2 – 4
Soft	<20
Tap water + 15°C	<15
Distilled water[11]	50 – 200
Soil	500

Table 20 : Approximate corrosion speed of zinc coating

Example :
Standard quality ductwork is manufactured of galvanized steel sheet, class Z275, with a zinc coat layer thickness of 20 μm (Z275 is coated with 275 g zinc distributed equally on both sides of a 1 m^2 large steel sheet).

With an approximate corrosion speed of 50 – 200 μm/year a layer with 20 μm thickness would only last for a few months if exposed to condensation water!
A comparison between mean values in gram per m^2 and year and μm per year shows that they are 7 to 1.

11.1.4 Is standard quality good enough?

A recommendation on what to choose as ductwork material in different corrosive environments is given in Table 21. As shown in the table most of the duct materials (with the exception of unprotected steel sheet) are suitable for use in environments with low or moderate corrosivity (class M0 – M2). Should the expected corrosivity however be higher either a better material (e.g. stainless steel) or one or several additional layers of corrosion protection (plastic or paint) have to be applied to the duct surface.

Example:
Should a standard type of duct (Z275 – see §11.1.3) be used indoors at constantly high air humidity (i.e. Environment class M4A with very large corrosivity) it has to be protected by "AG100+AM100+AT100" which means by three equally thick (100 μm) layers of tar- or resin-modified epoxy paint. As described before (see §11.1.4) these paint layers should be chosen with different colours.

[11] The same corrosion speed will occur when a zinc layer is exposed to condensation water

Sometimes it might be necessary either to choose a more corrosion-proof material than the ordinary galvanized steel or to protect the surface of the ducts with one or several additional layers of high-quality paint as listed in the table. Should this be the case it is important to regularly check the paint for damages and to improve the paint layer whenever needed.

One good way to simplify the control for paint damages has been used e.g. in the nuclear industry where required layers of paint have been applied with different colours. A scratch on the paint will then be easily detected by the colour of the lower layer showing up. Several colours shown will show that the damage goes deep down through several layers of the paint. Another advantage will of course also be that the quality of the contractor's workmanship is easy to control.

Choosing a right combination of material and corrosion protection paint can prolong the life span of the ductwork even in corrosive environments to some twenty years (after which it will probably anyhow be replaced for other reasons).

11.1.5 Plan for the exchange of worn-out equipment

As described earlier (§ 8.1) is important to provide ample space for the installations. A correct space planning of the installations should achieve that they can be:

- transported into the building (Figure 90);
- installed (Figure 91);
- tested;
- maintained (Figure 92);
- repaired (Figure 93);
- and exchanged when worn out (Figure 94).

11.1.6 Plan for a good work environment

The need for access should take care of industrial welfare and safety. Often the maintenance personnel have to carry heavy tools and equipment, e.g. replacement filters, to the plant rooms. They should be able to do this job in a safe and comfortable way. Ladders are e.g. difficult to use when carrying burdens and both hands are needed for climbing.

The same considerations for the work environment should be made for the plant rooms – they represent working places and should be equipped with ample space for the jobs to be done, with adequate lighting and painted surfaces. Major repairs and the exchange of equipment necessary in the future should be prepared already when the equipment is installed the first time. Heavy equipment, like fans and water chillers can neither be carried nor lifted manually. Necessary lifting tools, floors that will be able to carry the loads, transport openings and doors have to be provided. Vertical transports might need cranes and derricks, horizontal wide enough doors.

Environment classes			Material				
			Steel sheet hot rolled and cold-rolled	Hot dip galvanized steel sheet	Steel sheet metallized with aluminium–zinc (AlZn)	Aluminium sheet	Stainless steel
Environment class	Corrosivity	Examples	Surface coating				
M0	None	Indoors in dry air, e.g. in heated rooms	Prescribed surface coating	Z275	AZ150	None	1.4301 according to EN 10 088-2
M1	Insignificant	Indoors in air with changing temperature and humidity and insignificant level of air pollutants, e.g. in unheated rooms	Prescribed surface coating	Z275	AZ150	None	1.4301 according to EN 10 088-2
M2	Moderate	Indoors at moderate influence of humidity and moderate levels of air pollutants. - Outdoors in inland parts in air with low levels of air pollutants, e.g. in a larger area not densely built-up.	BG40 + AT80	Z275	AZ150	None	1.4301 according to EN 10 088-2
M3	Large	In air with raised levels of aggressive air pollutants – e.g. in larger population centres or in industrial areas. – At sea or near coast however not in zone with salt-water splash.	BG40 + AM80 + AT80	Z275 + minimum 25 µm plastic coating Z275 + AG80 + AT80	AZ150 + minimum 25 µm plastic coating AZ150 + AG80 + AT80 AZ185	None	1.4436 according to EN 10 088-2
M4A	Very large	Indoors and outdoors at constantly high air humidity or constant condensation. In salt- or fresh water or in earth.	BG40+ AM100 + AM100 + AT100	Z275 + AG100 + AM100 + AT100	AZ150 + AG100 + AM100 + AT100	CG25 + AM100 + AT100	1.4436 according to EN 10 088-2
M4B	Very large	Indoors and outdoors in industrial areas with high levels of aggressive air pollutants, e.g. certain chemical industries as wood-pulp, refineries or fertilizer industries.	As M4A	As M4A	As M4A	CG25 + AM100 + AM100 + AT100	1.4436 according to EN 10 088-2

Table 21 : Choose of ductwork material in different corrosive environments

Explanation to abbreviations in Table 21:

- A = Tar - alternatively resin-modified epoxy acc to SIS 18 52 05
- B = Zinc-rich epoxy according to SIS 18 52 04
- C = Epoxy-isocyanate-based priming paint
- G = Priming paint
- M = Intermediate paint
- T = Top (finishing) coat

The figures after respective paint code indicate dry layer thickness in µm.

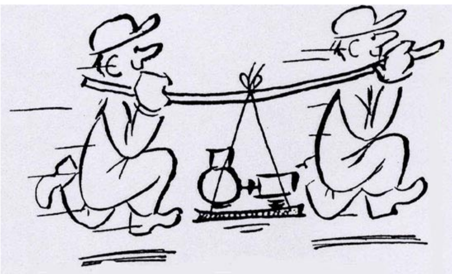


Figure 90 : transported into the building…

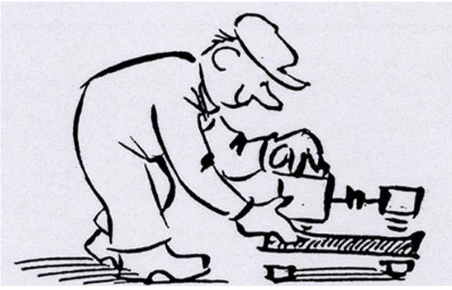


Figure 91 : installed…

Figure 92 : serviced and maintained…

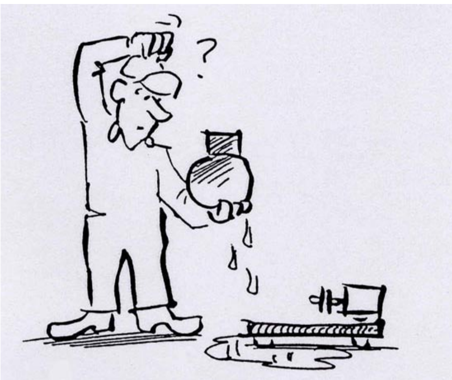


Figure 93 : repaired…

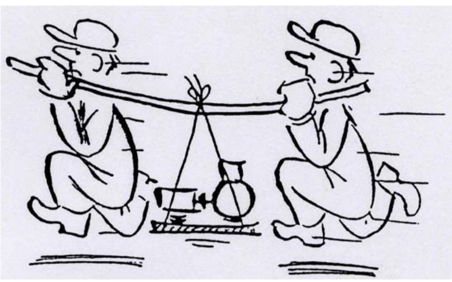


Figure 94 : …and exchanged when worn out.

11.2 MAINTENANCE – HOW?

11.2.1 The need for maintenance manuals

The dependability and durability of the building installations depends on the applied care and maintenance. The maintenance staff should have appropriate maintenance manuals adapted to the size, the operation conditions, the maintenance organization etc. The maintenance manual should include data about dated overhauls, and regular maintenance work. Normally the designer having an overview writes the maintenance manual based on data supplied by the contractors on specific equipment.

It is important that the installation is clearly marked with designations of equipment that need to be controlled or maintained. The descriptions in the manual are of little value unless it refers to components using the same designations. This is even more vital when it comes to safety – good and easily understandable instructions, marked installations and trained personnel – are well-suited precautions.

Systems and equipment necessary for the protection of the users – fire dampers, ducts and fans used for extraction of fire gases, sprinkler systems etc. have to be checked regularly. How this control is done and how often it should be done should be stated either in the maintenance manual or in a special safety manual. It is important that the one who has executed this work notes this in the manual with date and comments.

How and why e.g. fire dampers are checked is described in chapters 1.6, 7.1.7, 7.6.3 and 13.

The safety precautions necessary should be studied in a risk analysis and be exercised by the responsible personnel under supervision of an expert.

11.2.2 Well-trained personnel gives results

The maintenance people have an important role to play. It is to a large extent the result of their work that decides whether the building will function as intended creating a good and healthy environment for the users. Many studies have shown the importance a good thermal climate and a good air quality has on comfort and well being and how a good environment can lead to higher productivity in e.g. offices and better study results in schools.

To obtain this – and prevent that the building in the worst of cases from becoming a “sick building” – well designed and well built installations is a prime requirement. But – without well-adapted maintenance – even the best installation can prove to be a bad investment. To employ well-trained and ambitious personnel is on the other hand a good investment.

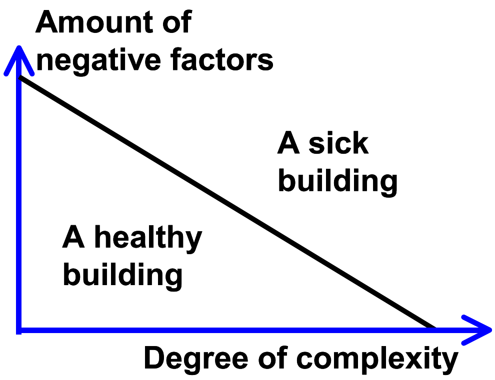


Figure 95 : Relationship between complexity of building installations and the result obtained

The figure above intends to show the relationship between complexity of building installations and the result obtained. The horizontal axis shows an increasing degree of complexity with simple installations to the left. The vertical axis shows upward an increasing amount of negative factors:

- lack of interest in maintenance;
- lack of skill to maintain;
- lack of maintenance means;
- and other lacks of the same kind.

This shows that the more complex installation that is chosen for the building, the greater is the risk that the building could suffer from SBS, the sick building syndrome, in the future unless it is maintained properly. The more simple installation to the left is more "forgiving" to human carelessness and negligence. To summarize – when taking an investment decision one should also be aware of the simultaneous decision that is taken of the future requirements on maintenance of the same. Unless the proper means are reserved in the future for appropriate maintenance a simpler installation would probably have been a better choice at the expense of missed possibilities.

11.2.3 The need for operation manuals

Many of the chapters in this book have pointed at important questions to be solved during design and installation in order to result in a well functioning installation. The way to operate the installations at different conditions in the most safe and cost-effective manner should be written down in the operation manual.

The operation manual should correspond with the actual installation as shown on the as-built drawings (§ 10.2) and be written in an easy understandable way. Wherever suitable the text should be accompanied by illustrations.

As for the maintenance manuals it is normally one of the designers who will write the maintenance manual. The designer who has the best overview of all the installations and knows how they are supposed to work together and also is familiar with the need of the users should be chosen for the job. For specific equipment he will base the work on data provided by his colleagues in the design team and on information supplied by the contractors.

11.2.4 Marking and labelling

Likewise stated for the maintenance work it is important that the installations are clearly marked with designations of equipment that is vital for the operation and/or need to be measured or controlled. The operation manual is of little value unless it refers to components using the same designations.

For ductwork it makes future work easier if the ducts are marked in a permanent way with arrows showing the normal flow direction and accompanying text stating type of air (supply, exhaust, extract, return etc) and the system designation number. This marking or labelling should be repeated at regular intervals and when passing in or out of shafts.

This is even more vital when it comes to equipment providing safety, e.g. fire dampers and extinguishers. Good and easily understandable instructions, marked installations and trained personnel are well-suited precautions that could save lives.

11.3 DUCTWORK CLEANING

The reason why ductwork has to be clean has been discussed in chapter 7.4.6.

11.3.1 When to clean?

Normally the time for cleaning is decided after a visual inspection of the ductwork (see also § 7.4.6). This can be done either with television inspection or manually through inspection openings using flashlights and mirrors.

The television inspection is done with a small TV-camera mounted on a robot that is capable of moving inside the ducts. The camera relays its signal back to a monitor and a video recorder. The length movement of the camera-robot is indicated on a scale to provide evidence on where special attention should be paid. As the equipment is fairly expensive and needs skilled personnel special contractors normally provide the job.

11.3.2 Cleaning methods

Methods used for cleaning ductwork include dry cleaning, wet cleaning, disinfecting, encapsulation and duct lining removal. Dry cleaning is performed when the contaminants can be removed by simple mechanical means or when the use of water is not practical.

The usual cleaning procedure is to isolate a section of ductwork and provide a negative pressure using a vacuum cleaner at one end. Cleaning proceeds from the other end of the section towards the end with the vacuum. Various optical devices are used to observe the progress of the cleaning inside the ductwork.

Manual cleaning by hand washing is performed when access is easy or when the duct is large enough to allow personnel to move around inside the duct. Should this be the case one should be aware of the risk of insufficiently dimensioned duct hangers (see § 9.2.2). They would then have to withstand not only the weight of the duct itself but also that of the person and necessary equipment. In both cases – manual cleaning from the outside or from the inside – spacious clean-out openings or manholes are required.

Smaller ducts can be cleaned with tools using rotating brushes and spray wands. Using a variety of chemicals that kill or control the growth rate of microorganisms performs decontamination.

Encapsulation is used to prevent erosion and to contain loose fibrous insulation and the incorporated nutrient and organic materials. Removal of duct lining material is usually the preferred method of cleaning when it is possible to do so.

People in the building are usually well protected during the cleaning procedure if the section being cleaned is isolated from the general air handling system and a HEPA filtered vacuum cleaner is utilized. The use of decontaminants and encapsulating agents is more problematic. The chemicals used should be approved for such application. Workers should have personal respiratory protection and should wear clothing suitable for the work. Most workers wear disposable facemask filters, gloves and washable clothing.

The long term effectiveness of duct cleaning is not well documented. Methods to evaluate duct cleanliness are not well developed and range from simple hand wiping of a small surface area to the use of contact microbial growth plates

Most of the examples presented in previous chapters have shown details from ductwork installations without stating where or in what type of building the photo has been taken.

In some cases however it might add interest if the examples are accompanied with some background information about the building and the reason for the chosen installation alternative.

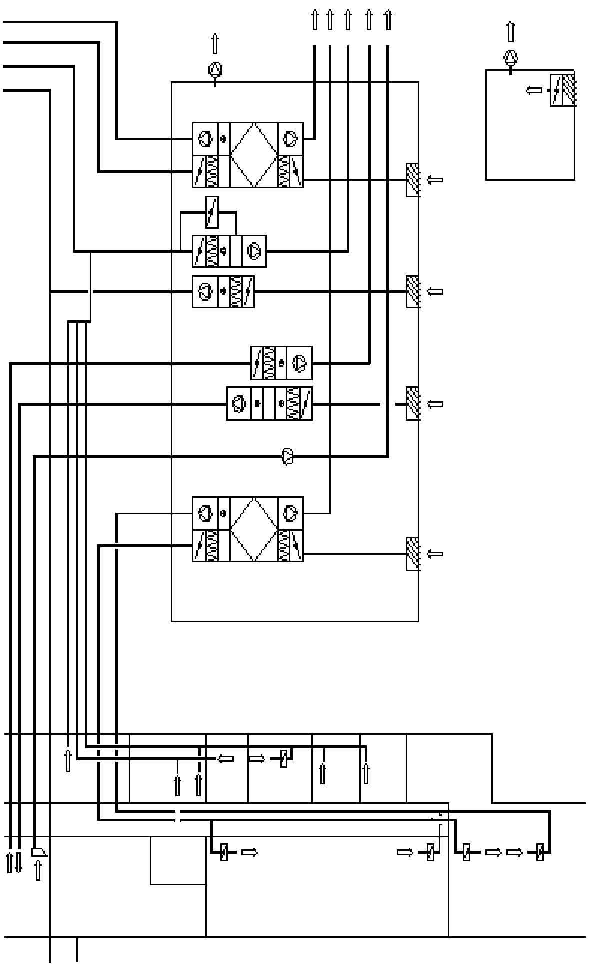


Figure 96 : Typical flow chart for a ventilation system. The designations used are probably self-explanatory.

12.1 THE ROYAL SWEDISH MUSIC ACADEMY, STOCKHOLM

Background

The Royal Swedish Academy of Music graduating e.g. music teachers forms a part of the Stockholm University.

The building was inaugurated in 1975 and renovated in 1995. The architecture of the building, the result of an architectural competition, was given a round form shaped like half of a musical G clef to link up with the use of the building. The other half of the G clef will be added if and when the building is extended in the future.

Figure 97 : Exterior from the street.

Figure 98: Exterior towards the courtyard

Floor

Before the renovation in 1995 the exercise rooms on both sides of the corridor were connected to a common supply duct in the corridor false ceiling space. The exhaust air from the rooms was overflowing into the corridor and collected at one common exhaust air grille before being lead back to the fan room located in the basement of the building.

The students have to train playing their instruments and therefore need exercise rooms where they and their teachers neither disturb other students nor vice versa. The intermediate walls between the rooms and the doors toward the corridor thus were provided with high noise reduction values. The required privacy was however not achieved completely due to noise transmission through the original ventilation system.

A very important issue during the renovation – when the ventilation system was to be upgraded with higher airflow – was therefore to prevent noise being transmitted from the plant room to the exercise rooms and between these through the ductwork.

The new ductwork

The round form of the corridors required a special solution. A new fan room was built in one of the exercise rooms at the centre point of the corridor and each of the exercise rooms was provided with its own supply and exhaust air duct system (Figure 102).

The air-handling unit is provided with plenum chambers on both the supply and exhaust side. These rectangular plenum ducts are clad on the inside with thick absorbents to reduce the fan noise towards the connecting ducts. On top of each of these two plenum chambers, the branch ducts to the exercise rooms are connected. With this solution having parallel ducts run to and from the each room there is neither any transmission of sound between the rooms when they are used for practise nor any disturbing fan or ventilation noise.

Figure 99: Rectangular ducts and plenums for supply (insulated) and extract air are connected to separate round ducts, one set for each exercise room. These ducts have manual airflow dampers.

Figure 100 : From the fan room the ducts are passing through the ceiling space to the rooms.

The supply ducts run alongside each other in the false ceiling space in the corridor and the exhaust ducts from the exercise rooms are running up in the attic entering the fan room underneath the high placed windows.

The result

Sound level measurement showed that the set noise goals were met with the new installations.

Figure 101: Photo from plant room showing ducts emerging from the corridor and the attic

Figure 102 : The new supply and extract ducts are installed in the ceiling space and connected to the fan room and the different exercise rooms.

12.2 'THE FIRST HIGH RISE BUILDING', SERGEL, STOCKHOLM

Background

This case study building was the first of five rather identical high rise office buildings in the City Centre of Stockholm. The architecture of the building was the result of an architectural competition (all five buildings, similar in height and dimensions, had its own architect). They were the result of a drastic reconstruction of a large part of the downtown area of the city when most of the old 18th and 19th century buildings were torn down and replaced with new ones.

The building was inaugurated in 1959, which was an extremely hot summer in Sweden. As typical for the time, the window/wall ratio was high, 76%. Following the normal design in Sweden at that period, the building was not equipped with any comfort cooling. The supply and exhaust air was distributed through concrete shafts connected on each floor to branch duct systems. As there was no shadowing from other buildings – the indoor temperature during the hot summer 1959 rose to above 35°C and the top floors of the building had to be abandoned for a few weeks.

The 1997 renovation

After nearly thirty years of operation the building was thoroughly renovated in 1997. All installations were exchanged and the old ventilation system was scrapped and exchanged for a modern air-conditioning system. New plant rooms were built on the roof of the building connecting to the old concrete shafts.

The new ductwork

Instead of using the shafts as plenums for supply and exhaust air respectively, the shafts were literally filled with circular ducts as each floor plan was provided with its own separate supply and extract ducts.

As each floor represents its own fire cell, the supply and exhaust ducts are provided with fire dampers (and regulating dampers) in the plant room as shown in Figure 103.

Figure 103: Ducts for the different floors pass down through common shafts, one for supply and one for extract air.

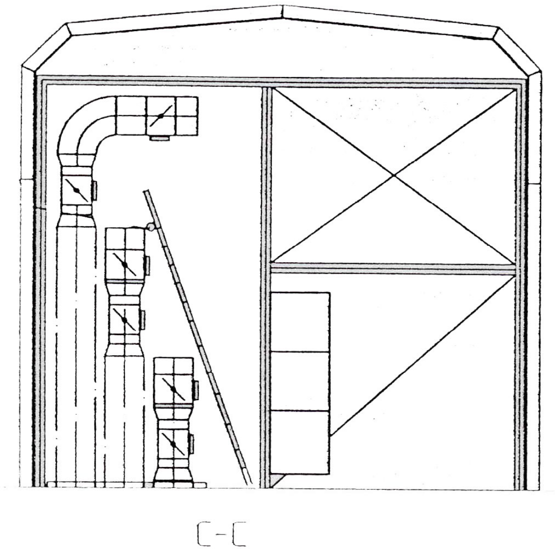


Figure 104 : Cross section "C-C" (see Figure 105) through part of the top floor fan room. The (extract) ducts to the left are the ones shown on the photograph (see Figure 103)

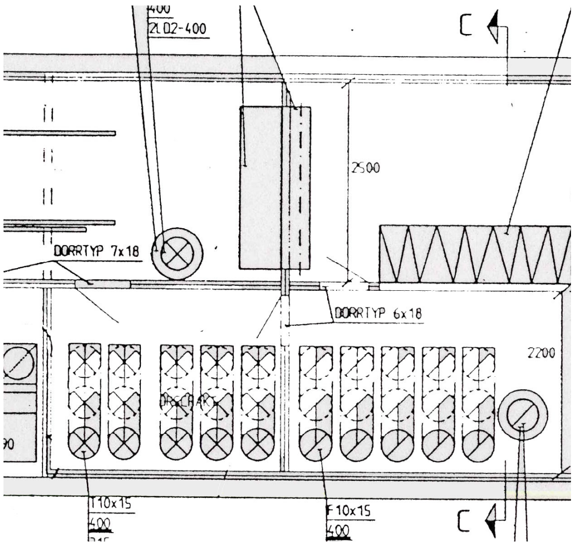


Figure 105 : Part of the fan room drawing with the extract air ducts to the right and the supply air ducts to the left. All these ducts are 400-mm diameter.

This technical solution required that fifteen ducts be installed in each of the shafts. This was possible by using circular ducts. The ducts were also delivered in 6-m lengths thus reducing the number of joints considerably. The very compact installation reduced the necessary space for the vertical shafts and increased thus the floor area that could be let.

The design of the duct systems had to be studied in detail on how the supply and extract ducts were entering or emerging from the shafts to prevent unnecessary collisions and facilitate the installation work. The ducts were tightness tested in turn as they were installed to prove that they were fulfilling the tightness requirements of class C.

12.3 LARGE OFFICE BUILDING IN STOCKHOLM

This office building, “Garnisonen” (the Garrison) from 1970, has a total length of 350-m and was built to accommodate several public authorities.

Before the design phase started this very large building was the subject of thorough analysis and detailed official reports covering architectural design and building installations. The latter have been shown as a result of the former. The ventilation ductwork is hidden above false ceilings only when needed for acoustical reasons. The ductwork itself, mostly using round ducts and being painted in different colours, has been used as an interior architectural element as shown in some of the following photographs.

Figure 106 : Close-up view of supply air register with sound silencer

Figure 107 : Symmetrical design of the ducts results in the same pressure drop at each register

Figure 108 : One of the courtyards in the building

Figure 109 : The building has an open design and is provided with sprinklers. Daylight enters through the glass roof of the interior courtyards.

Figure 110 : The ducts are visible and used by the architect as part of the interior design.

12.4 OFFICE BUILDING IN GOTENBURG

The Scandiaconsult office building in Gothenburg inaugurated in 1988 has also applied the same principle as the previous example: “Do not hide the ventilation ducts unnecessarily”. Use the full room volume for ventilation and install false ceilings only where required for acoustical reasons.

Figure 111 : Supply air register

12.5 A SELECTION OF THE WORST

While the previous case studies are interesting state-of-the-art examples of duct systems, experience shows that many field systems suffer from major flaws that can arise from all six phases defined in chapter 13.1. Here is our top-ten selection:

12.5.1 Lack of hygiene

Figure 112 : Ducts exposed outside on construction site.

Figure 113 : Bends exposed inside on construction site.

These ducts have been exposed to rain and pollutants emitted near the construction site (e.g., dust), and possibly fouled by animals and dead insects. These conditions are ideal for microbial growth.

12.5.2 Let's change the duct shape!

Figure 114 : Rectangular to circular reducer

This unnecessary transition between rectangular and circular ducts generates an unnecessary pressure drop.

12.5.3 Did you say pressure drop?

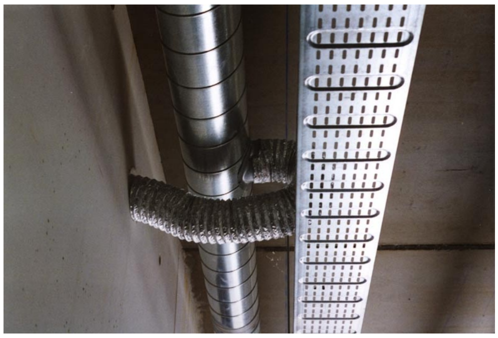


Figure 115 : Flexible duct

This flexible extract duct has an unnecessary tortuous path as well as wrinkles, both of which contribute to an increased pressure drop.

Figure 116 : Inappropriate use of flexible ducts

12.5.4 Now, how am I going to put fibre glass around that duct?

Figure 117 : Rectangular duct to be wrapped with insulation.

The insulation and vapour barrier will be poorly installed on the rectangular part of that system unless it is dismantled. Air and vapour passage through the leaks of the vapour barrier on the top part of the duct will cause condensation on the outer duct wall.

12.5.5 Not meant to be seen!

Figure 118 : Branching between a flexible and a rigid duct.

Not only is this damaged extract duct ugly, it also uses excessive fan energy because of leaks and increased pressure drops.

12.5.6 Talking about leaks and energy losses?

This flexible aluminium duct is part of an air heating system in France. The duct has an enormous hole leading to a false ceiling. The building insulation (10 cm mineral wool) was installed at the false ceiling, which means that a significant amount of hot air was simply lost to the outside. Note also that this duct should have been insulated !

Figure 119 : Leak found at a supply air terminal device.

12.5.7 Don't put your hand inside!

Figure 120 : Sharp screws increase the risk of injuries during maintenance operations

13.1 WHY DO WE NEED CHECKLISTS ?

The ductwork system's life can be divided into six major phases:

- The **P**rogramme:
  This phase aims at defining the owner's needs - e.g., the foreseen occupation scenarios of the building. Requirements on general issues - e.g., energy use, accessibility, and noise transmission - are also stated to avoid any negligence on items, especially those that are not covered by regulations. This phase mostly involves the building owner or a representative, and a programmer for large projects. A main contractor that will be responsible for the whole building construction process may be appointed by the owner at the end of that phase.

- The **S**ystem choice:
  The objective of this phase is to analyse the programme constraints together with the local environment of the building to choose the type of system that will be used. Therefore, the system designer must make sure that he receives the adequate information from the previous prescribers. The outcome of this phase lies in the definition of the ventilation principle that is retained. The system description could comprise of the main characteristics of the air treatment plant, a sketch of the system's layout, a description of the intended control strategy, as well as a first estimate of the energy use of the proposed solution(s). The system and building designers are the actors mostly involved during that phase, but the owner or a delegate should check that the system choice retained is compatible with known needs.

- The **D**esign:
  The system's characteristics are detailed during this phase. This includes detailed drawings of the installation, pressure drop, cost, and energy calculations, specifications of insulation thickness, etc. The system designer is the participant who is mostly involved during that phase as a follow-up of work carried out in the previous phase. The design phase normally results in a system specification and drawings that are used as tender invitation documents.

- The **I**nstallation:
  One of the tenderers has been awarded the contract for the ventilation system. This installer puts the ductwork system together during that phase according to the specifications laid out in the design phase. Therefore, the installer must make sure that he receives specifications from the designer with sufficient details to perform the work.

- The **T**esting, Adjusting, and Balancing (**T**AB):
  Before a building or part of a building is put to use, the duct system must be tested, adjusted, and balanced. That is, an inspection of the duct system and fire protection installations must be performed to demonstrate that it is clean, tight, balanced, ready for operation, and correctly documented. The specifications and as-built drawings of the installation must be available to the commissioner to complete that phase.

- The **M**aintenance:
  This phase starts as soon as the system is put in use. It consists in regular checks (e.g., of airflow rates), replacements (e.g. of filters), and work (e.g., cleaning) that has to be performed to ensure that the system operates correctly. Specifications, as-built drawings, and instruction manuals must be available to the plant manager.

Because ductwork systems involve many professionals during the life of the building (Table 22), it is vital that these people understand their duties and responsibilities to avoid misunderstandings or omissions that can affect the system's performance. To this end, checklists are useful tools to make sure no important aspects have been forgotten, and to help organise the work in a rational order. This organisation is key because making decisions at some point that put into question earlier decisions becomes more difficult and more expensive as the building construction process advances (Figure 121).

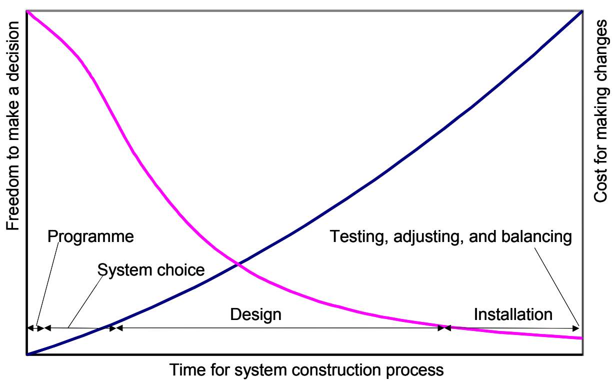


Figure 121 : Freedom to make a decision and cost involved versus time of building construction process.

13.2 HOW TO USE THE CHECKLISTS ?

The following checklists are practical quality assurance tools. There are six main entries corresponding to the first five phases of the life of a system: programme, system choice, design, installation, testing-adjusting-balancing, and maintenance. A phase may involve several people, e.g., the design phase involves the architect and the different building services engineers. The main entries contain a list of requirements, checks, and warnings for each phase of the building life (Figure 122).

Building life phase	
Check pre-requisites	
1. A check on an item addressed in an earlier phase.	☑
Require that	
1. A requirement on an item generally addressed in more details under “Specific requirements”.	☑
Check!	
1. A check on an item generally addressed in more details under “Specific requirements”.	☑
Be careful!	
1. A warning regarding common issues related to that phase.	☑

Figure 122 : Generic structure of “building phases” checklists.

Under the “**Check pre-requisites**” heading, one will find checks to make sure that the tasks required at an earlier stage, and are necessary to proceed with the system construction, have been performed.

Under the “**Require that**” heading, one will find requirements on items.

Under the “**Check**” heading, one will find checks that have to be performed on general items. These checks are generally addressed in more detail in the section “Specific requirements”.

Under the “**Be careful**” heading, one will find a list of warnings on common issues related to that phase.

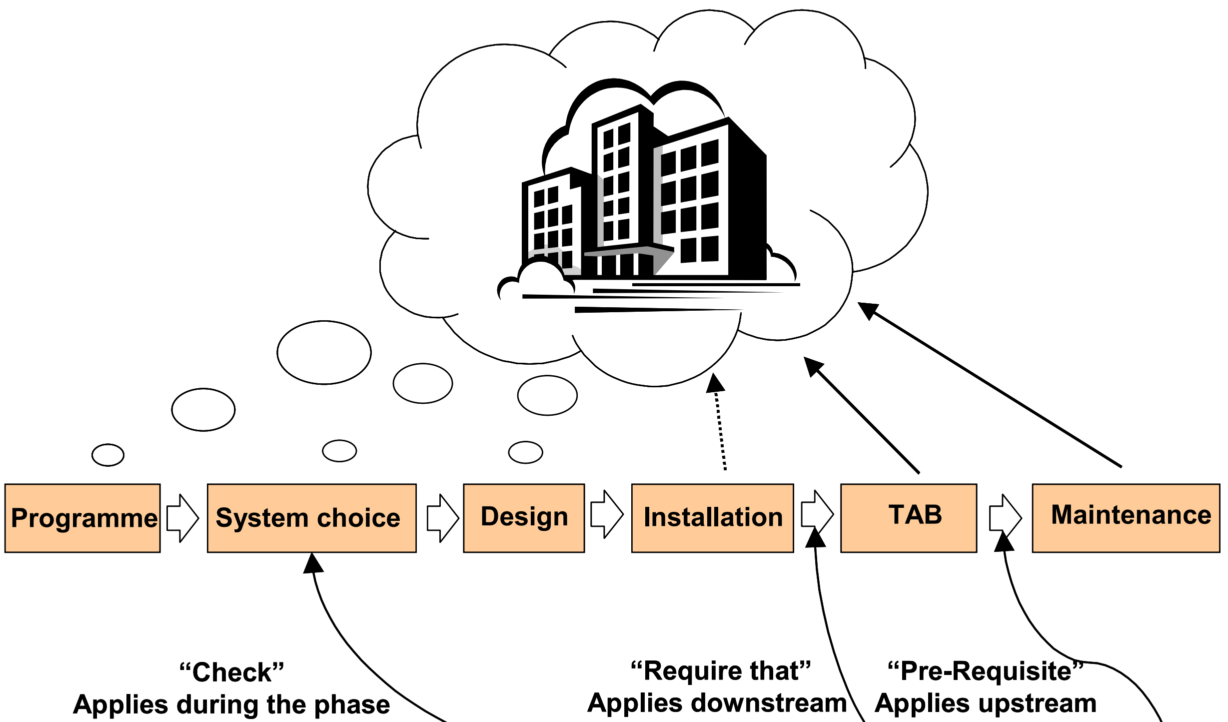
Detailed checklists that address technical issues in more details can be found under “**Specific requirements**”. Their generic structure is shown in Figure 123.

Important note:
Marks “☑” indicate that the items have to be tacked off. Blank checklists can be printed using the CD-ROM. Items that must be tacked off are shown as a blank box: “☐”.

Actor / Phase	Programme P	System choice S	Design D	Installation I	TAB T	Maintenance M
Owner or representative	☑	☑			☑	☑
Programmer*	☑					
Main contractor*		☑	☑	☑	☑	
Architect		☑	☑	☑	☑	
System designer		☑	☑	☑	☑**	☑**
Fire safety coordinator*			☑	☑	☑	☑
Installer			☑***	☑	☑***	
Commissioner			☑***	☑	☑	
Building manager*						☑
Plant manager*						☑
Occupants	☑*					☑

* *where applicable* ** *by providing correct conditions* *** *could improve the quality*

Table 22 : Those involved during the ductwork system’s life



Specific requirement						
Check pre-requisites	**P**	**S**	**D**	**I**	**T**	**M**
1. A requirement on the specific item addressed in that checklist.						☑
Require that	**P**	**S**	**D**	**I**	**T**	**M**
1. A requirement on the specific item addressed in that checklist.				☑		
Check!	**P**	**S**	**D**	**I**	**T**	**M**
1. A check on the specific item addressed in that checklist		☑				
Be careful!	**P**	**S**	**D**	**I**	**T**	**M**
1. A warning regarding common issues to that specific item.		☑	☑			

Figure 123: Flow chart showing the relation between the headings of the checklists and the phases.

13.3 BUILDING PHASES

13.3.1 Programme

Require that			
1.	In each phase, the ductwork characteristics (principles, layout, sizing, materials, etc.) must be shown to be compatible with the proper use of the installation and the building.	☑	
2.	In each phase, the ductwork must be shown to comply with all applicable regulations.	☑	
3.	Ductwork layout constraints are taken into account at early stages of the building design.	☑	§ 8.1
4.	Initial costs, operating costs, and Life Cycle Cost calculations of the solutions envisioned are made.	☑	§ 7.2
5.	The ventilation principle retained must be compatible with the building's operation and its surroundings.	☑	§ 2.1
6.	Energy losses in the duct system must be limited. An estimate of those losses must be made.	☑	§ 4
7.	Electric and heating energy use predictions are made and presented separately.	☑	
8.	The ductwork leakage must limited to be compatible with the proper use of the installation.	☑	§ 7.10
9.	Where necessary, the use of thermal insulation should be envisioned to comply with the requirements on energy losses, fire safety, and noise transmission.	☑	§ 7.5
10.	Pressure drop calculations are made. Pressures drops must be shown to be compatible with the proper adjustment of the airflow rates, and must account for energy losses and space demand.	☑	§ 7.3
11.	Provisions must be made so that the air supplied to the occupied spaces is clean and healthy.	☑	§ 7.4
12.	The structural integrity of the ductwork must be checked.	☑	§ 7.7
13.	The noise generated in or transmitted through the ductwork must be limited. (Specify an upper limit for the background noise if necessary.)	☑	§ 7.8
14.	The ductwork must be checked by the fire safety coordinator.	☑	§ 7.6
15.	The duct materials must not corrode prematurely.	☑	§ 11.1
16.	The air terminal devices chosen are to ensure a good air distribution within the room and to be compatible with the rest of the design of the ductwork system.	☑	
17.	The construction of the ductwork is planned and co-ordinated with the other networks of the building.	☑	§ 9.2
18.	The ductwork shall be tested, adjusted, and balanced. The points addressed in the TAB checklist must be checked by the commissioner. The test results are sent to the building owner, along with all the documentation that is necessary to properly operate and maintain the system..	☑	§ 10
19.	The ductwork must be easy to clean and maintain.	☑	§ 11.3
20.	The ductwork must be safe for use and maintenance.	☑	§ 11
21.	Someone (e.g., the architect) must be designated to be responsible for handing over the checklists to the owner or its representative.	☑	§ 13
22.	The checklists are filled out during the system choice, design, installation, and TAB phases.	☑	§ 13

Be careful		
1.	The prescriber should clearly define his needs! For this, a programmer may help him.	§ 5
2.	Investment and operating budgets not only be evaluated sequentially, but also globally!	§ 7.2

13.3.2 System choice

Check pre-requisites			
2.	The building designer has made space provisions for the ductwork installation (e.g., fan rooms, service shafts, false ceilings, location of fresh air intakes and exhaust).	☑	§ 7.1

Require that			
2.	Space is assigned to the ductwork system.	☑	§ 8.1
3.	The fire safety coordinator is informed of the system choice.	☑	§ 7.6
4.	Where applicable, networks for water, electricity, EMCS, etc., account for the ductwork lay-out constraints.	☑	§ 9.2

Check!			
2.	The ventilation principle is defined. It is compatible with the programme requirements.	☑	§ 2.1
3.	The major characteristics of the air treatment plant are defined.	☑	
4.	The sketch of the system's layout takes into account the building design and building environment constraints.	☑	§ 7.1
5.	The intended control strategy is described.	☑	§ 4.6
6.	A first estimate of the energy use is made.	☑	§ 7.9
7.	First estimates of the initial costs, operating costs, and Life Cycle Costs of the solutions envisioned are made.	☑	§ 7.2
8.	The system choice is shown to be compatible with the programme.	☑	§ 7.1
9.	The checklists relevant to that phase are filled out.	☑	§ 13

Be careful!			
2.	The system choice phase is key. The space assigned to the ductwork is almost definitively set by the end of that phase.	☑	§ 7.1

13.3.3 Design

Check pre-requisites			
1.	Check the system choice checklist items.	☑	§ 13

Require that			
1.	The technical information provided by the designer to the ductwork contractor includes: - detailed lay-out drawings; - specifications for the ductwork components (characteristics of rigid and flexible ducts, fire dampers, access openings, regulating dampers, hangers and supports, etc.); - particular requirements on items such as ductwork airtightness, cleaning access, etc.; - any special requirements; - references of the applicable standards.	☑	
2.	Ducts must be clean when installed.	☑	§ 7.4
3.	Where applicable, networks for water, electricity, EMCS, etc., account for the ductwork lay-out constraints.	☑	§ 9.2
4.	All ATD airflows must be measured and adjusted to their correct value.	☑	§ 10.4
5.	The ductwork has to be leak tested.	☑	§ 10.5

Check!			
1.	The ductwork system is compatible with the programme definition and requirements.	☑	§ 7.1
2.	Initial costs, operating costs, and Life Cycle Cost calculations have been performed.	☑	§ 7.2
3.	The energy use has been assessed. Electricity and heating energy use are presented separately.	☑	§ 7.9
4.	A ductwork airtightness class is specified.	☑	§ 7.10
5.	Is thermal insulation necessary? If yes, specify insulation material and insulation thickness according to acceptable U-values to limit conduction losses.	☑	§ 7.5
6.	Pressure drop calculations have been made. The pressure drop in the ductwork is shown to be acceptable.	☑	§ 7.3
7.	Cleaning access is good. Filter locations and classes have been specified where necessary.	☑	§ 7.4
8.	The ducts, hangers, and supports are strong enough for the specific use.	☑	§ 7.7
9.	Predicted noise levels comply with the programme requirements.	☑	§ 7.8
10.	Dampers or fireproof insulation are such that duct penetrations through walls do not diminish the fire safety of the walls, i.e., they are compatible with the EI class. R-requirements are specified for hangers and supports.	☑	§ 7.6
11.	An environmental class is specified to avoid corrosion damages. For specific applications, a duct material is specified.	☑	§ 11.1
12.	The registers are compatible with the control of the airflows and provide an adequate air distribution in the room.	☑	§ 10
13.	The design includes fixed sockets for measuring instruments for measuring the total airflow of the plant both for commissioning and for future monitoring of plant performance.	☑	§ 10
14.	The control strategy is compatible with the programme (building use) and the duct design (dampers, registers, sensors, etc.).	☑	§ 4.6
15.	The checklists relevant to that phase are checked.	☑	§ 13

Be careful!		
1. Good design is the pre-requisite to good ventilation system performance!		
2. The layout should be such that the ductwork is easy to install, clean, maintain, and replace.		§ 11.1
3. The duct design must be compatible with the programme requirements!		§ 7.1

13.3.4 Installation

Check pre-requisites		
1. The technical information provided by the designer is complete (see design checklist)	☑	

Require that		
1. The ductwork documentation is updated. It includes as-built drawings.	☑	§ 10.2

Check !		
1. The products and workers' skills are in line with the design requirements as specified.	☑	
2. The workers are aware of the procedures to properly deal with the ductwork on site - e.g., sheltered storage to avoid fouling, mounting and sealing procedures, manufacturer's instructions.	☑	
3. The fan is properly installed according to the manufacturer's instructions.	☑	
4. The checklists relevant to that phase are filled out.	☑	§ 13

Be careful!		
1. Installation plays a major role in the ventilation system performance. Its operation can be greatly affected by installation defects.		
2. Installation represents a significant fraction of the cost of an air distribution system.		§ 8.2
3. There must be some co-ordination with the installation of the other networks of the buildings, namely with water pipe networks and cable ladders to avoid collisions.		§ 9.2

13.3.5 Testing, Adjusting, and Balancing (TAB)

Check pre-requisites		
1. The documentation (detailed drawings of the ductwork installations, specifications for the materials and devices as well as for the maintenance schedule) are available.	☑	§ 10

Require that		
1. The documentation (detailed drawings of the ductwork installations, specifications for the materials and devices as well as for the maintenance schedule) shall be available to the building manager to ease maintenance and retrofit.	☑	§ 10

Check!		
1. The system has been properly balanced and documented.	☑	§ 10.4
2. The system has been leak tested and complies with the requirements.	☑	§ 10.5
3. Fire protection installations are operational.	☑	§ 7.6
4. The ductwork is clean and ready for operation.	☑	§ 11.3
5. Test details should be included in the manuals for operation and maintenance.	☑	§ 11.2
6. A visual inspection the ductwork is carried out to make sure that the drawings are accurate and to check for major flaws or missing components such as cleaning openings, sensors.	☑	
7. The checklists relevant to that phase are filled out.	☑	§ 13
8. Someone (e.g., the HVAC contractor) must be designated to be responsible for handing over the checklists to the owner or its representative.	☑	§ 13

Be careful!
1. Ductwork systems should be commissioned and properly documented!

13.3.6 Maintenance

Check pre-requisites			
1.	The documentation (detailed drawings of the ductwork installations, specifications for the materials and devices, test protocols from the TAB procedures as well as manuals for the maintenance schedule) are available.	☑	§ 11.2
2.	The plant managers are properly trained.	☑	§ 11.2

Check!			
1.	Record test, changes, repairs, or problems and keep this information with the documentation of the system.	☑	
2.	For major repairs or renovation, revisit the checklists from the programme phase.	☑	§ 13
3.	The maintenance schedule is followed and updated.	☑	§ 11.2

Be careful!		
1.	A ductwork system is subjected to mechanical stress and air pollution.	
2.	Equipment failures will occur and may affect directly or indirectly the system's operation and performance.	
3.	Design and installation flaws unnoticed at commissioning may reveal themselves only after a few years of operation.	
4.	The system needs a regular maintenance to function properly!	§ 11

13.4 SPECIFIC REQUIREMENTS

The list of checklists for specific requirements is given in Table 23. The references of the chapters where these requirements are addressed are also given in this table.

General issues	
1. Lay-out	§ 7.1
2. Cost-effectiveness	§ 7.2
3. Ventilation principles	§ 2.1
Energy related issues	
4. Energy Use	§ 7.9
5. Airtightness	§ 7.10
6. Thermal insulation	§ 4.3 § 7.5
7. Pressure drop	§ 7.3
IAQ concerns	
8. Clean air supply	§ 7.4
Important boundary conditions	
9. Strength	§ 7.7
10. Noise	§ 7.8
11. Fire protection	§ 7.6
12. Corrosion	§ 11.1.3
13. Duct material	§ 11.1.4
Component related aspects	
14. Air terminal devices	§ 2.2.13
15. Access	§ 2.2.10 § 7.1.5
Air flow related issues	
16. Balancing a ventilation system	§ 10.4
17. Control strategy	§ 4.6

Table 23 : List of checklists for specific requirements

13.4.1 Layout

Check pre-requisites	P	S	D	I	T	M
1. Provision must be made at the early stages of the building design to have enough space for the ductwork installation. Therefore, fan rooms, service shafts, false ceilings, location of fresh air intake and exhaust must be studied early in the design process.		☑				

Require that	P	S	D	I	T	M
1. The ductwork layout must be compatible with the proper use of the installation and the building. It accounts for space demand, pressure drop, installation, or cleaning and servicing access issues.	☑					

Check!	P	S	D	I	T	M
1. The ductwork layout accounts for space demand, pressure drop, installation, or cleaning and servicing access issues.		☑	☑			

Be careful!	P	S	D	I	T	M
1. The layout should be such that the ductwork is easy to install.		☑				

13.4.2 Cost-effectiveness

Require that	P	S	D	I	T	M
1. Initial costs, operating costs, and Life Cycle Cost calculations of the solution are made.	☑					
2. The choice between different options takes into account initial costs, operating costs, and Life Cycle Cost.	☑					

Check!	P	S	D	I	T	M
1. The choice between different options takes into account initial costs, operating costs, and Life Cycle Cost.		☑	☑			

Be careful!	P	S	D	I	T	M
1. The labour cost represents a significant fraction of the cost of a ductwork system.			☑	☑		

13.4.3 Ventilation principles

Check pre-requisites	P	S	D	I	T	M
1. The needs and constraints—e.g., occupancy, climate, indoor and outdoor pollution sources—are clearly identified.		☑				

Require that	P	S	D	I	T	M
1. The ventilation principle retained must be compatible with the building's operation and its surroundings.	☑					

Check!	P	S	D	I	T	M
1. The ventilation principle must be adapted to the needs and constraints—e.g., occupancy, climate, and indoor and outdoor pollution sources.		☑	☑			
2. Identify the advantages and drawbacks of various options (e.g., cost, space, indoor air quality, control of air distribution, and potential moisture damage).		☑	☑			

Be careful!	P	S	D	I	T	M
1. All ventilation principles have advantages and drawbacks.	☑	☑	☑			

13.4.4 Energy use

Check pre-requisites	P	S	D	I	T	M
1. Airtightness and thermal insulation requirements are clearly stated. Refer to airtightness and thermal insulation checklists.				☑		

Require that	P	S	D	I	T	M
1. Split-up in separate zones could if shown to give better adaptation to user's needs and shorter air transport through ductwork. Energy losses in the duct system must be limited. An estimate of those losses must be made.	☑					
2. Electric and heating energy use predictions are made and presented separately.	☑					
3. Air infiltration through the building shell is such that it does not affect the ductwork system's operation. It is taken into account in ventilation energy use.	☑					

Check!	P	S	D	I	T	M
1. The energy impact of ventilation takes into account ventilation losses, distribution losses, fan energy use. Energy losses in the duct system are limited.		☑	☑			
2. Avoid unnecessary pressure drops.		☑	☑			
3. Specify an adequate leakage class and thermal insulation requirements to limit distribution losses.			☑			
4. Use energy-efficient fans.			☑			

Be careful!	P	S	D	I	T	M
1. A heat recovery unit allows one to recover energy in the outgoing air stream, but it also increases the fan energy use. Therefore, depending on the climate and the building characteristics, it may result in an energy penalty!		☑	☑			

13.4.5 Airtightness

Check pre-requisites	P	S	D	I	T	M
1. Airtightness requirements are expressed according to Eurovent 2/2 or a similar guideline/standard.				☑	☑	

Require that	P	S	D	I	T	M
1. The ductwork leakage must be limited to be compatible with the proper use of the installation. A duct leakage limit must be specified.	☑					

Check!	P	S	D	I	T	M
1. Each seam and joint is carefully sealed.				☑		
2. Identify adequate airtightness requirements.						
3. Identify proper duct system components or sealing materials. (Choose between quality acrylic-based adhesives, EPDM rubber, or silicon for your specific application. It shall not emit toxic gases.)			☑	☑		
4. The sealing material shall be able to withstand the pressure, temperature, and humidity stress in normal operation of the system.				☑		
5. The sealant shall not be used as a mechanical support.				☑		
6. Avoid tailor-made parts.				☑		
7. Test the ductwork for leakage.					☑	

Be careful	P	S	D	I	T	M
1. Installation is key, especially when conventional sealing techniques - e.g., mastic, tape - are used.			☑	☑		
2. Quality factory-fitted sealing devices are very effective to limit duct leakage provided that simple rules be respected - e.g., avoid tailor-made parts.			☑	☑		

13.4.6 Thermal insulation

Check pre-requisites	P	S	D	I	T	M
1. Places where insulation and vapour barriers are necessary are specified (along with the type and thickness of insulation material and type of vapour barrier and, when applicable, external cladding).				☑		

Require that	P	S	D	I	T	M
1. Where necessary, the use of thermal insulation and vapour barriers should be envisioned to comply with the requirements on energy losses, fire safety, and noise transmission.	☑					

Check!	P	S	D	I	T	M
1. The use of thermal insulation, in combination with a vapour barrier, should be considered when water condensation on duct surfaces is expected. Depending on the location, the thermal insulation and the vapour barrier might have to be protected by an external cladding, e.g. aluminium sheet.			☑			
2. Estimate the necessary U-values to limit conduction losses. Identify insulation material and insulation thickness.			☑			
3. If thermal insulation is used for fire protection, make sure that it complies with applicable regulations and standards.			☑			
4. Do not leave insulation material exposed during construction.				☑		
5. Check that the insulation material and the vapour barriers have not been damaged (torn, wet, etc.)				☑		

Be careful !	P	S	D	I	T	M
1. Insulation should not release fibres or toxic materials.			☑	☑		

13.4.7 Pressure drop

Check pre-requisites	P	S	D	I	T	M
1. The preliminary layout accounts for pressure drop issues.			☑			

Require that	P	S	D	I	T	M
1. Pressure drop calculations are made. Pressure drops must be shown to be compatible with the proper adjustment of the airflow rates, and must account for energy losses and space demand.	☑					

Check!	P	S	D	I	T	M
1. Duct connections on both sides of the fan must be properly chosen and installed.			☑	☑		
2. Air velocities in the ductwork are not too high.		☑	☑			
3. The pressure drops are large enough to ensure the stability of the airflows.			☑			

Be careful!	P	S	D	I	T	M
1. A higher pressure drop will cost fan power and thus more energy and money during operation!			☑			

13.4.8 Clean air supply

Check pre-requisites	P	S	D	I	T	M
1. The number and location of cleaning/servicing access openings is specified.				☑		
2. The number and location of filters is specified, along with the filter classes.				☑		

Require that	P	S	D	I	T	M
1. Provisions must be made so that the air supplied to the occupied spaces is clean and healthy.	☑					
2. The ducts are clean when installed.	☑					

Check !	P	S	D	I	T	M
1. Take into account potential pollutant sources and the quality of the exterior air.		☑	☑			
2. Air filters are used if necessary. In that case, a filter class is specified.		☑	☑			
3. The ductwork materials are able to withstand standard cleaning procedures—e.g., brushing, vacuum cleaning, chemical disinfection—that are expected to be necessary during the course of operation.			☑			
4. There are cleaning access panels (see access checklist).			☑			
5. The ducts are clean when installed and when the installation is handed over.				☑	☑	
6. Inspect ducts, fan blades, or coils regularly. If needed, have them cleaned.						☑
7. Watch for stagnant water.						☑
8. In small diameter ducts, watch for declining airflows as a result of fouling.						☑
9. Air filters are clean and regularly changed.						☑
10. In case of persistent complaints from the occupants, have an air quality diagnostic done.						☑

Be careful!	P	S	D	I	T	M
1. Watch for stagnant water, which is ideal for microbial growth.						☑
2. Microbial growth often occurs in air intake ducts with internal insulation.			☑			☑

13.4.9 Strength

Check pre-requisites	P	S	D	I	T	M
1. The number, type, and location of hangers/supports are specified.				☑		

Require that	P	S	D	I	T	M
1. The structural integrity of the ductwork must be checked.	☑					
2. The ductwork must be able to withstand the positive or negative operating pressures.	☑					
3. The distance between and size of the hangers shall be such that the installation can withstand, if applicable, a spot load of one person in addition to the dead weight of the duct.	☑					

Check!	P	S	D	I	T	M
1. Risk analysis 1. Exposure to temperature extremes, earthquakes, sudden stoppage of airflow or any other conditions specific to the installation should be considered where necessary.			☑			
2. Risk analysis 2. The occurrence of fatal accidents to people who have been wrongly using rectangular ducts as working platforms instead of scaffolds or ladders suggests making sure that the installed ductwork can withstand a spot load of 1 kN (corresponds approximately to the			☑			

	weight of a person).						
3.	Hangers and support systems are of correct type and correctly installed. Fire-classed duct should have R-classed hangers.				☑	☑	
4.	Do not use damaged ducts.				☑		
5.	The ductwork should be handled with care and must not be damaged during maintenance work.						☑

Be careful!		**P**	**S**	**D**	**I**	**T**	**M**
1.	Ducts should not be used as working platforms instead of scaffolds or ladders.				☑		☑

13.4.10 Noise

Check pre-requisites		**P**	**S**	**D**	**I**	**T**	**M**
1.	The number, location, and characteristics of devices such as sound attenuators or anti-vibration isolators are specified.				☑		

Require that		**P**	**S**	**D**	**I**	**T**	**M**
1.	The noise generated in or transmitted through the ductwork must be limited.	☑		☑			
2.	No toxic material can be released from internal liners.	☑					

Check!		**P**	**S**	**D**	**I**	**T**	**M**
1.	Design measures are taken to limit aerodynamic noise.		☑	☑			
2.	Evaluate sound levels and compare with acceptable sound levels.			☑			
3.	Use silencers if necessary.			☑			
4.	Specify the location of devices such as sound attenuators or anti-vibration isolators.			☑			

Be careful!		**P**	**S**	**D**	**I**	**T**	**M**
1.	Ventilation systems are not bound to make noise.			☑			
2.	Occupants often complain about ventilation system noise.			☑			
3.	The fan is the primary sound source in a mechanical ventilation system. However, inappropriate duct components and leakage can generate other noise; the ductwork can also allow or enhance cross-talk between different rooms of a building.			☑			

13.4.11 Fire protection

Check pre-requisites		**P**	**S**	**D**	**I**	**T**	**M**
1.	The locations where fire protection methods are used—e.g., fire dampers, fireproof insulation—are specified. Applicable standards are referenced.				☑		

Require that		**P**	**S**	**D**	**I**	**T**	**M**
1.	The ductwork must be checked by the fire safety coordinator.	☑					
2.	Fire dampers should be certified to follow, and be installed according to, requirements in EN 23456.			☑			
3.	The insulation material—e.g., mineral wool—has been classed as fulfilling the requirements according to EN 34567.			☑			

Check!		**P**	**S**	**D**	**I**	**T**	**M**
1.	Duct hangers for fireproof classed ducts have to withstand standard fire during same period of time as the duct. Mark drawings with area to have same type of fireproof hangers.			☑			
2.	Identify location of fireproof walls and slabs penetrated by ducts.			☑			
3.	Identify proper fire class and technical option.			☑			

		P	S	D	I	T	M
4.	If fire dampers are chosen, they are classed and certified according to applicable standards and regulations.				☑		
5.	Fire dampers and fireproof insulation are correctly installed where specified by the designer with certified products.				☑	☑	
6.	The fire dampers are regularly checked as part of the maintenance procedures.						☑

Be careful!		**P**	**S**	**D**	**I**	**T**	**M**
1.	Ducts passing through fire classed walls and slabs must not diminish the fire safety.			☑			

13.4.12 Corrosion

Check pre-requisites		**P**	**S**	**D**	**I**	**T**	**M**
1.	The environmental (corrosivity) classes are specified.				☑		

Require that		**P**	**S**	**D**	**I**	**T**	**M**
1.	The duct materials must not corrode prematurely.	☑					

Check!		**P**	**S**	**D**	**I**	**T**	**M**
1.	Choose the ductwork quality according to the aggressiveness of the environment.			☑			

Be careful!		**P**	**S**	**D**	**I**	**T**	**M**
1.	Corrosion damage on ductwork installed in aggressive environments often leads to leaking and unsafe installations with drastically reduced lifetime.			☑			☑
2.	Corrosion damage is a very common reason for equipment failures - choose materials and corrosion protection suitable for the local environment.			☑			☑

13.4.13 Duct material

Check pre-requisites		**P**	**S**	**D**	**I**	**T**	**M**
1.	Duct material and duct thickness are specified.				☑		

	Require that	**P**	**S**	**D**	**I**	**T**	**M**
1.	The ductwork materials must be compatible with the proper use of the installation and the building.	☑					

Check!		**P**	**S**	**D**	**I**	**T**	**M**
1.	Choose between galvanised, stainless steel, aluminium, and plastic coated products for your specific application.			☑			
2.	The material has to be compatible with the potential corrosion damages.			☑			
3.	Specify duct material and duct thickness.			☑			

Be careful		**P**	**S**	**D**	**I**	**T**	**M**
1.	Choose, if possible, standard ducts of galvanised steel Z 275 which means lowest cost and a freedom to choose among a large variety of standard components - check however the local corrosion environment!			☑			

13.4.14 Air terminal devices (ATD)

Check pre-requisites	P	S	D	I	T	M
1. The number, type, characteristics, and location of the air terminal devices are specified.				☑		

Require that	P	S	D	I	T	M
1. The air terminal devices chosen ensure an adequate air distribution within the room and are compatible with the rest of the design of the ductwork system.	☑					

Check!	P	S	D	I	T	M
1. Take into account ductwork design issues such as pressure drop, sound transmission, airflow control, and room air distribution when choosing air terminal devices.			☑			
2. The ATDs are tightly sealed to the duct or plenum box.				☑		
3. Limit envelope leakage by tightly sealing the ATDs to the wall.				☑		
4. Regularly inspect and, when necessary, clean supply and extract ATDs. (Significant deposition is usually found on extract ATDs.)						☑

Be careful!	P	S	D	I	T	M
1. The location of the ATDs can greatly influence the comfort perceived by the occupants. Air distribution in rooms is not covered in this book.			☑			

13.4.15 Access

Check pre-requisites	P	S	D	I	T	M
1. The preliminary layout accounts for access issues.			☑			
2. The number and location of inspection/servicing/cleaning access openings is specified.				☑		

Require that	P	S	D	I	T	M
1. The ductwork must be easy to clean and maintain.	☑					

Check!	P	S	D	I	T	M
1. Transport ways. There has to be enough space to transport the equipment into the building—heavy equipment needs cranes, forklifts, etc. The doors are wide enough, slabs designed to carry the loads.			☑			
2. Space for ductwork. There has to be sufficient space to properly install the components, and maintain, repair, or replace them when necessary.			☑			
3. Access to the major components of the ductwork (fan, filters, AHU, coils, dampers, etc.) is good.			☑			
4. Cleaning access is good. There are cleaning access panels or openings.			☑			

Be careful!	P	S	D	I	T	M
1. Maintenance work can be considerably impeded if access issues have not been taken into account at the design stage.		☑	☑			

13.4.16 Balancing a ventilation system

Check pre-requisites	P	S	D	I	T	M
1. The documentation of the ductwork includes the location of regulating devices as well as the airflow rates that have to be met at the air terminal devices.					☑	
2. The design includes fixed sockets for measuring instruments for measuring the total airflow of the plant both for TAB and for future monitoring of plant performance.					☑	

Require that	P	S	D	I	T	M
1. All ATD airflows are measured and adjusted to correct values.	☑					

Check!	P	S	D	I	T	M
1. Use preferably the proportionality method to balance the system.			☑		☑	
2. Adjust the airflow rates to the design values.					☑	

Be careful!	P	S	D	I	T	M
1. It is necessary to emphasise the importance of adjusting the ventilation systems before they are taken into operation. The system will most often be a failure if this duty is neglected.			☑		☑	
2. Self-balancing devices are practical, however, they usually induce larger pressure drops than simple dampers.			☑			

13.4.17 Control strategy

Check pre-requisites	P	S	D	I	T	M
1. The control systems—i.e., detailed flow charts and specifications of devices such as sensors or actuators—are detailed (not covered in this book).				☑		
2. The number, type, and location of regulating devices—e.g., regulating dampers—are specified.				☑		
3. The control systems are well documented.					☑	☑

Require that	P	S	D	I	T	M
1. The control strategy is compatible with the programme (building use) and the duct design (e.g., pressure drop).		☑	☑			

Check!	P	S	D	I	T	M
1. Can energy savings be achieved with variable airflow rates?		☑				
2. Is a variable airflow rate solution cost-effective or should the building be split-up in different ventilation zones?		☑	☑			
3. Specify the type of control strategy. (Control systems are not covered in this book.)			☑			
4. Is the maintenance personnel properly trained for these systems?						☑

Be careful	P	S	D	I	T	M
1. Significant energy savings can be achieved with adequate control strategies.			☑			
2. The control strategy chosen has a large influence on the system's design.		☑	☑			
3. Air quality demands often make it necessary to operate the ventilation system during unoccupied time periods.			☑			

14 ANNEX

This handbook is based on expert knowledge derived from field experience, industry, and research. Here is a selection of other handbooks and bibliographies that may be useful to the reader. The reader may refer to the literature survey for more detailed information on specific subjects.

14.1 HANDBOOKS, BIBLIOGRAPHIES

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14.3 QUANTITIES AND UNITS

Symbol	Quantity	Units
Δp	pressure difference	Pa
Δp_{ref}	reference pressure difference	Pa
A	surface area	m^2
C	leakage coefficient	$(m^3/s)/Pa^n$
C_d	discharge coefficient	-
c_p	specific heat capacity at constant pressure	J/(kg K)
c_{pa}	specific heat capacity of dry air at constant pressure	J/(kg K)
c_{pw}	specific heat capacity of water vapour at constant pressure	J/(kg K)
E	energy	J
ELA_{ref}	effective leakage area at Δp_{ref}	m^2
f_{ref}	leakage factor at Δp_{ref}	$(m^3/s)/m^2$
h	specific enthalpy	J/kg
K	leakage coefficient normalised by duct surface area	$(m^3/s)/(m^2\,Pa^n)$
l, L	length	m
L_θ	latent heat of vaporisation at temperature θ	J/kg
m	mass	kg
n	flow exponent	-
p	pressure	Pa
P	power	W
q_m	mass flow rate	kg/s
q_V	volumetric flow rate	m^3/s
t	time	s
T	temperature	K
U	estimated U-value	$W/(m^2\,K)$
x	vapour ratio	kg/kg
Φ	heat flux	W
θ	temperature	^oC
ρ	density	kg/m^3
ρ_a	air density	kg/m^3

Symbol	Meaning
$\propto$	is proportional to

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AIRWAYS

Energy Conservation in Buildings
and Community Systems Programme

Improving ductwork
A time for tighter air distribution systems

A status report on ductwork airtightness in various countries with recommendations for future designs and regulations

F R Carrié
J Andersson
P Wouters
Editors

European Commission
Directorate General XVII for Energy

International Energy Agency
Air Infiltration and Ventilation Centre

TIGHTVENT 171

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A time for tighter air distribution systems

A status report on ductwork airtightness in various countries with recommendations for future designs and regulations

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Front page picture: Bend with separate outlet for cleaning (courtesy Lindab Ventilation AB). A double sealing gasket of EPDM rubber provides a tight reliable joint.

Contents

Foreword

A large number of modern European buildings are equipped with ducted air distribution systems. Because they represent a key parameter for achieving a good indoor climate, increased attention has been given to their performance during the past fifty years. One aspect that is particularly developed in this handbook concerns the airtightness of the ductwork, which has been identified as a major source of inadequate functioning and energy wastage of HVAC systems.

These investigations were carried out within the framework of the DUCT project (1997-1998) whose objectives may be summarised as follows:

1. Quantify duct leakage impacts;
2. Identify and analyse ductwork deficiencies;
3. Propose and quantify improvements;
4. Propose modifications to existing standards.

DUCT was funded in part by the SAVE II ("Specific Action on Vigorous Energy Efficiency") programme of the Commission of the European Communities - Directorate-General for Energy (DG XVII). It involved five teams representing three different countries:

- Ecole Nationale des Travaux Publics de l'Etat, Lyon, France;
- Belgian Building Research Institute, Brussels, Belgium;
- ALDES Aéraulique, Lyon, France;
- SCANDIACONSULT, Stockholm, Sweden;
- Centre d'Etudes Techniques de l'Equipement, Lyon, France.

The following persons have contributed to DUCT:

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Target audience

This handbook is aimed primarily at policy makers, HVAC manufacturers and installers, maintenance contractors, architects, building managers, and building services engineers interested in ductwork performance. It focuses on sheet metal ducts that are mostly used in Europe although most of the information also applies to other types of ductwork systems (plastic-and-wire composite, fibreglass board, concrete, etc.). It includes expert knowledge derived from research and industry, as well as practical information based on surveys and field work. Calculation details are condensed to put the emphasis on end results and qualitative information.

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Chapter 2 : Quality requirements for ductwork systems	F.R. Carrié, J. Andersson
Chapter 3 : Review of codes and standards	D. Ducarme, A. Bossaer, P. Wouters
Chapter 4 : Ductwork airtightness: state-of-the-art review of construction and installation technologies	F.R. Carrié, A. Bossaer, J. Andersson
Chapter 5 : Traditions in the design and installation of duct systems	O. Faure
Chapter 6 : Field measurements	A. Bossaer, F.R. Carrié, J. Andersson, P. Wouters, M. Kilberger
Chapter 7 : Air distribution system leakage versus energy, indoor air quality and costs	F.R. Carrié, O. Faure, J. Andersson
Chapter 8 : Potential energy impacts of a tight air duct policy at the European level	P. Wouters, A. Bossaer
Chapter 9 : Outcome of the international DUCT seminar in Brussels, June 1998	P. Wouters, A. Bossaer
Chapter 10: Recommendations for future technical and governmental measures	F.R. Carrié, P. Wouters, J. Andersson
Chapter 11: Conclusions	F.R. Carrié

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- Swedish Council for Building Research, Figure 17, Figure 18, Figure 19.

Chapter 1 Introduction

The primary function of a building is to provide occupants with an environment that is suitable for their activities and well being. In fulfilling this role, outdoor perturbations and internal loads must be processed to achieve a good indoor climate. However, because there are a number of underlying issues, space conditioning in buildings has been given increased attention over the past few years. In fact, it is estimated that it represents about a fourth of the final energy demand in the EU. In addition, climate control is strongly related to public health and productivity concerns and recent studies[1] suggest that it has an effect on measures of productivity such as absence from work or health costs. These usually lie between 5 % and 15 %.

In this context, the efficiency of air distribution systems is a very active field of investigation. These systems are often used in modern European buildings as a strategy to control thermal conditions and indoor air quality. Many problems have been reported in relation to energy use and peak power demand, clean air supply, flow balancing and airtightness etc. The purpose of this handbook is to give an overview of these aspects with a special focus on duct leakage and its consequences.

Although this topic of study has been visited in the late fifties in Sweden, leading to the first ductwork airtightness requirements in the Swedish AMA guideline in 1960, this concern seems rarely present today in most other European countries. In the context of energy conservation, sustainable development, and harmonisation of standards and regulations in Europe, this issue needs to be re-addressed to evaluate the implications of a tight air duct policy at the European level.

The contents of this handbook are briefly described below:

- Chapter 2 gives an overview of quality requirements of ductwork;
- Chapter 3 summarises ductwork airtightness related standards in Europe and some other non European countries;
- Chapter 4 looks at today's ductwork technology. It includes a review of ductwork construction, installation and rehabilitation techniques that may be used to limit duct leakage;
- Chapter 5 is concerned with traditions in the design and installation of duct systems;
- Chapter 6 deals with duct leakage field measurements in European countries. Little information is available on this subject, however, field data from the SAVE-DUCT project suggest that the ductwork airtightness is in general very poor;
- Chapter 7 discusses the energy, indoor air quality and cost issues associated with duct leakage. Sample calculations are performed based on realistic data;
- Chapter 8 is dedicated to a macroscopic approach to the energy implications of a tight air duct policy at the European level;

[1] See for instance Wyon, D. P. Healthy Buildings and their impact on productivity. In Indoor Air 93. Vol. 6, Proceedings of Indoor Air. 1993. pp. 3-13.

- Chapter 9 consists of a synthesis of issues brought to light by practitioners, manufacturers, and policy makers in the international seminar on ductwork airtightness held in Brussels June 10-11, 1998;
- Chapter 10 is more particularly geared towards the implementation of a tight air duct policy, with recommendations for technical and governmental measures.

These investigations were carried out within the framework of the DUCT project (1997-1998; Cf. appendix) funded in part by the SAVE programme of Commission of the European Communities - Directorate-General for Energy (DG XVII).

Chapter 2 Quality requirements for ductwork systems

Airtightness	**Fire protection**
Thermal insulation	**Corrosion**
Pressure drop	**Installation**
Clean air supply	**Life Cycle Cost**
Strength	**Design issues**
Noise	**Commissioning and maintenance**

The key role of an air distribution system is to provide clean air (sometimes at required specific thermodynamic conditions) to rooms so as to dilute or extract pollutants and / or to condition spaces. In achieving this goal, many other issues have to be examined to comply with the essential requirements of the Construction Products Directive (EU) and to obtain an acceptable indoor climate at a minimum cost. The purpose of the chapter is not to give a comprehensive list of those issues but rather to focus on a few aspects that are closely linked to the ductwork.

It is important to have a properly designed ductwork, i.e.:

1. It shall be tight and secure the air transport through the system (§ 2.1);
2. It shall have such a heat resistance that energy losses are restricted (§ 2.2);
3. The system shall have a low resistance to the flow to minimise the fan power demand and energy use (§ 2.3);
4. Components shall be laid so that they are accessible for cleaning and shall, if necessary, be supplied with cleaning facilities (§ 2.4);
5. They have to be able to withstand normal handling and installation stresses as well as the positive or negative operating pressure of the system in which they will be integrated (§ 2.5);
6. Noise should be prevented from getting through to the occupied spaces (§ 2.6);
7. Duct systems shall not contribute to the spread of fire, smoke or gases (§ 2.7);
8. The materials should be chosen according to the aggressiveness of the environment to limit corrosion damages (§ 2.8);
9. The ductwork shall be safe and easy to install (§ 2.9);
10. It should preferably use standard sizes, facilitating prefabrication of ducts and components, thus allowing for shorter delivery times and possibly lower costs.

Along with Life Cycle Cost issues (§ 2.10), all of these design requirements need to be integrated at the design stage as it may influence the building design. An interesting illustration lies in the choice of round rather than rectangular ducts (§ 2.11).
In general, a compromise must be found between these issues, the cost of the plant and the building as a whole. As a simple example, a larger duct will have a lower pressure drop; however, the additional space required may not be compatible with the budget and the building design.

Finally, evidence suggests that commissioning and maintenance plays a major role in securing optimum system performance. Special care should be given to these aspects (§ 2.12).

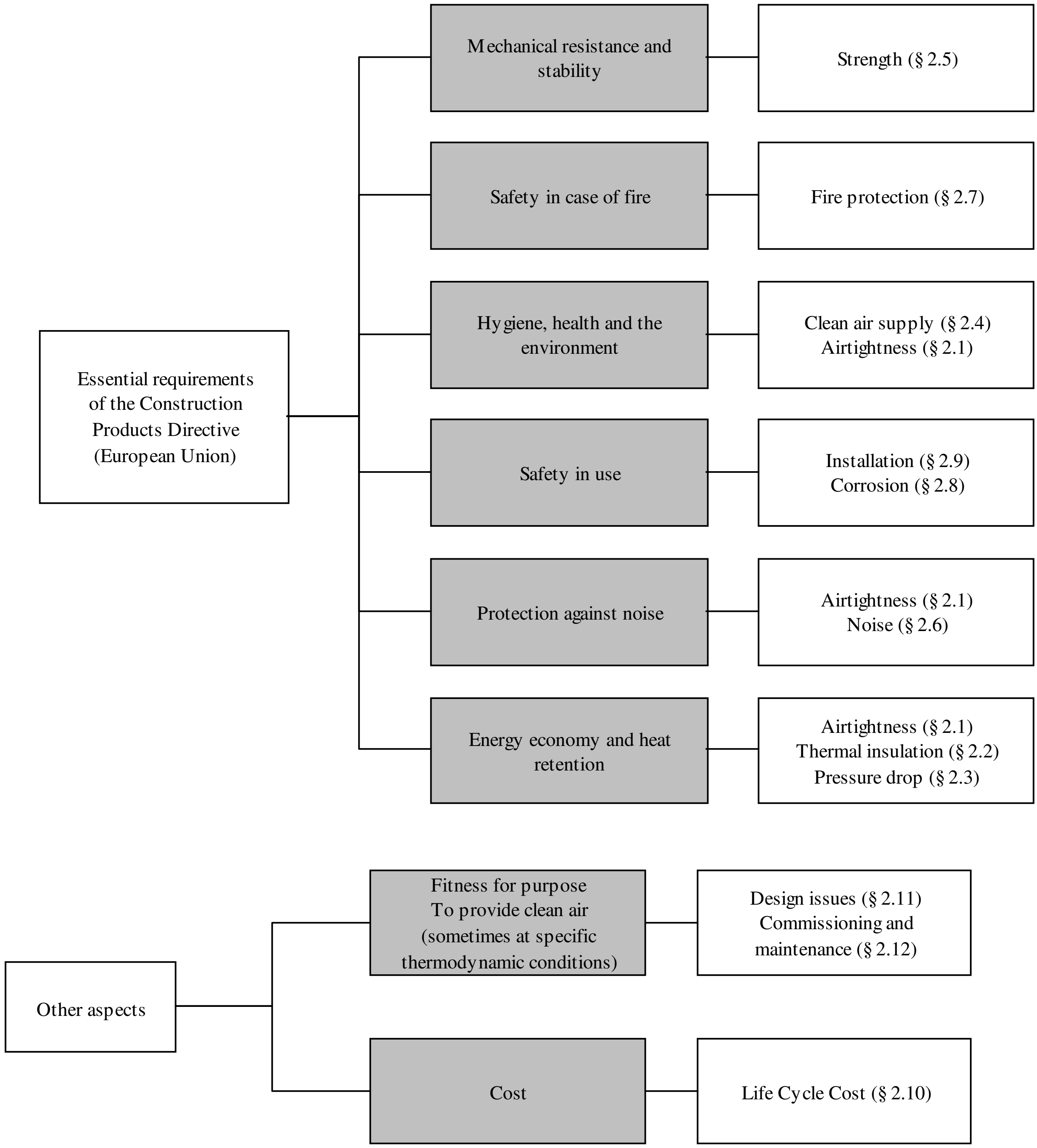

Figure 1: Ductwork requirements.

2.1 Airtightness

In most of the member states, it is commonly accepted that the ductwork airtightness is not a key issue to efficiently distribute the air within the building and thus leakage tests are viewed as an unnecessary expense. However, as stated in EUROVENT Guidelines 2/2, a ductwork airtightness limit may be required to minimise the cost and the energy penalty due to an over-sized or inefficient plant, and/or to ease the flow balancing process, and/or to have control over the leakage noise. Other impacts such as the entry or release of pollutants through leaks or the in/ex filtration to unconditioned spaces can be foreseen, with potentially large effects on energy use, power demand, indoor air quality, and comfort-effectiveness. To provide a general (however simplified) picture, we have represented, schematically, duct leakage implications in Figure 2. To avoid these problems, the use of quality commercially available products should be considered and particular attention should be paid to the installation process.

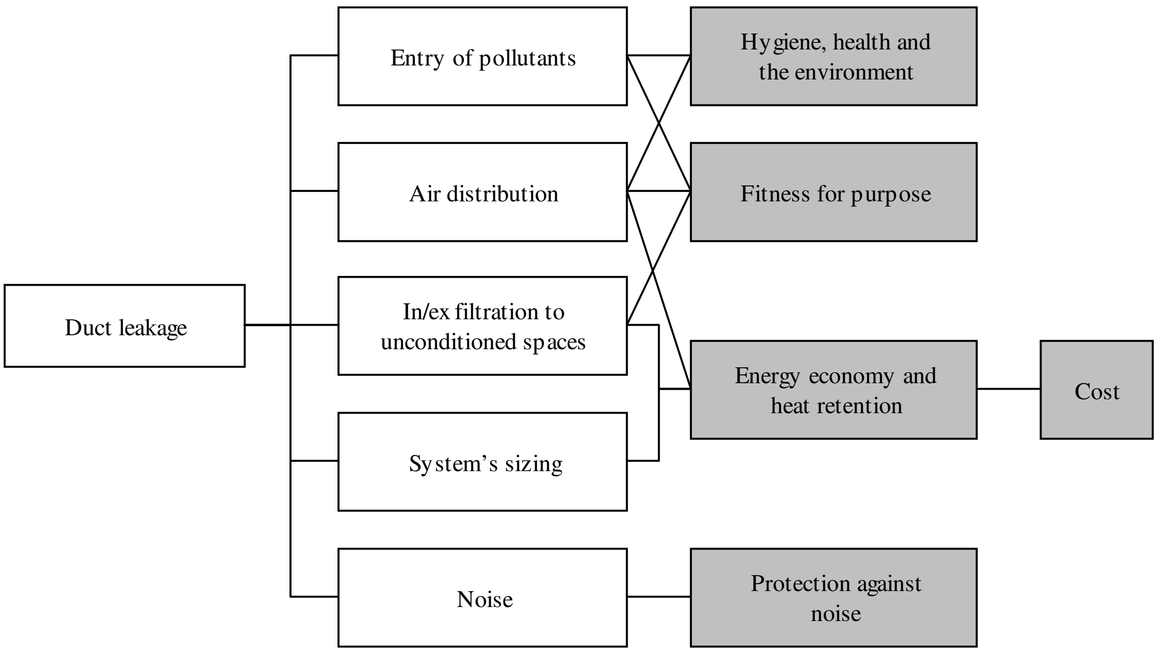

Figure 2: Flow chart of duct leakage implications.

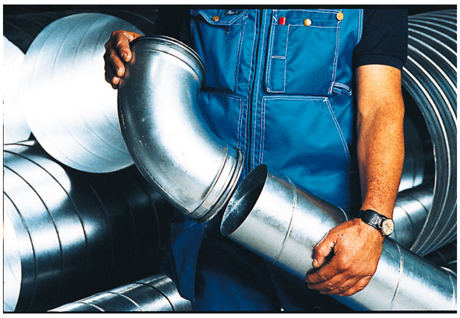

Figure 3: Lindab*Safe® sealing system (courtesy Lindab Ventilation AB). A double sealing gasket of EPDM rubber provides a tight reliable joint.*

2.2 Thermal insulation

Air distribution systems may be used for heat recovery, or for heating, or air conditioning. The air in the extract ducts may be used to pre-condition the incoming outdoor air that is transported through the supply ducts. In such cases, the ductwork should be insulated to limit conduction losses (i.e. thermal losses through the duct shell). The use of thermal insulation, in combination with a vapour barrier, should also be considered when water condensation on duct surfaces is expected.

2.3 Pressure drop

In a ductwork system, pressure can be viewed as energy created by the fan that can be reversibly converted into kinetic energy (airflow), or irreversibly dissipated by wall friction or turbulence effects (e.g. in a bend or a sudden expansion). These losses, commonly called pressure drops or flow resistances, must be overcome by the fan to meet the desired flow rates at the registers. Also, pressure drops are expensive in that they are directly linked to the fan energy use. These two points imply that calculations taking into account the resistance of every component (including filters) should be carried out at the design stage. This task can become quite complicated in the case of a complex system. However, some HVAC manufacturers provide their customers with computerised tools enabling them to compare the performance of different designs. The calculation is of course simpler and more accurate if it is based on the use of prefabricated duct components that have been laboratory tested.

2.4 Clean supply air

During operation of an air distribution system, dust and other contaminants (e.g. condensed water) may deposit onto surfaces such as ducts, fan blades, or coils. This may lead to microbial growth on the surfaces, especially on air intake ducts with internal thermal insulation, and to the entry of polluted air within the occupied spaces. Such contamination becomes a health hazard to the occupants. In some cases, especially for smaller dimension ductwork carrying moist air, e.g. from bathrooms, a considerable decline of the delivered airflow rates may be expected (Luoma et al., 1993; Wallin, 1994). The building manager and occupants generally ignore these issues. To minimise these effects the system needs to be inspected and, if needed, cleaned periodically. This implies that maintenance or inspection schemes be accounted for at the design stage to ensure a good accessibility of such components as fans, filters, and air ducts. Also, the materials shall neither emit pollutants nor enhance the growth of microorganisms that could be transported to the living-areas. They shall be able to withstand standard cleaning procedures (e.g. brushing, vacuum cleaning, chemical disinfection) that are expected to be necessary during the course of operation.

Figure 4: Bend with separate outlet for cleaning (courtesy Lindab Ventilation AB).

2.5 Strength

The ductwork can incur physical damage during shipping and handling, as well as during later work or inspection on or near the system. It is important that the ductwork be resistant to stresses commonly applied during these operations. The ductwork also needs to be able to withstand the positive or negative operating pressure of the system in which it will be integrated. This information is usually readily available from the manufacturers. Hangers and support systems shall be constructed so as to ensure a secure installation and operation. Distance between and size of the hangers shall withstand spot loads in addition to the dead weight of the duct. A spot load of 1 kN (about the weight of a person) is used in VVS AMA 98 (1998). The reason for this Swedish requirement lies in the occurrence of fatal accidents to people who have been wrongly using rectangular ducts as working platforms instead of scaffolds or ladders. Exposure to temperature extremes, earthquakes, sudden stoppage of airflow or any other conditions specific to the installation should be considered where necessary.

2.6 Noise

Noise can either be generated in or transmitted through the ductwork. It is a major source of complaints. Aerodynamic noise (due to the airflow) can be limited with good design:

- Low air velocity in the ductwork;
- Use of round ducts;
- Use of bends with large internal radii;
- Smooth transitions and changes in flow direction;

- Use of low-noise control valves;
- Low air leakage.

As for noise propagation through the ductwork, the integration of silencers should be considered.

Figure 5: Cylindrical type silencer combining passive sound attenuation by rock wool with reactive attenuation (neutralisation of noise by the addition of opposite sound). The Noise Negator is used as a component in the HVAC systems of commercial buildings or domestic dwellings (courtesy ALDES Aéraulique).

Figure 6: Silencer bend for use in ventilation systems where space considerations or other circumstances prevent the use of straight silencers (courtesy Lindab Ventilation AB).

2.7 Fire protection

The main rule in all countries is that a building installation - a ventilation duct, a pipe or a cable - passing through a fire partition must not decrease the fire protection properties of the structure, i.e. the wall with the passing duct shall be as safe as a combination as the original wall itself without the passing duct. The fire protection quality of the construction is often classified in three ways that can be used solely or in combination:

- ***Integrity***, i.e. the possibility of the construction to be tight to flames and smoke - normally designated with the letter **E**;

- ***Insulation***, i.e. the possibility of the construction to withstand heat on the fire side of the construction without having the other side heat up to a temperature where a new fire will start on that side of the construction - normally designated with the letter **I;**
- ***Resistance to mechanical strain*** caused by the fire - normally designated with the letter **R**.

As an illustration, fire walls classified as **EI 60** are able to withstand the standard fire during 60 minutes and still be tight to fire and flames without risk of starting a fire on the other side of the wall. There are mainly two ways to obtain a wall of equal fire resistance with and without a passing duct:

- Insulating the duct so as to prevent the fire from breaking through the duct wall and spread to the other side;
- Using a fire damper, at the wall, that closes when a fire is detected (Figure 7).

Figure 7: Fire damper to be used at a fire cut-off partition (courtesy ALDES Aéraulique).

2.8 Corrosion protection - Environmental class

Corrosion damage on ductwork installed in aggressive environments often leads to leaking and unsafe installations with drastically reduced lifetime. It is thus important to choose the ductwork quality according to the aggressiveness of the environment. Helpful advice to the designer and contractor is given in VVS AMA 98 (1998) where the corrosion impact on ductwork is stated for six different “environment classes”, from “M0” (“in dry indoor air, e.g. in heated spaces”) with “no aggressiveness” through to“M4B” (e.g. for “indoor and outdoor in industrial areas with high level of aggressive air contaminants, e.g. some chemical industries such as pulp mills, refineries or fertiliser industries”) with “very high aggressiveness”. The recommendations given in VVS AMA 98 should normally result in an expected lifetime of the installation of 20 years or more. Thus, choosing the right corrosion-proof material combination will normally result in lower life cycle costs even though the first installation cost might be higher. There is also a more generic environmental advantage with higher quality material - longer life span of the installation and thus less need for replacement reduces waste and material use.

2.9 Installation

Field studies indicate that the installation process plays a major role in the performance of the system. Added to this fact is that, in general, installation represents a significant fraction of the cost of an air distribution system. It is therefore essential that the ductwork is quick and easy to install, and is adapted to the workers' skills. For this reason, the right choice of the products is an important factor. These issues should also be considered at the design stage (e.g. to take into account the accessibility of the ducts for sealing).

2.10 Life cycle cost

The choice between different ventilation products is often based on the initial cost (i.e. on the cost of the equipment and the installation). Today's concern about energy efficiency and quality assurance brought to light the need to evaluate ventilation systems on a Life Cycle Cost (LCC) basis since it includes both operating costs and the costs for writing off the investment over a given period of time, normally fifteen or twenty years. The LCC of an installation should ideally incorporate all of the criteria that imply a cost. However, decision criteria that cannot be reliably referenced to a cost (e.g. indoor air quality, ease of use) should be considered separately.

2.11 Design issue example : round versus rectangular ducts

Early in the design phase, it is often possible to choose between different design alternatives. For ventilation design, one early decision is whether to use round or rectangular ductwork - or more often to use a suitable combination between the two. What then are the main differences between the two? The advantages with the round system include:

- Connecting two circular spiral wound ducts only requires one fitting, whereas rectangular ducts are connected by use of a completely separate flanging system. The round ducts can have any length between the connections, a duct length of 3 m is standard but 6 m is also frequently used. On the other hand, the length of a rectangular duct is limited by the size of the steel sheet usually to less than 2 m and therefore requires many more connections;
- 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;
- The installation cost is normally lower, at least in countries where round ducts have been in use for a longer period of time. The overall cost of a duct system built with circular ducts is distinctly lower than one with rectangular ducts;
- The installation is simpler to carry out and the installation time for a circular duct system is normally shorter, sometimes only a third of that for a similar rectangular system;
- The pressure drop in circular duct system is often lower than in a rectangular duct at the same air velocity due to industrially manufactured and more aerodynamically designed duct components such as elbows and branches;
- The noise generated in straight ducts is normally of no significance while the noise generated e.g. in elbows might cause problems at higher air velocities. Circular duct components have normally known properties while ‘tailor-made’ parts in rectangular ducts are less well known;
- The circular 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 must be considered case by case;
- The weight of the round system is lower. Thus, the amount of steel needed is smaller, which, on a larger scale, has environmental benefits.

Fire insulation of a duct to a specified fire safety class might be possible to obtain with a thinner insulation layer on a round duct (the weak points on a rectangular duct, in this case, are the corners where the insulation material is compressed to a thinner, thickness than on the rest of the duct perimeter. The round duct does not have any corners!).

- Ductwork is measured and tailor-made for each installation. Using round ductwork with standard sizes (the diameters of the ducts increase by 25 % upwards: 80, 100, 125, 250 mm, etc.) normally decreases the waste when the ducts do not fit. The round duct or component does not have to be scrapped, it can be used somewhere else in the building, there are probably plenty of ducts of the same diameter.

The main advantage with a rectangular duct is that, for the same free cross area, it can be flattened, i.e. be made wider but lower. In buildings with restricted room heights it could thus be easier to cross underneath beams and other space restrictions. On the other hand, if considered early in the design phase, it might be possible to use parallel round ducts instead of a flat rectangular one. Normally, the best solution is a compromise between round and rectangular. For example, rectangular ducts might be used at the start of the system (near the fan), where the airflow ducts are large. Further on, with the airflow being distributed to smaller ducts, the ducts should be round.

2.12 Commissioning and maintenance

Ductwork systems should be commissioned and properly documented as recommended in the Nordic guidelines “Indoor climate – Air quality” (NKB, 1991). The Swedish VVS AMA 83 (1984), on which practically all building contracts are based in Sweden, requires that, before a building or a part of a building is put into use, an inspection of the duct systems and fire protection installations be performed to demonstrate that it is clean, ready for operation, and correctly documented. For this, fixed sockets for measuring instruments shall be provided in the main ducts for measuring the total airflow of the plant both for commissioning and for future monitoring of plant performance. VVS AMA 83 furthermore requires that all airflows be measured and adjusted to correct values, that the ductwork be leak tested and recorded, and details should be included in the manuals for operation and maintenance. Detailed drawings of the ductwork installations, specifications for the materials and devices as well as for the maintenance schedule shall be available to the building manager to ease maintenance and retrofit.

2.13 References

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Chapter 3 Standards review

EUROVENT Guidelines 2/2

National standards and building regulations

European Committee for Standardisation (CEN)

3.1 Introduction and summary

This chapter gives an overview of standards and building regulations related to the airtightness of air distribution systems in Europe. It looks at existing standards as well as those currently under preparation at the European level. Some non-European countries are also included. First, EUROVENT Guidelines 2/2 are described, as the leakage classes defined in this document are essentially similar to those that are adopted in many national standards in the member states. We then review the existing standards or pre-standards at the national level, as well as existing building regulations or guidelines/recommendations. Finally, the work carried out at European level, in the European Committee for Standardisation (CEN) is presented.

3.2 EUROVENT Guidelines 2/2 "Air leakage rate in sheet metal air distribution systems"

3.2.1 Introduction

EUROVENT is the European Committee of Air Handling and Air Conditioning Equipment Manufacturers. It was created in 1959 and the following countries are members of this committee: Belgium, Finland, France, Germany, Great Britain, Italy, Netherlands, Norway, Sweden, Turkey.

The foreword of the EUROVENT guidelines mentions:

"*EUROVENT has the aim, at the European level, to facilitate closer ties between the companies of the profession, to promote all desirable and possible exchanges between European manufacturers and to contribute to an improvement of the profession. EUROVENT represents the profession in relation with the European authorities and the International Organisations*."

In 1996 EUROVENT merged with CECOMAF, the committee of refrigeration equipment industries. Most of the standards or guidelines in member states as well as the CEN pre-standards (in preparation) rely on a ductwork airtightness classification that is essentially similar to the EUROVENT Guidelines 2/2 "Air leakage rate in sheet metal distribution systems".

This document applies to laboratory and field tests of the ductwork between the air handling unit and the air terminal devices.

3.2.2 The leakage factor

The leakage factor is the leakage flow rate at a known static pressure per m^2 of duct surface area:

$$f_{ref} = \frac{q_{vl}}{A}$$ *Equation 1*

where:

f_{ref} is the leakage factor at a reference pressure Δp_{ref} (m^3 s^{-1} m^{-2});
q_{vl} is the leakage volume flow rate (m^3 s^{-1});
A is the duct surface area (m^2).

The leakage factor depends on the pressure Δp_{ref} at which the leakage airflow rate is measured. According to this document, it shall be set to the arithmetical mean value of maximum and minimum values of static pressure difference across the ductwork (Pa).

3.2.3 Leakage classes

This document defines three classes of airtightness (A, B and C) for normal ventilating and air-conditioning installations. The classification is based on the quantity:

$$K = \frac{f_{ref}}{\Delta p_{ref}^{0.65}}$$ *Equation 2*

where:

K is the leakage coefficient per m^2 of duct surface area (m^3 s^{-1} m^{-2} Pa$^{-0.65}$).

This quantity gives a measure of the ductwork leakage which should be independent of the static test pressure in the ductwork[2]. The next table gives the upper limits of this quantity for the three different classes.

Class A	K_A =	$0.027 \cdot 10^{-3}$ m^3 s^{-1} m^{-2} Pa$^{-0.65}$
Class B	K_B =	$0.009 \cdot 10^{-3}$ m^3 s^{-1} m^{-2} Pa$^{-0.65}$
Class C	K_C =	$0.003 \cdot 10^{-3}$ m^3 s^{-1} m^{-2} Pa$^{-0.65}$

Table 1: Airtightness classes defined in the EUROVENT Guidelines 2/2. Note that for laboratory duct testing, these values are divided by 2.

[2] Assuming a flow exponent of 0.65 and low measurement errors (see chapter 6).

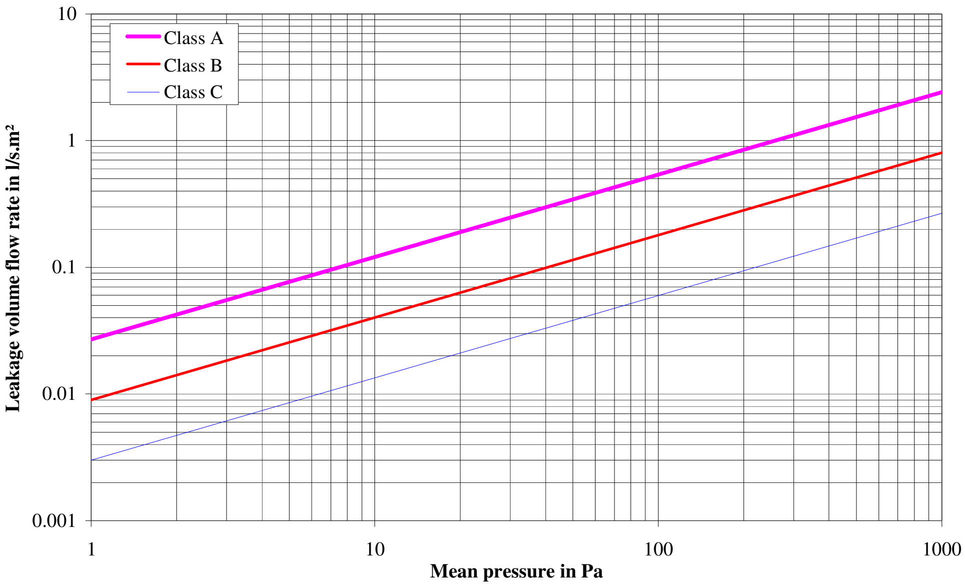

Figure 8: Leakage volume flow rate per m² duct area as a function of the mean static pressure.

Also, a graph included in this document enables the test operator to calculate:

- The leakage airflow as a function of the mean pressure and the duct area;
- The leakage airflow as a percentage of system airflow rate.

3.2.4 Testing

➢Fan pressurisation method

The ends of the test section are sealed. Then, the leakage factor is determined by artificially creating a (or a series of) pressure differential(s) in the test section and by measuring the leakage flow rate (fan pressurisation method).

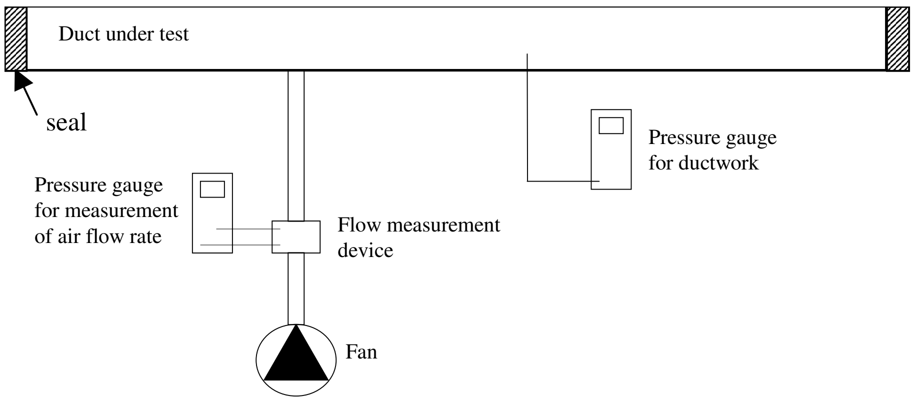

Figure 9: Ductwork leakage testing with fan pressurisation technique.

➢Test pressure

The test pressure for Class A and B ductwork should not exceed 1000 Pa or the maximum design static gauge duct pressure, whichever the smaller. For Class C ductwork, the pressure can be increased to 2000 Pa. The test pressure shall not be less than the design operating pressure.

The next table gives the upper limits of the leakage volume flow rate for the 3 classes at typical test pressures.

Class	Maximum leakage factor ($m^3 \cdot s^{-1} \cdot m^{-2}$)	Test static pressure difference (Pa)			
		2000 Pa	1000 Pa	400 Pa	200 Pa
A	f_A	-	$2.4 \cdot 10^{-3}$	$1.32 \cdot 10^{-3}$	$0.84 \cdot 10^{-3}$
B	f_B	-	$0.8 \cdot 10^{-3}$	$0.44 \cdot 10^{-3}$	$0.28 \cdot 10^{-3}$
C	f_C	$0.42 \cdot 10^{-3}$	$0.28 \cdot 10^{-3}$	$0.15 \cdot 10^{-3}$	-

Table 2: Maximum leakage factor for the 3 classes and for typical test pressures.

➢Test procedure

For circular ducts at least 10 % of the total surface shall be tested, and for rectangular ducts at least 20 % shall be tested. In either case the area to be tested shall normally be at least 10 m².
It is noteworthy that there is no specific information on the duct surface area measurement.
If the air leakage rate does not comply with the Class requirement, the test shall be extended to include an additional equal percentage of the total surface area. If the system is still too leaky, the total surface area shall be tested.

3.3 National standards and building regulations

3.3.1 Overview

This chapter gives an overview of the standards, building regulations and/or guidelines that exist in different countries. Due to the current European standardisation process, development of new national standards is not expected in the member states.

Table 3 gives a non-exhaustive list of pre-standards, standards, guidelines, and building regulations in some European countries, Australia and the United States.

Country	Document	Type	Application	Description
Australia	AS 4254-1995	Standard	All	Ductwork for air-handling systems in buildings
Austria	ÖNORM M 7615	Standard	All	Lüftungstechnishe Anlagen – Leckverlust in Luftleitungen
Denmark	DS 447	Standard	All	Code of Practice for Ventilation Installations
Denmark	DS 1122.1	Standard	Sheet metal	Strength and airtightness – testing
Denmark	DS 1122.2	Standard	Sheet metal	Strength and airtightness – requirements
Europe	PrEN 13403	Pre-standard	Insulation ductboard	Ductwork made of insulation ductboards
Europe	PrEN 1507	Pre-standard	Rectangular sheet metal	Rectangular sheet metal air ducts. Strength and leakage.
Europe	PrEN 12237	Pre-standard	Circular sheet metal	Circular sheet metal air ducts. Strength and leakage.
Europe	prEN 13180	Pre-standard	Flexible	Dimensions and mechanical requirements for flexible ducts
France	NF X 10-236	Standard	Sheet metal	Degré d'étanchéité dans les réseaux de distribution d'air en tôle
Germany	DIN V 24194	Pre-standard	Sheet metal	Dichtheitsklassen von Luftkanalsystemen
Sweden	AMA 98	Specification guideline	Sheet metal	General requirements for Material and Workmanship
Switzerland	VSHL 63123	Standard	Sheet metal	Leckverluste in Luftverteilanlagen aus blech
The Netherlands	NEN-EN 1507	Pre-standard	Rectangular sheet metal	Rechthoekige dunwandige metalen luchtleidingen. Sterkte en lekkage.
The Netherlands	NEN-EN 12237	Pre-standard	Circular sheet metal	Ronde dunwandige metalen luchtleidingen. Sterkte en lekkage.
United kingdom	DW/144	Standard	Sheet metal	Specification for sheet metal ductwork
United States	ASHRAE 152 P	Pre-standard	All	Method of test for determining the design and seasonal efficiencies of residential thermal distribution systems

Table 3: Non-exhaustive list of pre-standards, standards, guidelines, and building regulations in some European countries, Australia and the United States.

3.3.2 European countries

➢Sweden

Specification Guideline	Standard	Regulation
☑	☐	☐

Nearly all buildings and their installations are performed according to the AMA specification guidelines (AMA 83, 1984; Allmän Material- och Arbetsbeskrivning, i.e. General Requirements for Material and Workmanship). The AMA requirements are made valid when they are referred to in the contract between the owner and the contractor. AMA refers to relevant national Swedish standards and European norms. The 1983 version of AMA which had been used for 15 years has recently been reissued as AMA 98. The airtightness classes are similar to those defined in EUROVENT 2/2.

The need for tight systems has been identified in this country since the early sixties. The requirements have evolved over time in conjunction with technology progress:

- AMA version 1966:

Two “tightness norms” A and B, to be spot checked by the contractor; minimum tested surface is 10 m²;

- AMA version 1972:

Requirements transformed into two “tightness classes” A and B (same as EUROVENT classes). Class A was the requirement for the **complete duct system** in the air handling installation (i.e. including dampers, filters, humidifiers and heat exchangers). It was advised to meet Class B when:
  - The system operates for more than 8 hours/day;
  - The air is treated (cooling, humidification, high class filters etc.);

- AMA version 1983:

In this version of AMA tightness Class C is added. The following requirements are given:
  - Class C for round ductwork larger than 50 m²;
  - Class B for round duct systems with a surface smaller than 50 m² and also for rectangular ductwork;
  - Class A for visible supply and exhaust ducts within the ventilated room;

- AMA version 1998:

In this version of AMA, a tightness Class D has been added (3 times tighter than Class C). It will be an optional requirement for larger circular duct systems.

Besides specifying classes which have to be met, AMA also requires commissioning of all ventilation and air conditioning systems:

- Measurement and adjustment of all extracted and supplied airflows in the building; the result should be within ± 15 % (including the measurement error);
- Measurement of the duct system leakage:
  - Done by the contractor as part of the contract;
  - Parts to be checked chosen by the owner’s consultant;
  - Round duct systems 10 % of the duct surface; rectangular duct systems 20 % of the duct surface.

If part of the system is found to be leakier than required the tested part shall be tightened and another equally sized part of the system shall be tested. If the second tested part is also found to be too leaky, the complete installation has to be tested and tightened until the requirements are fulfilled. The cost for these additional tasks is covered by the contractor.

➢Denmark

Specification Guideline	Standard	Regulation
☑	☑	☑

Guidelines specify Class A for systems with only exhaust or in case the ventilation runs less than 8 hours a day. For more than 8 hours a day, a Class B ductwork is recommended. Airtightness of ductwork is often checked by visual inspection at commissioning. In general, it is measured only if required in the technical prescription, in case of large projects, or in case of problems. Standard DS 447 describes a code of practice for ventilation installations. The building code requires that the ductwork airtightness be specified in the technical prescriptions of projects.

➢United Kingdom

Specification Guideline	Standard	Regulation
☐	☑	☐

DW/144[3] "Specification for Sheet Metal Ductwork" gives a classification of ductwork airtightness according to the CEN documents prEN 12237 and prEN 1507. The requirements for the airtightness of the ductwork mentioned in DW/144 depend on the operating pressure:

Duct pressure class	Static pressure difference limit		Maximum air velocity (m/s)	Air leakage limit (l/s per m²)
	Positive (Pa)	Negative (Pa)		
Class A – low pressure	500	500	10	$0.027 \cdot \Delta p^{0.65}$
Class B – medium pressure	1000	750	20	$0.009 \cdot \Delta p^{0.65}$
Class C – high pressure	2000	750	40	$0.003 \cdot \Delta p^{0.65}$

Table 4: Air leakage limits for different pressure classes.

According to DW/144, testing of the ductwork is only mandatory for the high pressure classes. In the case of low and medium pressure, testing is not part of the ductwork contract unless it is required in the job specification. The testing should be performed according to DW/143 – "A practical guide to ductwork leakage testing".

The following duct areas to be tested during an air leakage measurement are recommended:

- High pressure ducts: whole area tested;
- Medium pressure ducts: 10 % of the ductwork randomly selected and tested;
- Low pressure ducts: untested.

[3] Note that DW/142, which was the reference document until 1998, has been reissued as DW/144.

If an air leakage measurement on a randomly selected part (10 %) of a medium pressure ductwork reveals that the requirements are not fulfilled, the test has to be performed again on two other randomly selected duct sections. In the case of successive failures, there shall be a right to require the contractor to apply remedial measures to the complete ductwork system. Items of inline plant, such as air handling devices, sound attenuators, heat exchangers etc. will normally not be included in an air leakage test.

Recommended test pressures and the corresponding leakage rates are given in Table 5.

Static pressure difference (Pa)	Maximum leakage of ductwork (l/s.m²)		
	Class A	Class B	Class C
200	0.84	0.28	
400	1.32	0.44	
800		0.69	0.23
1200			0.30
1500			0.35
2000			0.42

Table 5: Recommended test pressures and corresponding air leakage rate according to DW/144.

DW/144 describes also in detail the requirements for seams, cross joints, fastenings, etc. for different types of ductwork, for example regarding the presence of sealant.

➢ Belgium

Specification Guideline	Standard	Regulation
☑	☐	☑

At present there is no standard in Belgium regarding ductwork airtightness.

There is no building regulation applicable for private projects. However, for public buildings, general technical prescriptions (Typebestek 105, article C14, luchtleidingen) require that the ductwork class (A or B) be specified in the specific technical prescriptions. By default, Class A is required. However, if:

- the nominal airflow rate of the network is above 3 m³/s;
- the air is cooled or humidified;
- if the daily on-time is more than 12 hours;

Class B is required. The prescriptions do not give requirements for the testing of ductwork. The prescriptions require the leakage airflow rate be added to the nominal airflow rate for the determination of the airflow rate of the fan. If the leakage airflow rate does not meet the requirements, the following has to be done:

- Tighten the tested part;

- Perform a test on a part of the system that has to include the first one and be twice as large;
- If the leakage airflow rate is still too large the same procedure should be repeated once more. If the result is still not good enough, the ductwork should be tested as a whole. The airtightness should be improved until the requirements are fulfilled.

➢Switzerland

Specification Guideline	Standard	Regulation
☐	☑	☐

There is a Swiss standard based on the EUROVENT Guidelines 2/2. Although there is no regulation in Switzerland, a ductwork class is often required in technical prescriptions for large projects. At commissioning, one or several sections of the ductwork are generally tested.

➢The Netherlands

Specification Guideline	Standard	Regulation
☑	☐	☐

There are no official standards on ductwork in the Netherlands. The European pre-standards prEN 1507 and prEN 12237 (see § 3.4) are used as pre-standards: NEN 1507 and NEN 12237. Although there are no official building regulations, ductwork manufacturers follow the national LUKA specifications, which make a classification according to EUROVENT: class A, B and C. LUKA is the association of Dutch manufacturers of ductwork. The goal of LUKA is the determination of quality standards for the production and installation of ductwork, the organisation of quality control of ductwork from members, the organisation of training courses for installers, the distribution of quality certificates etc. A quality handbook was edited by LUKA in which the different requirements are described in detail.

As regards the airtightness, the installations made by the LUKA-members are supposed to comply with the class B requirement. The following additional aspects are mentioned in the LUKA specifications:

- the tested part should be mounted, but not yet insulated;
- the tested part should have an area of at least 10 m² and should not exceed 30 m²;
- in a laboratory test, the leakage airflow should not exceed 50 % of the required value.

➢France

Specification Guideline	Standard	Regulation
☐	☑	☐

Standard NF X 10-236 *“Degré d’étanchéité à l’air dans les reseaux de distribution d’air en tôle”* is similar to the EUROVENT 2/2 document.

Two other standards deal with the duct leakage:

- NF XP P 50-410: *“Installation de ventilation mécanique contrôlée – Règles de conception et de dimensionnement”*

This standard states that leaks are supposed to be localised at the registers and correspond to an arbitrary value of 10 % of the nominal maximal airflow rate of the register;

- NF P 50-411: *“Exécution des installations de ventilation mécanique”*

This standard states that the installation must be so that the airtightness is compatible with the good functioning of the system and specifies also (vaguely) the types of materials which have to be used to ensure a good airtightness.

➢Germany

Specification Guideline	Standard	Regulation
☐	☑	☐

The pre-standard DIN V 24194 “Ducting for ventilation equipment; air leakage classification of sheet metal duct systems” classifies the ductwork airtightness similarly to EUROVENT 2/2. However, the standard does not describe any test method.

➢Finland

Specification Guideline	Standard	Regulation
☑	☐	☑

The national building code of Finland *“Indoor Climate and Ventilation in Buildings – Regulations and Guidelines”* specifies three leakage classes A, B and C (identical to those of EUROVENT 2/2). An extra class K is defined for enclosed air conditioners, equipment rooms and chambers for fans and other assemblies.

➢Austria

Specification Guideline	Standard	Regulation
☐	☑	☐

ÖNORM M 7615 defines three tightness classes (A, B, and C) based on the leakage factor concept similarly to EUROVENT 2/2. This norm concerns all ventilation ducts installed in buildings except for ducts in hospitals and ducts containing toxic gases. This document recommends tightness classes depending on the operating pressure (< 630 Pa or ≥ 630 Pa) and the airflow rate (return: lower or greater than 3 m^3/s; supply: lower or greater than 2 m^3/s). In addition, the norm describes the calculation of leakage and testing procedure. Although not mandatory, this “ÖNORM” is specified in nearly every public or private tender.

3.3.3 Non-European countries

➢ Australia

Standard AS 4254, *"Ductwork for air-handling systems in buildings"* (version 1995) deals with the requirements for air-handling systems in buildings. A part of the standard is dedicated to the airtightness of ductwork. The requirements in AS 4254 are based on a static pressure classification, which is given in Table 6.

Pressure class	Operating pressure range, Pa
125	≤ 125
250	126 to 250
500	251 to 500
750	501 to 750
1000	751 to 1000
1500	1001 to 1500
2500	1501 to 2500

Table 6: Pressure classes in AS 4254.

Depending on the pressure class, the standard gives requirements for the duct sealing. These requirements are not values, but only prescriptions about the parts that have to be sealed. This is shown in Table 7.

Static pressure classification, Pa	Seal class	Sealing required
≥ 1000	A	All transverse joints, longitudinal seams[4] and duct wall penetrations
750	B	All transverse joints and longitudinal seams
500	C	Transverse joints
< 500	---	Ductwork to be sealed only where required by the designer

Table 7: Sealing requirements in AS 4254.

For unsealed, low pressure ducts the standard gives leakage airflow rates to apply for design purposes. These are given in Table 8.

Duct pressure (Pa)	Leakage airflow (l/s per m²)	Leakage airflow EUROVENT Class A (l/s per m²)
25	0.52	0.22
60	0.94	0.39
125	1.46	0.62
250	2.27	0.98

Table 8: Leakage rate in unsealed low pressure ducts.

The sealing of ductwork can be done by means of mastics, liquids, gaskets or tapes. Each of these sealing techniques are described briefly in the standard.

[4] A seam is defined as the joining of two longitudinally oriented edges of duct surface material occurring between two joints.

Special requirements are given for kitchen exhaust ductwork sealing.

➢United States

ASHRAE standard 152P (draft of 97/3) describes in a detailed way the test method for determining the design and seasonal efficiencies of residential thermal distribution systems. It applies to single-family detached and attached residences, with independent thermal systems.
The standard describes a method to determine the leakage airflow rate of the duct system **to outside**. Briefly, the method consists of the following steps:

- Measurement of the leakage airflow rate of exhaust and supply ductwork to outside, for a pressure of 25 Pa (positive or negative). Therefore the building is first pressurised with a blower door and then the pressure between the building and the ductwork is brought to zero by regulating the speed of the fan for the duct pressurisation. The measured flow through the fan connected to the duct is the duct leakage to outside;
- Determination of the operating pressure as the average of the pressures at the different registers;
- Conversion of the measured duct leakage airflow to the leakage airflow at operating pressure.

3.4 European Committee for Standardisation (CEN)

3.4.1 Introduction

CEN is the European organisation responsible for the planning, drafting and adoption of standards. When the need for the development of a new standard has been clearly established and when it does not appear possible to use an existing reference document or one under development in a different forum (e.g. ISO), a team of experts is set up in the framework of a Technical Committee (TC). When consensus is reached on a draft in the TC, a thorough procedure, designed to ensure the general acceptability of the proposed standard, is then started. This procedure includes a public enquiry and adoption of the standard through a formal vote by each National CEN member; several majority criteria must be met for the standard to be ratified. The use of these standards is always the result of voluntary action by trade, industry and social and economic partners.

Within CEN, standards in the field of ventilation are being prepared by Technical Committee (TC) 156: “Ventilation for Buildings”. TC 156 consists of 9 Working Groups (WG). The following table gives an overview of these different Working Groups. As it can be seen, WG 3 deals with the standards about ductwork.

Working group	Description
WG 1	Terminology
WG 2	Residential ventilation
WG 3	Ductwork
WG 4	Terminal devices
WG 5	Air handling units
WG 6	Indoor climate
WG 7	System performance
WG 8	Installation
WG 9	Fire protection of air distribution systems

Table 9: Overview of the different working groups within CEN TC 156.

The following figure shows the position of standards related to ductwork airtightness in the field of standards related to mechanical building services within CEN TC156.

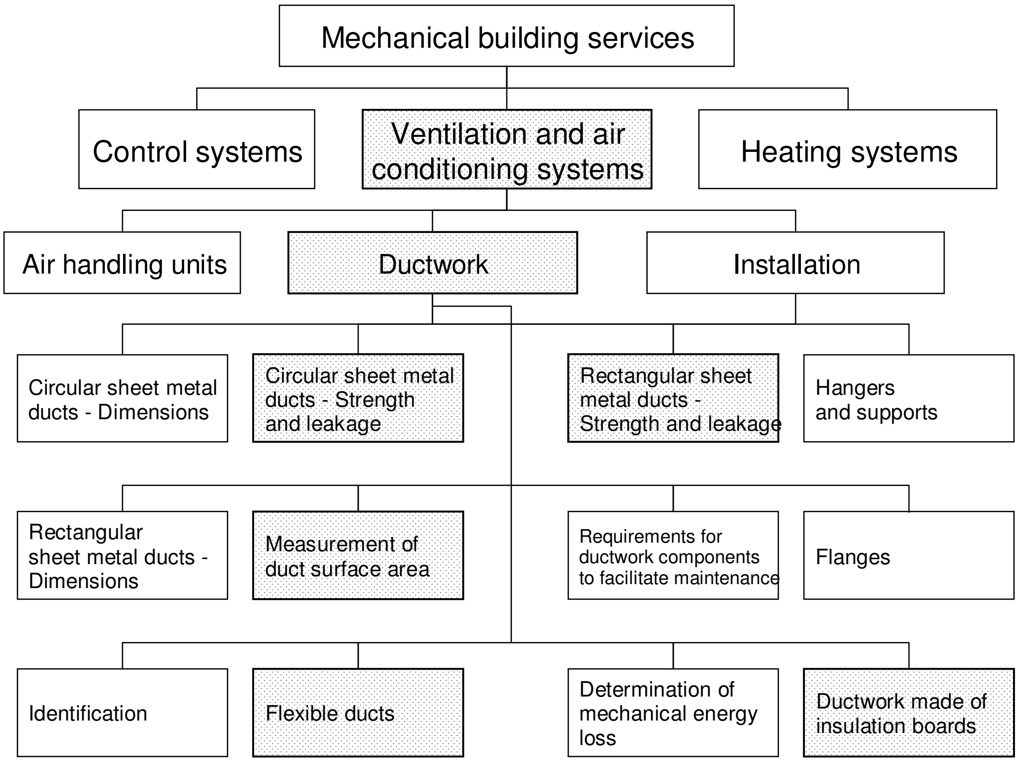

Figure 10: Ductwork airtightness related standards within CEN TC 156.

3.4.2 Circular sheet metal ducts: Strength and leakage – prEN 12237 (version of October 1998)

➢General

This standard specifies requirements and **laboratory** test methods for the strength and air leakage testing of **circular** ducts. It is applicable to circular ducts used in ventilation and air conditioning systems in buildings for human occupancy. Primarily, it refers to ducts made from steel, but it is also applicable for other metallic ductwork (e.g. aluminium and copper). The following characteristics are tested or inspected:

- Deflection of the installed duct;
- The air leakage of the duct.

➢Definition of leakage classes and requirements

The definition of the tightness classes has been adopted from the EUROVENT guidelines 2/2 (Table 1). The requirement is that the leakage factor shall not exceed 90 % of maximum leakage rate for the applicable tightness class.

➢Test equipment

The standard describes the test equipment to be used:

Fan with variable airflow rate, with an airflow capacity sufficient to maintain the required pressure level (Table 10).

- Airflow meter, with a maximum error of less than 4 % or 0.1 l/s (whichever is the greater value);

- Pressure gauge meter, with an accuracy of 10 Pa or 2 % (whichever is the greater value).

➢Test procedure to determine the leakage

For the test of the air leakage the ductwork shall be submitted to:

- A certain load, calculated from the mass of the duct (m_d):

$m_{test} = m_d + 1.5 \cdot m_d$

where $1.5 \cdot m_d$ is the external loading
This load is foreseen to cover loadings caused by insulation and to give some safety against transport damages.

- A certain pressure, as specified in the following table:

Class	Test static gauge pressure[(1)]			
	1000 Pa		400 Pa	
	+	-	+	-
A			X	X
B	X	X		
C	X	X		

[(1)] *For design pressures exceeding 1000 Pa, the test shall be carried out at that pressure.*

Table 10: Test pressures.

The test pressure has to be maintained until steady-state is reached. Then the leakage flow is recorded. The air leakage has to be given as the leakage factor, i.e. the airflow rate divided by the duct surface area. The leakage factor has to be determined with and without load.

➢Test report

A test report has to be made, including the following information:

- Manufacturer, number of tested ducts, duct material, design of joints;
- Cross sectional and longitudinal dimensions of the duct and sketch of test arrangement;
- Mass of insulation (if applicable);
- Test load;
- Distance between supports;
- Deflection;
- Ovality;
- Test pressure and leakage factor with and without load;
- Tightness class;
- Time, place and signature.

(Distance between supports; Deflection; Ovality: *Strength aspects*)

3.4.3 Rectangular sheet metal air ducts: Strength and leakage – prEN 1507 (version of October 1998)

This standard specifies requirements and test methods for the strength and air leakage testing of **rectangular** ducts, including joints. As regards duct leakage testing, this standard is very similar to prEN 12237.

3.4.4 Ductwork made of insulation ductboards – prEN 13403

This European Standard contains the basic requirements and characteristics for ductwork made of insulation ductboards, used in ventilation and air conditioning systems of buildings, subject to human occupancy. Ductboard is defined as a rigid board composed of insulation material body with one or both sides faced; ductboards are fabricated into rectangular or multisided duct sections; the outer facing is a duct vapour barrier and is supposed to make the duct airtight. The standard gives requirements regarding maximum air speed, resistance against pressure, airtightness, bulging and/or caving, supports and hangers, facilities for cleaning and requirements for materials (board stiffness, water vapour resistance, dimensional tolerances, acoustical absorption etc.). Regarding airtightness, the same requirements apply as in prEN 1507 and prEN 12237.

3.4.5 Handing over installed ventilation and air conditioning systems – prEN 12599 (Final draft, version 10/97)

This pre-standard details test procedures and measuring methods for handing over installed ventilation and air conditioning systems designed for the maintenance of comfort conditions (note that prEN 1507 and prEN 12237 apply to laboratory tests). It includes special measurements that shall be carried out only when required and especially agreed. Air leakage is among these special measurements that are detailed in the informative annex F. It refers to prEN 1507 and prEN 12237 but states that the test pressure should be adjusted to 200, 400 or 1000 Pa, whichever is closest to the mean operating pressure of the system.

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Chapter 4 Ductwork airtightness: state-of-the-art review of construction and installation technologies

Ductwork construction

Ductwork installation

Field test with aerosol-based duct sealant

4.1 Summary

The construction and installation of duct systems are two key aspects that have a major impact on ductwork airtightness. This chapter looks at today's technologies that may be used to limit duct leakage. It includes a short review of manufacturing processes. Also, installation issues are discussed as well as site sealing techniques. The last paragraph focuses on a field test of an aerosol-based internal-access technology in a European building.

4.2 Construction

Seams and joints should be suitably selected for the type of ductwork and leakage requirements. They should be compatible with the maintenance work (e.g. cleaning) to be performed on the system as well as the installers' skills and the time granted for site work. At the construction stage, the airtightness of individual components depends on the design (rectangular versus round, pressed versus segmented bends, flexible ducts, etc.) and assembly (seam type and welding quality). DW/144 (HVCA, 1998) gives a list of requirements to seal seams, laps, cross-joints and duct penetrations of different type. Also, DW/143 (HVCA, 1983) states that it is important "to make components with a good fit, and to use only enough sealant to make a satisfactory joint. A poor fit cannot be remedied by the use of more sealant – it will not work".

Factory-fitted sealing devices (e.g. gaskets, clips) are available on the market. They appear to be efficient at reducing the installation time and give very satisfactory results in terms of airtightness. Some manufacturers include in their brochures information about the airtightness of individual components or the air distribution system between air handling unit and the terminal devices. As for air handling units and terminal devices themselves, very little information is available from the manufacturers although experience shows that they can represent a significant source of leakage. Special care should be given to the fitting and sealing of maintenance panels and paths for electric wires, fluid pipes, etc.

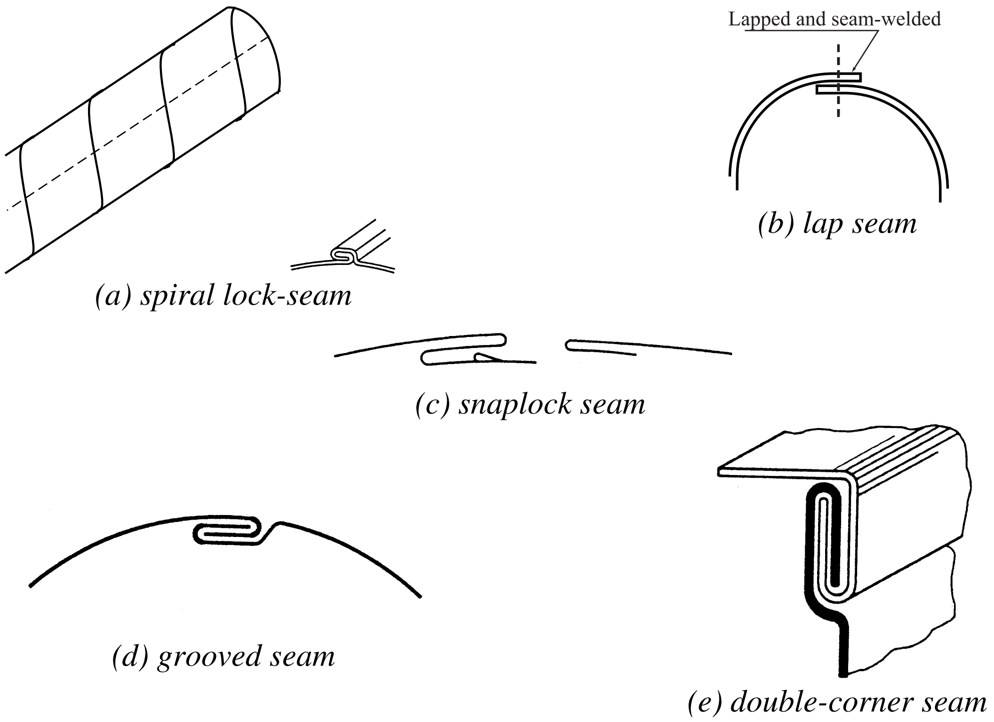


Figure 11: Examples of seams.

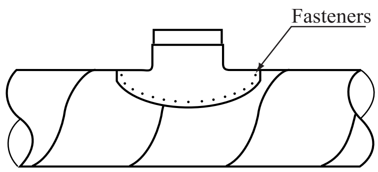


Figure 12: Saddle tap with spot-welds or fasteners.

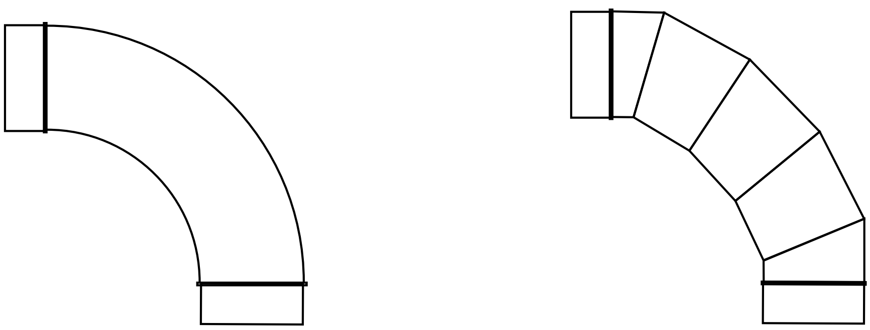


Figure 13: Pressed bend (left). Segmented bend (right).

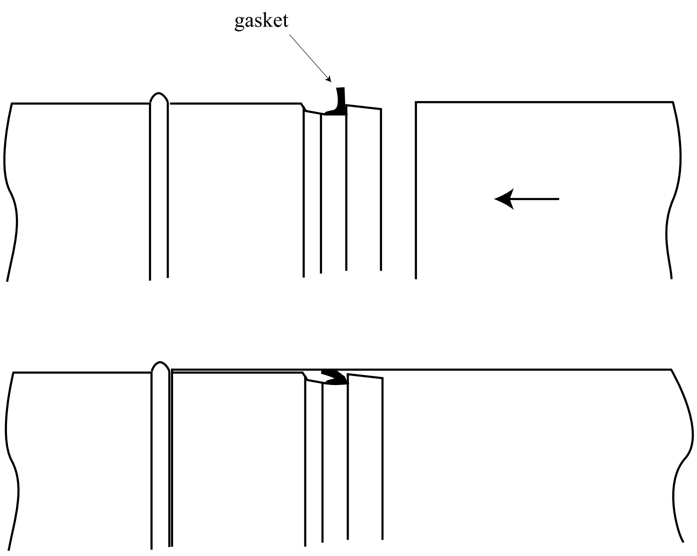


Figure 14: Pre-fitted sealing gaskets for circular ducts. Airtight rivets or plate-screws may be necessary to ensure the mechanical stability of the joint.

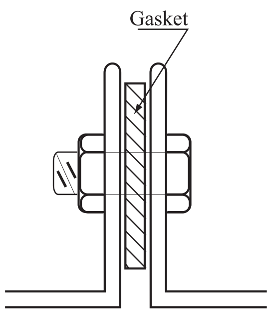


Figure 15: Sealing gasket at flange joint. Drive slips, fasteners, rivets or bolts are used to hold the pieces together.

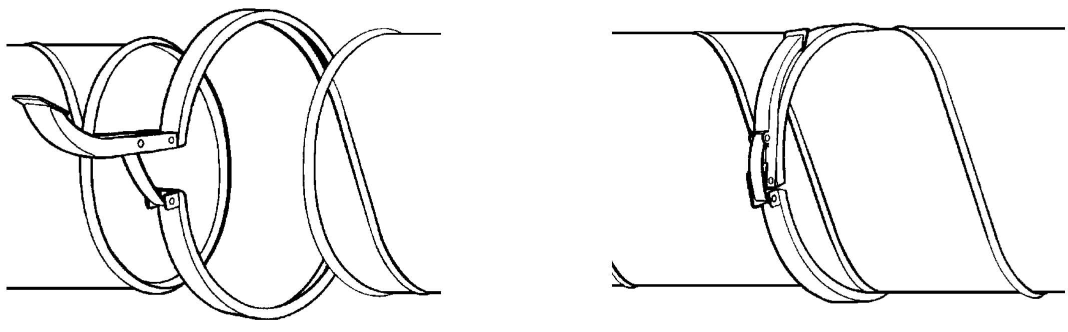


Figure 16: The clips ensure a good airtightness and the mechanical stability of the joint. These systems are mainly used for non permanent ductwork or ductwork which has to be cleaned regularly. LindabTransfer® system (Courtesy Lindab Ventilation AB).

4.3 Installation

To obtain an airtight system, particular attention should be given to leakage:

- at seams and joints;
- due to unnecessary holes or physical damage in duct runs;
- at air terminal devices;
- in the air handling unit.

The key advantage of ductwork components with factory-fitted sealing devices (e.g. gaskets, clips) for joints lies in the ease and rapidity in obtaining airtight duct runs. When quality products are used, the installation work mostly consists of ensuring the mechanical stability of the ductwork. Alternatively, when the components do not have pre-fitted sealing devices, additional work is needed at installation to avoid leakage at joints. Also, the installers should seal off unnecessary holes (for screws, rivets, measuring devices, etc.). Installation, inspection or rehabilitation work should be performed with caution so as to avoid physical damage to the ducts. Typically, significant leakage is found at the air terminal devices either because of poor connections to the ducts and against building materials, or because of internal cracks. Particular attention should be given to these parts. Finally, leakage in air handling units should be avoided using adequate sealing devices at maintenance panels and paths for electric wires, fluid pipes, etc. However, where intentional holes are necessary for fire protection reasons (to cool the motor), they should not be sealed.

In general the use of quality-products with factory-fitted sealing devices does not eliminate completely on-site sealing (for example the fastening against the body of a building). Nevertheless, they can spare the installers from doing much time-consuming and tedious tightening work. However, they are, in general, more expensive to purchase but the payback period decreases with increasing local costs of labour and energy. In fact, in many countries it is quite common to perform most of the sealing at installation although 'pre-tight' systems are available. These sealing methods could also be chosen for retrofitting leaky duct systems.

For site tightening of systems, five major methods are used:

- Gaskets;
- Tapes;
- Sealing compound;
- Internal duct lining;
- Aerosol-sealant.

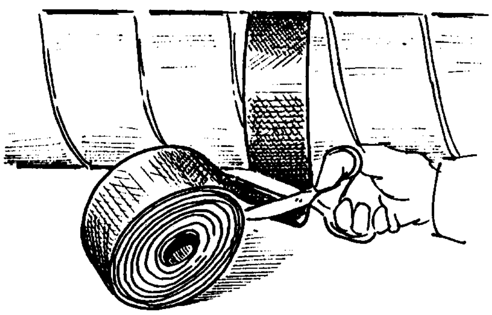
Sealants or sealing devices should be non-combustible unless any addition to the spread of fire can be considered to be negligible. They should not constitute any health hazard to the worker applying them or to the building occupants. The choice of a suitable sealing method should be based on criteria applicable to the studied duct installation such as type of ductwork, leakage status, required durability of the work performed, maintenance procedures, operation experience and costs, available space for installation or rehabilitation work.

4.3.1 External-access techniques

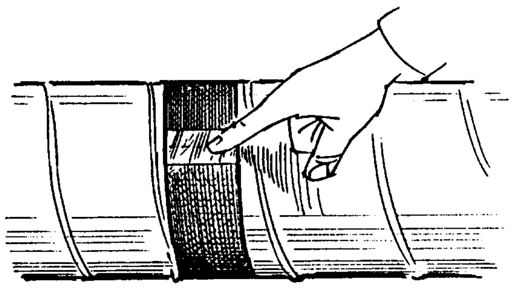
On site, (non-extruding) gaskets are put primarily on flange joints in new installations (similarly to Figure 15). Table 11 gives a summary of the other sealing media that may be used when the ducts are accessible from the outside.

	Heat shrink tape	Self-vulcanising tape	Sealing compound
Round ducts	yes	yes	yes
Rectangular ducts	no	no	yes
Flexible ducts	no	yes	yes
Joints	Butted or sleeved	Butted or sleeved	Any
Temperature range (application)	Heat to 125°C	-5°C to 80°C	> 5°C
Temperature range (service)	-30°C to 70°C	-40°C to 80°C	-20°C to 80°C

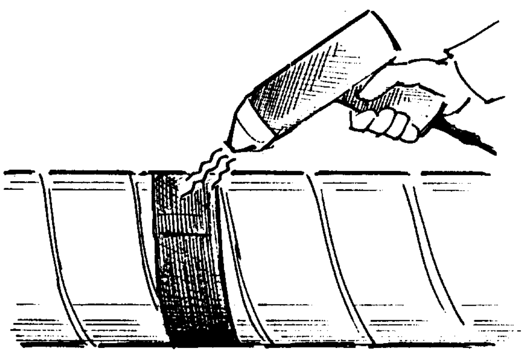
Table 11: External sealing methods.



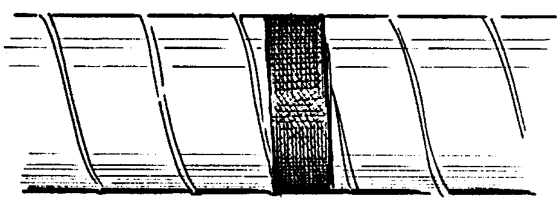
1. Wind the band around the duct. Cut it off with margin according to the manufacturer’s instructions



2. Apply special fastening tape at the overlap



3. Heat to the tape on all sides



4. Finished sealing

Figure 17: Use of heat shrink tape of polyethylene with a surface of thermoplastic glue (Courtesy Swedish Council for Building Research).

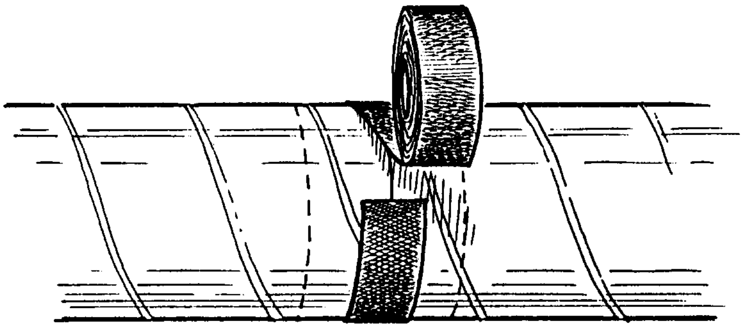
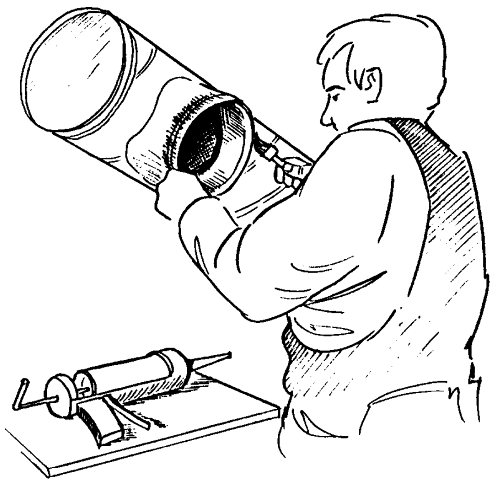


Figure 18: Self-vulcanising sealing tape applied around the duct with overlap. This method does not require any heating of the joint (Courtesy Swedish Council for Building Research).



The tightening is done with an elastic sealing compound either of butyl rubber base or acrylic latex with good adhesive capacity on steel. The sealing compound can be applied to the duct with a paintbrush from the outside. Adhesive tape or fibreglass bands are sometimes applied over the sealing compound. The sealing compound is also available in cartridges for plunger guns.

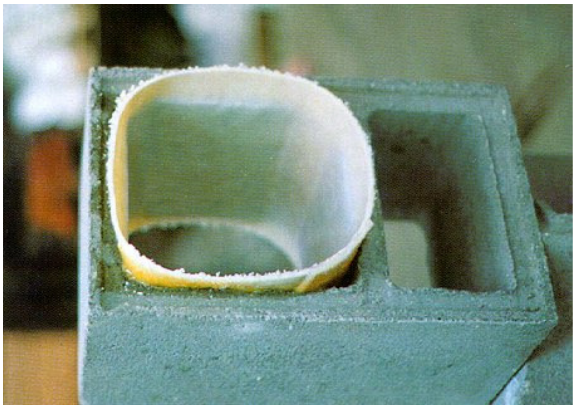
Figure 19: Application of sealing compound (Courtesy Swedish Council for Building Research).

4.3.2 Internal-access techniques

Two internal-access methods are summarised in Table 12. The common factor for these methods is that the sealing work is mainly performed from the ends of the ducts, which reduces the need to work on other building elements.

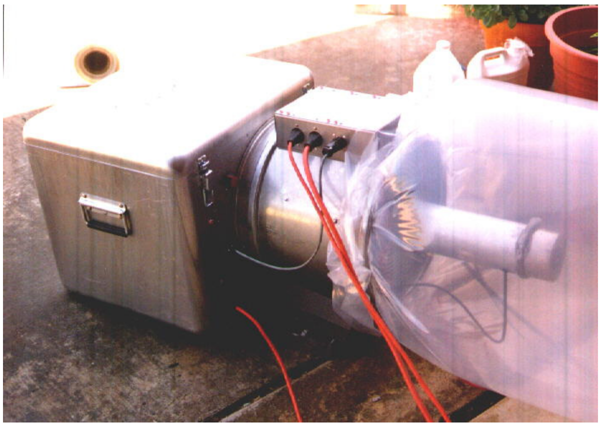
	Flexible plastic insertion	Aerosol-based sealant
Building materials	yes	Tested on wooden cavities used as ducts
Round ducts	no	yes
Rectangular ducts	no	yes
Flexible ducts	no	yes
Temperature range (application)		> 5°C and < 70°C (surface)
Temperature range (service)	< 80°C	< 80 °C (surface)

Table 12: Internal sealing methods.



This method is normally used to improve the airtightness of existing vertical concrete shunt ductwork. It consists of the insertion of a synthetic lining (Rolyner®) from the roof into the ductwork. Once the lining is put in place, it is pressurised with warm air. Consequently, the lining takes the form of the inside of the ductwork and hardens in that way afterwards. The ductwork airtightness is significantly improved (often by more than 95 %), without reducing significantly the cross-section (the thickness of the lining is about 3 mm). By the insertion of the lining the secondary ducts of the shunt system are blocked from the main duct. Therefore, the lining has to be perforated afterwards to establish the connections to the ventilation system of each apartments.

Figure 20: Insertion of plastic lining (Courtesy Bergschenhoek).



The method involves blowing an aerosol through the duct system to seal the leaks from the inside, the principle being that the aerosol particles deposit in the cracks of the ductwork as they try to escape because of the pressure-driven flow. Before the sealant is sprayed in, the registers are blocked and sensitive equipment (e.g. heat exchangers) should be isolated. To minimise the sealing time, large holes (larger than 6 mm across) should be sealed manually unless they are inaccessible. The device can also be used to measure the airtightness of the system before, during, and after the sealing process. The leakage area of a typical residential system can be reduced by more than 80 %. A duct improvement certificate that includes documentation of the time history of the sealing and the estimated annual savings is issued by the contractor. The technique is commercialised and increasingly used in US residences. At present, it is not commercially-available in Europe.

Figure 21: Aerosol injection device (Courtesy Aeroseal Inc.).

4.4 Field test with aerosol-based duct sealant

In the framework of the SAVE-DUCT project, the aerosol injection technique was tested on a 17 m^2 section of a rectangular sheet-metal duct system in a building of the BBRI (Belgian Building Research Institute). The airtightness was measured by the Aeroseal device itself at the beginning of the experiment and showed that the system was initially very leaky (ELA_{100} ≈ 4 cm^2/m^2, i.e. more than 9 times Class A).

Figure 22 shows the evolution of the leakage airflow rate at 100 Pa during aerosol injection. The sudden drop of the leakage after about 70 minutes is due to the manual sealing with tape of a large gap; the sharp increase after about 100 minutes is due to the fact that the part that was sealed manually came loose. It should be noted that fibreglass-reinforced mastic sealants can be used to perform manual sealing during the aerosol injection process. Significant aerosol deposition was observed in some leaks (Figure 23). However, the sealing rate slowed down after about 2 hours when the leakage airflow rate was at approximately 30 % of its initial value, which is still insufficient to reach Class A. It should be noted that the equipment used was not designed to produce the lower leakage levels desired in Europe. For European tightness levels, a smaller particle size, and a fan that maintains a flow at higher pressure would be desirable. Also changes in the design of the equipment is suggested since this experiment allowed the particle injection rate to be increased by 50 %.

In fact, there is an absolute leakage airflow rate limit associated with the equipment currently being utilised. At present, this device is designed for US residences, i.e. for very leaky systems (see chapter 6), and goes down to leakage flow rates of about 5-10 l/s at 25 Pa (12-24 l/s at 100 Pa). Although it is successfully commercialised in the US with the present design, Class A can be reached only for systems with a surface area larger than about 40 m^2. This is due to the fact that the particles are transported by the carrying (leakage) airflow, which tends to drop off as the pressure mounts in the system during sealing, due to the fan-curve of the device. Remember that the flow through the injector fan is all that is being forced through the leaks. As the leaks get smaller, the pressure seen by the injector fan increases, which reduces its flow. To maintain the flow rates needed to keep the particles in suspension, the fan would have to be particularly suited to the high duct pressures at low leakage levels. This problem could be solved by using a higher-pressure fan, however a more practical, more cost-effective solution could be to use an opening at the end of the ductwork to reduce duct pressure at the required flow rates.

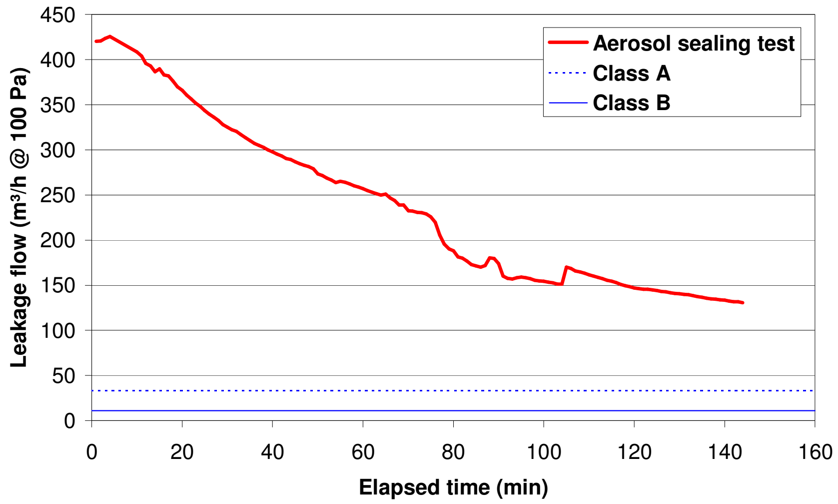


Figure 22: Leakage airflow rate at 100 Pa versus elapsed time during the aerosol injection test in a building of the BBRI.

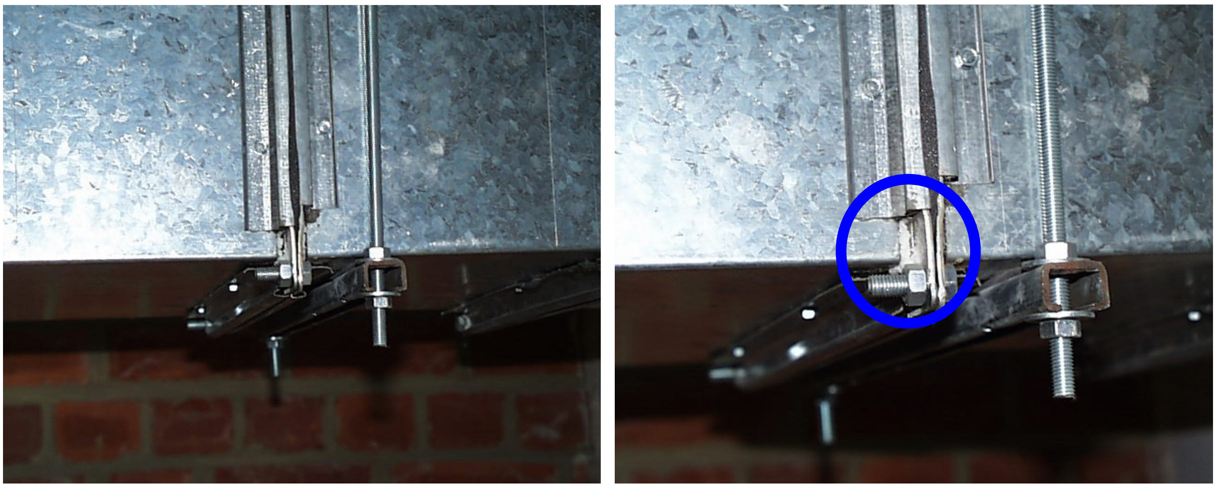


Figure 23: Detail of a leak during and at the end of the test. The white material indicated by the circle on the right hand-side is the seal created by the deposition of aerosol particles.

In Figure 25 the BBRI aerosol sealing test is compared with two experiments performed in two residences in the USA. The initial and final leakage factors are shown in Figure 26. Because both US tests were demonstrations, they were terminated prematurely (less than 1 hour - the complete sealing procedure usually lasts ½ - 3 hours for a typical residential duct system, depending on the initial leakage level and the size of the leaks). Still, leakage airflows were reduced to 26 % and 32 % of their initial values. Approximately the same result was obtained in the Belgian test, but the duration of the experiment was nearly three times greater. Also, the sealing rate was significantly lower in Belgium (Figure 25), which is partly due to much lower leakage flow rates. In addition, the system used for the Belgian test was a new prototype, which was later found to need straightening vanes to avoid swirl-induced deposition on the plastic tubing used to connect the aerosol injector to the duct system. Also, the fan did not have the same fan curve using a 50 Hz power-supply (as opposed to 60 Hz in the US). For the same leakage characteristics of the system, the fan delivers a lower (carrying) airflow rate at 50 Hz (see Figure 22).

In summary, this aerosol-based technique seems promising, however to be successfully used in Europe, development work should be undertaken to increase aerosol penetration in the system by using:

- Filtered openings at the ends of the duct run;
- A different fan that would be able to operate at higher pressures with a large enough carrying airflow;
- A different aerosol generator that would produce smaller particles that have lower settling velocities (note however that smaller particles also imply lower deposition efficiencies at the leaks).

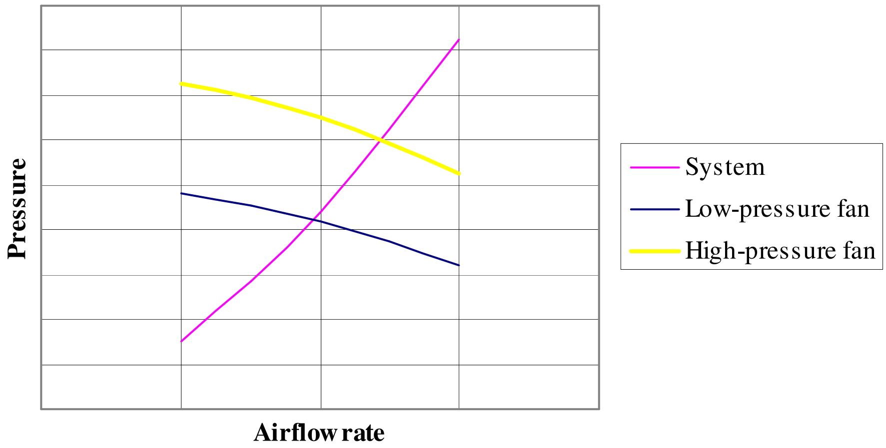


Figure 24: Effect of using a higher-pressure fan on (carrying) airflow rate.

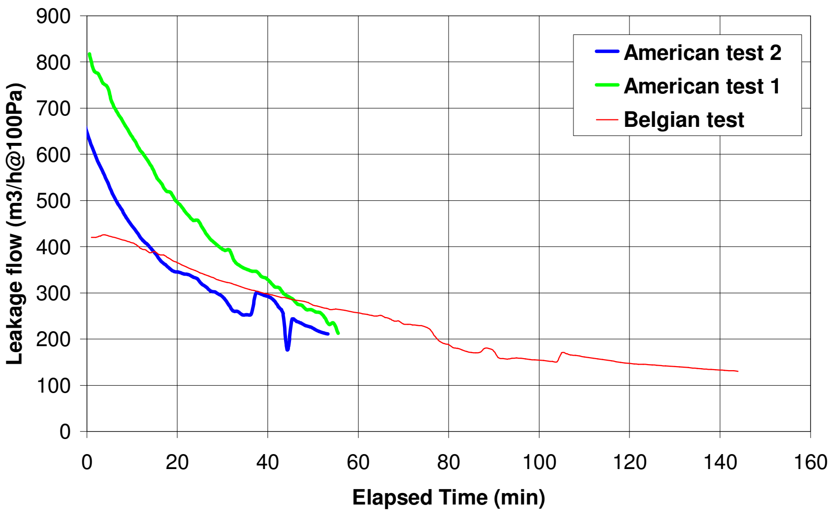


Figure 25: Leakage flow rate versus elapsed time during three aerosol injection tests.

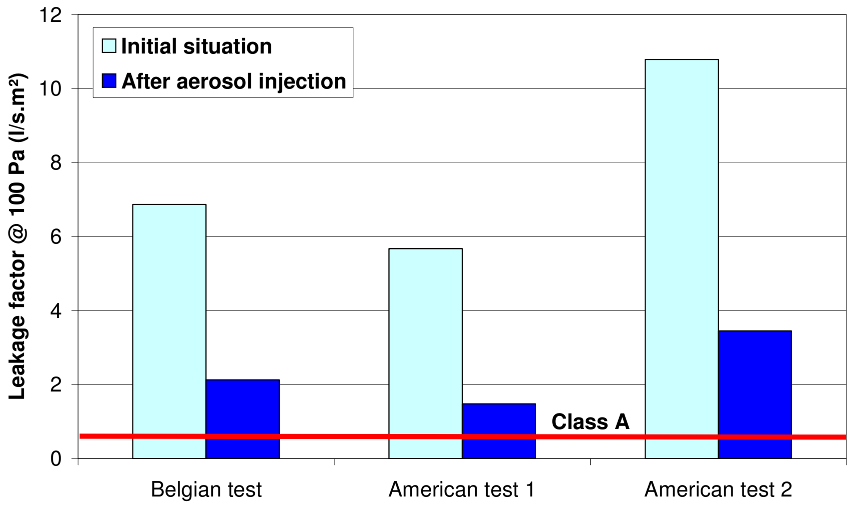


Figure 26: Initial and final leakage factor at 100 Pa for aerosol sealing tests on one Belgian and two US buildings (Class A: f_{100} = 0.54 l/s per m²). The tested surface areas are: Belgian test: 17 m²; American test 1: 40 m²; American test 2: 17 m².

4.5 Renovation

When retrofitting buildings with old and leaky systems, the replacement of the ductwork with new, clean, and tight ducts should be seriously considered. Where possible and compatible with the budget, it will be more effective than any rehabilitation techniques both on tightness and cleanliness aspects.

4.6 References

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Chapter 5 Traditions in the design, installation, and maintenance of duct systems

Small-scale survey

Traditions

Implications on ductwork airtightness

Incentives and barriers to better systems market penetration

5.1 Introduction

Duct system designs can vary considerably depending on the building type (single-family houses, multi-family buildings, or commercial buildings) and local customs. This may have a negative impact on the system's operation and maintenance because of the wide price and performance range of the many commercially-available products. Traditions in the installation (that differ considerably between countries) can also contribute to poor performance.

This chapter aims at giving improved knowledge about these aspects to help with drawing up a statement of habits in European countries. It is mainly based on ALDES' experience over the past 25 years. A small-scale survey among 25 professionals (HVAC design offices, installers, maintenance contractors) is also used as an illustration on some issues.

5.2 Small-scale survey

25 HVAC professionals were surveyed in Belgium, France, Italy, Spain, and Sweden (Table 13). It is clear that the sample is not representative, however, it provides an interesting picture of the traditions and common thoughts of some experienced professionals who work on air ducts from the design table to the actual installation. The questionnaire was divided into 3 parts aimed at the different types of professionals surveyed. It was filled out by the interested parties without any assistance from us.

The major issues addressed by the survey are listed below:

- Frequently-used types of systems (types of ducts, components, etc);
- Practical ways of installing;
- Costs;
- Incentives and barriers to using higher-quality materials or more effective techniques;
- Rehabilitation techniques;

- Need for skilled labour;
- Cleanliness of installations;
- Maintenance.

	Belgium	France	Italy	Spain	Sweden
Design office/Architect	3	2	2		3
Installation contractor/Manufacturer	5	4	3	2	1
Maintenance contractor/Manager	2				2
Total	10	6	5	2	6

Table 13: Sample of the small-scale survey.

5.3 Traditions

5.3.1 Type of systems

As regards the most frequently-used ducted systems in new construction, the European Union can roughly be divided in three major zones:

	Frequently-used ducted systems
Nordic regions	Balanced mechanical ventilation with heat recovery; air heating or cooling with heat recovery
Middle regions	Mechanical exhaust ventilation; air heating or cooling
Southern regions	Air conditioning (commercial buildings)

Table 14: Frequently-used ducted systems.

5.3.2 Duct Material

Metal is the most frequently used material either for rectangular or round ducts. Plastic is another material that is often used in single-family houses as it is cheap and compatible with the fire regulations for air ducts. On the other hand, fibre glass boards and brick are not used very much. The reason certainly lies in health and safety issues. Note that in several European countries (e.g. Germany) blowing air through fibre glass ductwork is forbidden.

5.3.3 Duct shape

Especially in the Nordic countries, both designers and contractors would rather use round ducts as they are manufactured with standard sizes. However, the market penetration of rectangular ducts is significant in the other regions and especially in the Southern countries.

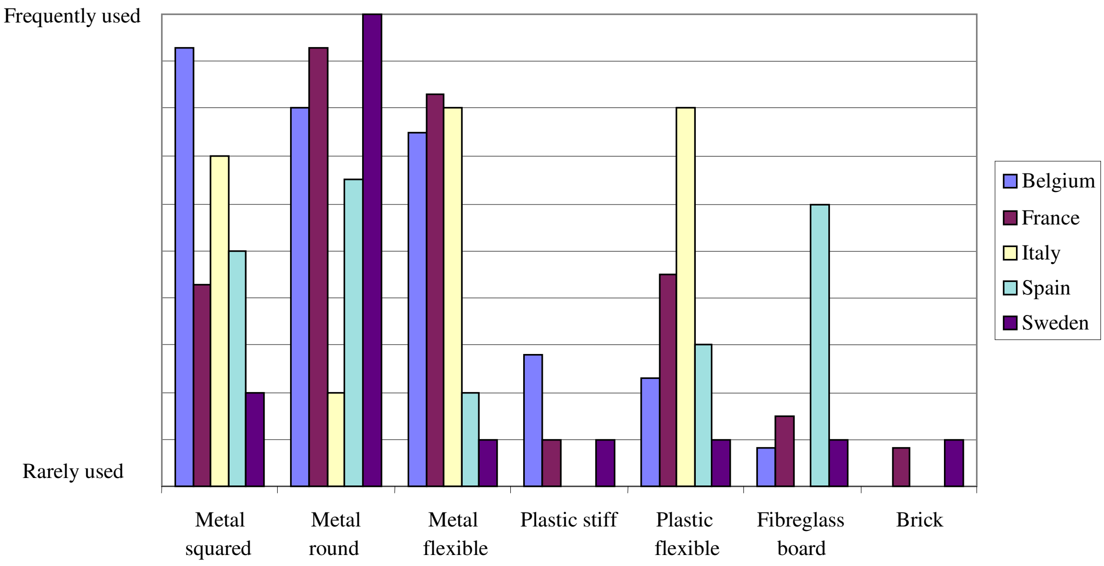


Figure 27: Type of ductwork frequently used. Data from small-scale survey.

5.3.4 Connecting systems at joints

In Nordic countries, the factory-fitted lip-seal system (that is airtight and that can be dismantled) is widely used. Although, this technique is increasingly used in some other countries such as the Netherlands or Germany, in other countries, ducts are most commonly sealed on site using adhesive tapes in combination with mastic or screws (note that the use of mastic or screws is not systematic). Flange systems are often used with rectangular ducts or with systems that need to be dismantled regularly for maintenance purposes. The parts are connected with screws and the sealing media is either mastic or rubber gaskets.

5.3.5 Clean ducts

The Nordic countries appear to be aware of the need to have clean systems. Thus, inspection hatches are frequently encountered to provide access to the interior of the ductwork. Cleaning is undertaken if needed after (regular) inspections. The inspection interval lies between 2 to 9 years although it is sometimes reduced in special applications (e.g. hospitals). Robot cleaning is not used very much because of the significant investment for the equipment. Furthermore, the robots may be hindered by obstructing screws or rivets stretching inwards. In the remaining countries however, cleaning access is in general fairly poor and duct systems are rarely inspected or cleaned. In these instances, maintenance is often restricted to a minimum. Furthermore, when being installed or being repaired, installations are rarely cleaned.

When high Indoor Air Quality (IAQ) is required an installation that has just been completed usually runs for a while before it is actually used (parts like filters are replaced at that time).

5.3.6 Rehabilitation

Duct systems are rarely rehabilitated.

5.3.7 Context of standards and regulation

In practice, although designers are not necessarily aware of duct leakage issues, they know about guidelines, standards and regulations (whether international, European, or national) related to ductwork airtightness. Note, however, that they frequently refer to these in the building specifications only in the Nordic regions and few other states. Consequently, the contractors in other countries are not very familiar with ductwork airtightness needs and requirements. This can lead to a significant gap between the design stage and the field work. However, as regards the cleanliness of the installation when it is handed over, installers seem to be aware of specific needs, standards and regulations on specific installations.

5.4 Implication on ductwork airtightness

Inadequate product selection and poor installation can severely affect the leakiness of an HVAC system. Special attention should be paid to the connecting parts and the connections themselves since these are the weakest points. Also, some (complex) components (e.g. air handling unit) are very difficult to get airtight. Conversely, it is fairly easy to have airtight straight ducts (either rectangular or circular) provided that the accessibility and the durability of the sealing media be taken into account. Professionals generally agree with this, although they do not seem to be quite aware of how leaky the components can be.

Insufficient care when maintaining and/or inspecting an installation can also lead to poor airtightness. Although professionals consider that inspection hatches do not induce significant leakage, they are sometimes found improperly sealed after a cleaning procedure. Also some sealing media in common use can be damaged by chemicals.

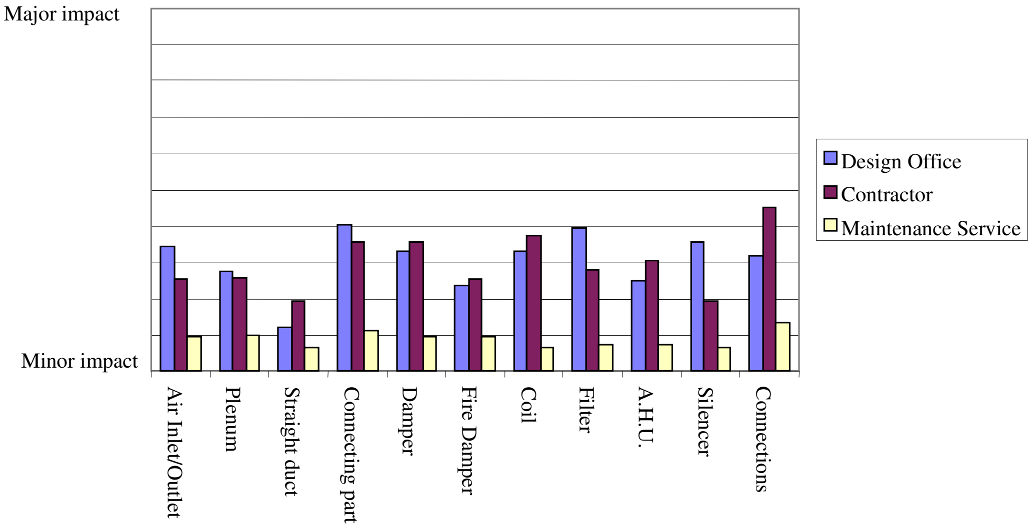


Figure 28: Perceived impact of several components on duct leakage. Data from small-scale survey.

5.5 Incentives and barriers to better systems market penetration

5.5.1 Cost issues

➢**Material cost**

In general, adhesive tape, either on a textile or aluminium base, results in the lowest material cost to connect air duct components. Mastic is mostly used in combination with tape to obtain tighter and more durable connections. It is slightly more expensive and therefore some professionals in Southern Europe use tapes alone. In general, factory-fitted rubber gaskets or O-rings on components result in a price increase of 10% to 50% depending on the components and market penetration in the different countries. Flange and clip systems lead to the highest costs but are of great interest where installations need to be dismounted.

➢Labour cost

It is generally estimated by manufacturers that the use of factory-fitted sealing gaskets results in airtight systems as well as a reduction of the installation time (which is estimated to be an average of 25% compared to conventional sealing with tape and/or mastic). Thus, the additional material cost may be compensated by a lower labour cost. However, this does not seem to be well-known especially among the contractors.

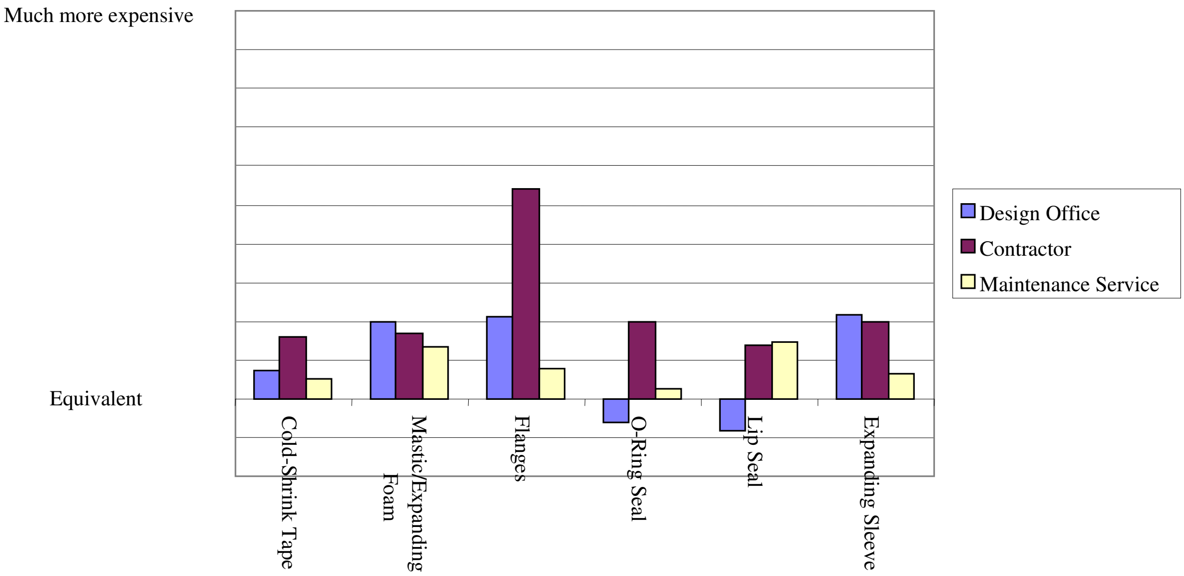


Figure 29: Perceived labour cost of several techniques compared to that of duct tape. Data from small-scale survey.

➢Maintenance costs

In general, professionals are aware of the interest of dismountable solutions such as O-Rings, lip seals, flanges or expanding sleeves to perform efficient maintenance on the ductwork.

➢Life Cycle Cost

Investment and operating budgets are evaluated sequentially and almost never globally, which leads to conflicts of interest between the different parties.

5.5.2 Possible actions

The major bottle-neck lies in the higher material cost of quality products combined with the sequential evaluation of the budget (as opposed to a Life Cycle Cost approach). An adequate regulation would probably be an effective way to promote air tight systems (see chapter 10). Although it may not be very well perceived by the manufacturers, designers, contractors, and investors, it presents the advantage of minimising the conflicts of interest between the end-users, the contractors and the designers.

Another way would be to better inform all interested parties of the benefits of tight systems and technologies such as pre-fitted sealing gaskets. Indeed designers and contractors seem to be sensitive to convincing arguments such as mounting ease and quickness, cleaning ease, or installation costs. As for end-users, they are receptive to issues such as safety, reliability, and lower operating cost.

5.6 Conclusion

Leaks in air distribution systems are most often encountered at connections and at special components or accessories since these are particularly difficult to get airtight (e.g heat exchanger). This is well-known among the professionals but the solutions adopted to limit leakage are extremely different depending on the local customs, requirements, and control procedures. For instance, whereas factory-fitted sealing gaskets are widely used in the Nordic regions and increasingly demanded in countries such as the Netherlands, more conventional techniques (e.g. tape plus mastic) are frequently used in Belgium, Italy, France, or Spain. In such countries, little attention is paid to duct leakage at installation and the airtightness of the systems is often poor (see chapter 6).

Although there is an increasing concern for well-maintained systems, this need does not seem to be either clear or taken into account by the interested parties in most countries. This need is better identified in the Nordic countries where the impact of poorly maintained systems on IAQ performance is well understood. This is probably linked to the widespread use of balanced systems with heat recovery (due to the severe climate conditions), which encourage one to pay particular attention to the cleanliness of the supply ducts.

Another key problem lies in the gap between the prescriptions at the design stage and the actual performance on site. Significant efforts should be undertaken to convince people to use adequate techniques to guarantee good performances on site. Control at commissioning is also an important aspect.

Possible actions towards better quality systems market penetration include incentives in new regulations and better marketing. It is important to stress techniques that bring together better quality in air distribution systems and significant energy savings (see chapter 7). However, any measure for improvement should take into account the fact that the major barrier lies in the cost issues as investment and operating budgets are evaluated sequentially and almost never globally.

Chapter 6 Field measurements

6.1 Summary

Although duct leakage can be a source of considerable problems, little is known about the ductwork airtightness status in most of the European member states. However, field experiments conducted in various countries suggest that air distribution systems are in general very leaky. Except in Sweden, low-quality ductwork is widely used and poorly installed, yielding leakage rates typically 30 times greater than those of EUROVENT 2/2 Class C systems. Typical problems include:

- Inadequate ductwork component selection;
- Insufficient sealing work at installation;
- Ill-fitted components;
- Worn tapes;
- Physical damage during inspection or maintenance work.

In addition, in some cases, ducts are found to be completely disjointed. All of these airtightness deficiencies, along with other problems often reported (dirty systems, inadequate design, absence of commissioning, poor maintenance, etc.), show the lack of attention paid to those systems.

6.2 Measuring ductwork airtightness

6.2.1 Flow through leaks

The airflow rate through a leak will vary depending on the pressure acting across it and the geometry of the opening. The most commonly used pressure / leakage relationship is:

$$Q = C\,\Delta p^{n} \qquad \textit{Equation 3}$$

where:

Q is the leakage flow rate (m^3/s);
Δp is the pressure differential across the leaks (Pa);
C is the leakage coefficient ($m^3\ s^{-1}\ Pa^{-n}$);
n is the flow exponent (-).

6.2.2 Fan pressurisation

By artificially creating a series of pressure differentials in the test section and by measuring the leakage flow rates, one can calculate the *C* and *n* defined in Equation 3. This measurement technique, called fan pressurisation, is by far the most commonly used to characterise the airtightness of ductwork systems and building envelopes.

6.2.3 Effective Leakage Area

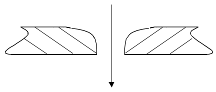
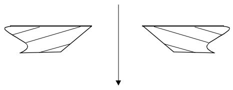
The Effective Leakage Area (ELA) concept is commonly employed to characterise the leakiness of a building envelope. The equation linking the pressure differential to the leakage flow rate is re-arranged as follows:

$$Q = C_d\ ELA_{ref}\ \sqrt{\frac{2\,\Delta p_{ref}}{\rho}}\left(\frac{\Delta p}{\Delta p_{ref}}\right)^{n} \qquad \textit{Equation 4}$$

where:
C_d is the discharge coefficient (-);
(perfect nozzle C_d=1; perfect sharp-edged orifice C_d≈0.6)
ELA_{ref} is the effective leakage area (m^2);
Δp_{ref} is a reference pressure differential across the leaks (Pa);
ρ is the density of air ($kg\ m^{-3}$).

The physical meaning of the Effective Leakage Area is that, at the reference pressure differential, the flow rate passing through the leaks would be the same as that leaking through an orifice of this same area under the same pressure differential. The reference pressure differential is set according to the typical pressure across the leaks.

There are two common sets of reference conditions to evaluate the airtightness of a building envelope:

Orifice type	C_d (-)	Δp_{ref} (Pa)
Perfect nozzle 	1.0	4
Sharp-edged 	0.6	10

For duct leakage applications, the operating pressure of the system should be taken as the reference pressure.

6.2.4 Leakage factor and leakage coefficient

In Europe, most ductwork airtightness standards propose a one-point measurement of the leakage flow rate at a given pressure differential (Δp_{ref}) and classify the installations similarly to EUROVENT 2/2, i.e. in terms of the leakage coefficient per square metre of duct surface area defined in Equation 3:

$$\frac{Q}{A} = f_{ref} = K\ \Delta p_{ref}^{\ 0.65}$$ *Equation 5*

where:

A is the (tested) duct surface area (m^2);
f_{ref} is the leakage factor at Δp_{ref} ($m^3\ s^{-1}\ m^{-2}$);
K is the leakage coefficient per m^2 of duct surface area ($m^3\ s^{-1}\ m^{-2}\ Pa^{-0.65}$).

It is noteworthy that this classification relies on an arbitrary flow exponent of 0.65 which according to DW/143 (1983) is justified by Swedish tests performed on a variety of constructions. However, measurements performed in other countries show a broad range of values. As for the reference test pressure itself, it can vary considerably. EUROVENT 2/2 is based on a mean operating pressure of the duct system. In European pre-standard prEN 12237 (1998), Δp_{ref} should be adjusted to 400 Pa, for Class A, to 1000 Pa for Classes B and C. In prEN 12599 (1997) (meant for *in situ* measurements), Δp_{ref} should be adjusted to 200, 400 or 1000 Pa, whichever is closest to the mean operating pressure of the system.

6.2.5 Apparatus

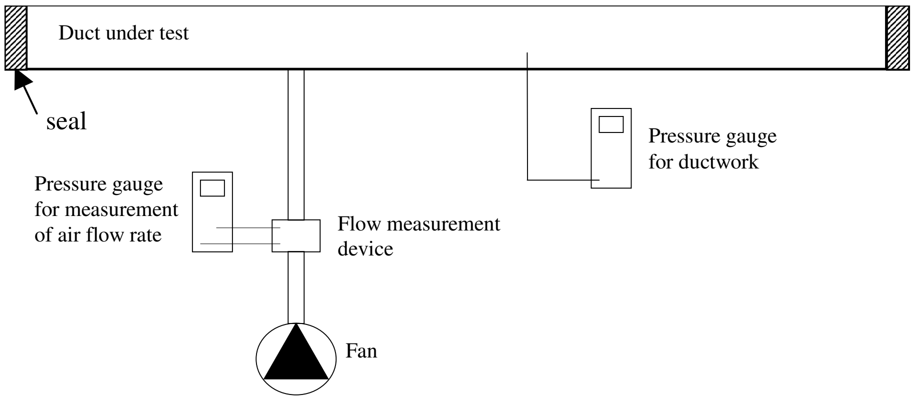


Figure 30: Fan pressurisation measurement principle and equipment

According to CEN prEN 12237 (1998), the test equipment should have the following accuracy:

- Airflow meter: 4 % or 0.1 l/s (whichever is the greater value);
- Pressure gauge meter: 2 % or 10 Pa (whichever is the greater value).

Special attention has to be given to the range of application of measurement devices. One ready-to-use duct leakage tester that is primarily commercialised in the US for low-pressure (operating pressure less than 250 Pa) residential and light commercial duct systems was found to be often inappropriate to check the compliance with European airtightness standards. The specific device combines the fan and the airflow measurement (minimum airflow about 10 l/s). Depending on the leakage airflow rate, different rings can be installed on the fan inlet in order to modify the measurement range. The airflow rate is determined by means of a pressure measurement in the fan of the device, by using equations provided by the manufacturer.

Laboratory tests (see Figure 31) were performed in the laboratory at BBRI and showed that at low flow rates (i.e. low fan pressures) significant errors can be made on the airflow rate, especially if the pressure behind the fan (= pressure in the ductwork) is significantly higher than the pressure in the fan (which occurs frequently in airtight systems).

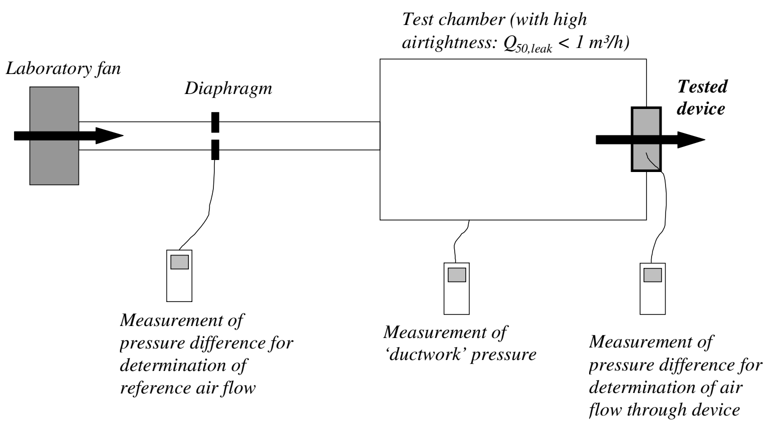


Figure 31: Set-up of the laboratory test performed at BBRI. The pressure in the chamber is changed with the laboratory fan.

This appears clearly in Figure 32 where the relationship between the error in the airflow measurement and the fan pressure (for the air flow measurement) is given for different ductwork pressures. According to the manufacturer, the pressure for the airflow measurement should not be lower than 25 Pa, in order to limit the error on the airflow rate. The figure below reveals that this minimum pressure is not a constant value but depends on the relationship between the fan pressure and the ductwork pressure.

It is clear that, to obtain reliable results from these laboratory tests, the airtightness of the test chamber is very important. This is because both airflow measurements are compared to determine the error by the device. As a consequence, the leakage airflow rate of the test chamber will cause additional errors, which should not be taken into account. The most critical situation appears for the lowest air flow (25 Pa pressure difference for the air flow measurement) and the highest duct pressure (200 Pa). In this case the airflow through the diaphragm is about 97 l/s (350 m³/h), while the leakage air flow from the chamber is about 0.55 l/s (2 m³/h), i.e. less than 1% of error. This means that the leakage of the chamber has little affect on the results presented in Figure 32.

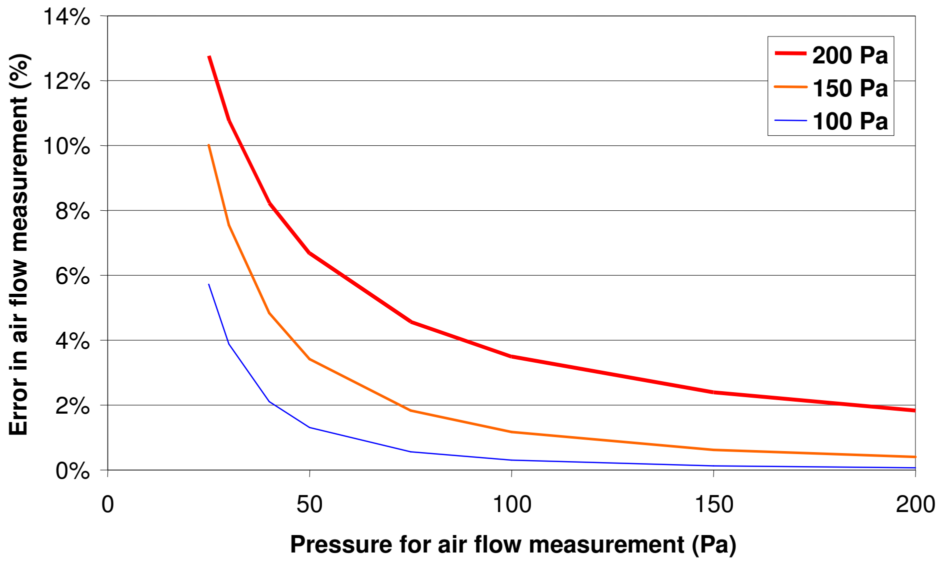


Figure 32: Influence of the ductwork pressure on the error of the airflow measurement at duct pressures of 100, 150 and 200 Pa.

By taking a fan pressure of 25 Pa, errors on the leakage airflow rate up to more than 10% can be made (overestimation of the leak).

6.2.6 Measurement uncertainties

It may be required to evaluate the level of accuracy of the measurements for certification, quality assurance, or research purposes. This is a complex field of study when the quantities to be defined are not directly measured (e.g. leakage flow at a reference pressure). Sherman and Palmiter (1995) have raised this issue for fan-pressurisation measurements. A pre-standard on building airtightness (ISO 9972) proposes a method to evaluate random errors (noise) alone. However, neither bias errors (i.e. systematic departures from the reference value), nor errors due to the model approximations are taken into account in this pre-standard. Attempts can be made to evaluate systematic errors based on numerical (Monte-Carlo) analyses, i.e. by assessing the impact of the modification of the measured values (pressure and flow rate) by values set according to the accuracy of the devices. The problem often lies in setting those values as bias errors are usually highly correlated.

6.3 Leak detection

Leak detection can be particularly useful for rehabilitation purposes. It is used to rapidly and reliably identify the location of duct leaks. Seven main techniques are used.

6.3.1 Smoke detection

Visible smoke is injected into the pressurised ductwork and escapes through the leaks. The detection is easy when the ducts are accessible. This method is commonly used in building applications. If a significant air barrier separates a substantial portion of the system from the conditioned spaces, a blower-door may be used to pressurise both the building and the ductwork. The air system is switched off and fresh air intakes as well as exhausts are sealed. The smoke is released (with a smoke stick) near each register. A large draft into the system indicates that air leaks to outside near that register. This method is commonly called the *smoke stick method.*

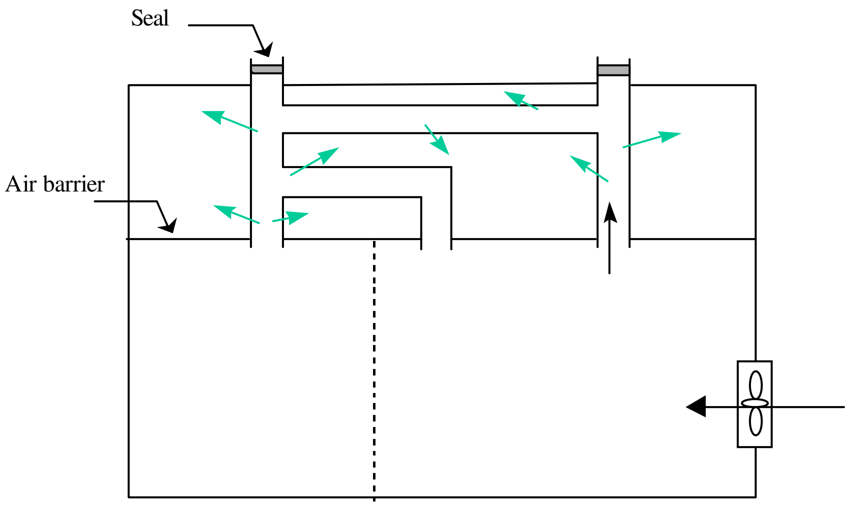


Figure 33: Blower-door set-up for smoke stick method.

6.3.2 Soap bubbles

The ductwork is pressurised and liquid soap is applied on the exterior surface. Bubbles appear at the leaks.

6.3.3 Pressure pan

The set-up and restrictions are the same as for the smoke stick method. A cake pan that has a pressure tap is used to cover each register one at a time (Davis and Roberson, 1993). If the pressure across the pan is high, this means that large leaks to outside are near that register. This method is commonly called the *pressure pan method.*

6.3.4 Blocked register pressure

A fan is used to pressurise the ductwork. All the registers are blocked and the pressures across the register seals are recorded using a small probe. The lowest pressure drop indicates potentially large leakage near that register.

6.3.5 Foam injection

Foam is injected in the pressurised ductwork and produces bubbles at the leaks. Similarly, special bubbles that produce foam at the leaks can be injected. The foam generally comes in ready-to-use pressurised cans.

6.3.6 Video camera inspection

A video camera is set up on a rolling mechanical cart and transported through the ductwork system. This technology is mainly used in cleaning procedures as it is possible to visualise the dust accumulated on the interior surfaces; however, one may take advantage of the cleaning procedure to detect major leaks. Restrictions apply to the dimensions and shape of the duct (small ducts, bends or wyes) and small leaks are difficult to detect.

6.3.7 Aerosol duct sealing

An aerosol of sealant particles is injected into the pressurised ductwork. The sealant particles find and seal the leaks automatically because of the pressure-driven flow. This method is described in more details in § 4.4.

6.4 Overview of existing European measurements

Among the member states, Sweden is probably the most advanced on this issue. Nearly every duct system is leak-tested and airtightness Class C (see EUROVENT 2/2) is commonly required and fulfilled in new installations. The situation appears to be quite different in the other European countries. Tests are very seldom performed in standard buildings, and thus the knowledge about the ductwork airtightness mainly relies on a few studies.

In the UK, Babawale *et al.* (1993) have investigated one forced air-heating system and have come to worrying conclusions in terms of energy use and comfort conditions. They recommend a research effort to ascertain the extent and impact of duct leakage in new and old building stock in the UK, especially when the ducts run through unconditioned spaces. However, such installations are not used very much in European countries in general. In Belgium, Ducarme *et al.* (1995) monitored a demand-controlled ventilation (DCV) system installed in an office building in 1993. It was shown that the ductwork airtightness is a key aspect for fully benefiting from the energy savings potential of the DCV. In this specific case, the initial ductwork airtightness was so poor that no savings at all could be achieved: whatever the demand was, the same airflow rate was supplied to the building, either to the occupied offices or to the corridor through the leaks. Afterwards, it proved to be very difficult and time consuming to improve the ductwork airtightness so as to meet EUROVENT Class A. Figure 34 shows the effect of different sealing activities on the airtightness of the ductwork. It is worthwhile mentioning that the working pressure of the system is about 100 Pa and the nominal ventilation airflow rate is about 180 l/s (650 m³/h), which means that in the initial situation the fan had to provide about 360 l/s (1300 m³/h) instead of 180 l/s (650 m³/h) !

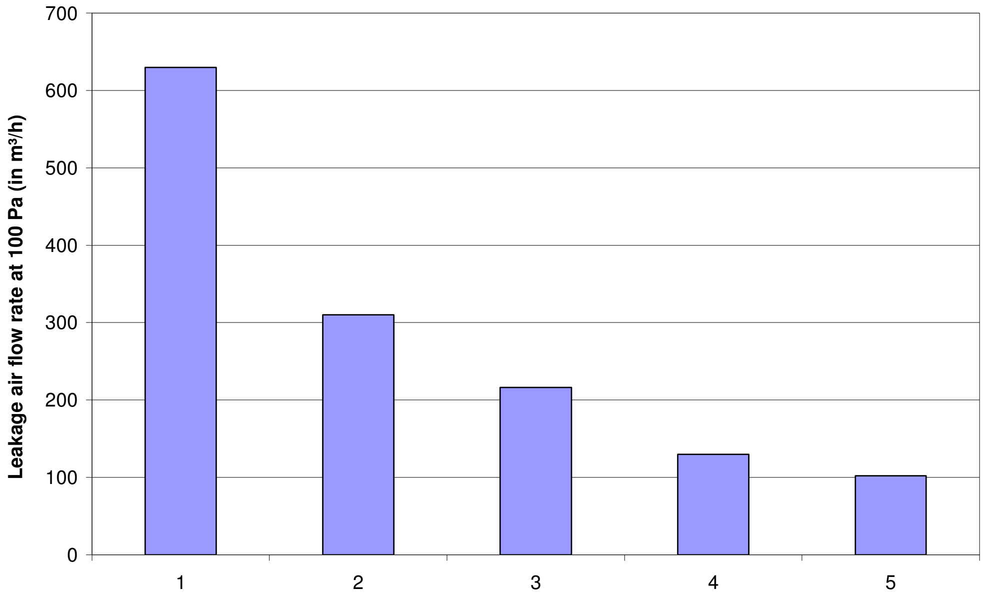


Figure 34: Systematic improvement of the airtightness of the ductwork in a Belgian office building with demand-controlled ventilation.

Pittomvils *et al.* (1996) investigated in detail, balanced ventilation systems equipped with heat recovery used in more than 170 very low energy houses built in the Flemish Region of Belgium by field and laboratory testing. The ductwork was so leaky that about one third of the air supplied by the fan at medium speed escaped through leaks before even reaching the ventilated rooms.

In France, Riberon *et al.* (1992) found "insignificant" duct leakage in 19 new single-family houses. However, Carrié *et al.* (1996) measured very large leakage rates in 9 duct systems in multi-family buildings, 8 in schools, 2 in a day-care centre, and 3 in office buildings. Their analyses show potentially large indoor air quality and energy use impacts at a national level.

6.5 Field measurements on 22 duct systems in France

This paragraph focuses on the field study conducted by CETE Lyon and ENTPE (Carrié *et al.*, 1996) that was funded in part by Ademe, and which is the basis of the SAVE-DUCT project. The sample included 9 duct systems in multi-family buildings (4 to 5 storeys), 8 in schools, 2 in a day-care centre, and 3 in office buildings. All of the buildings were located in the vicinity of Lyon, France. Significant deficiencies were observed, as shown in Figure 35.

Figure 35: Photograph of poorly installed duct connections.

The results are represented in Figure 36, and summarised in Table 15. It appears that the flow exponent has an average value considerably different from 0.65. Furthermore, it is found that except for one system, none can be classified according to the EUROVENT 2/2 airtightness classes. *K* is on average well above that of Class A ($K < 0.027\ 10^{-3}$ m s^{-1} $Pa^{-0.65}$).

	Flow exponent *n* (-)	*K* (l s^{-1} m^{-2} $Pa^{-0.65}$)	ELA_{100}/A (cm^2/m^2)
Multi-family buildings (9)	0.59 (0.05)	0.125 (0.050)	2.0 (0.8)
Non-residential buildings (13)	0.57 (0.04)	0.066 (0.035)	1.0 (0.5)

Table 15: Duct leakage field measurement results. Average values of n, K, ELA_{100}/A. The standard deviations are shown in parenthesis.

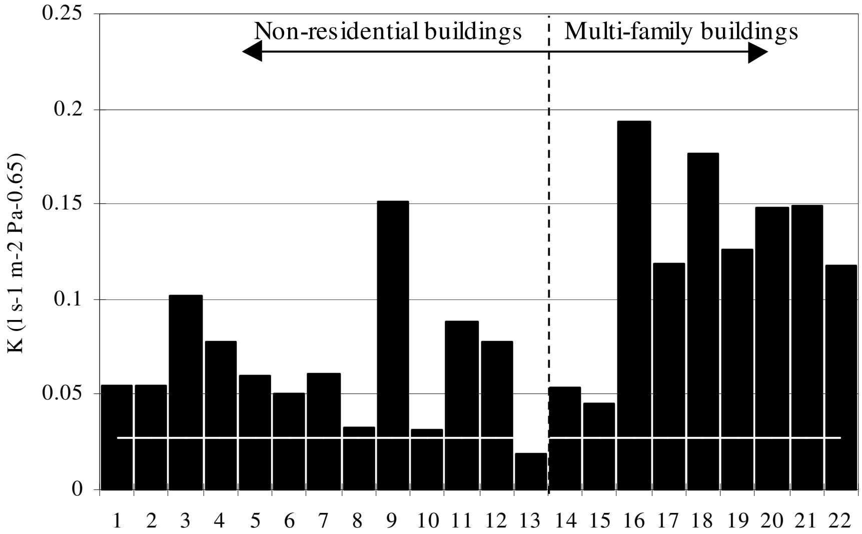


Figure 36: Duct leakage field measurements - Leakage coefficients.

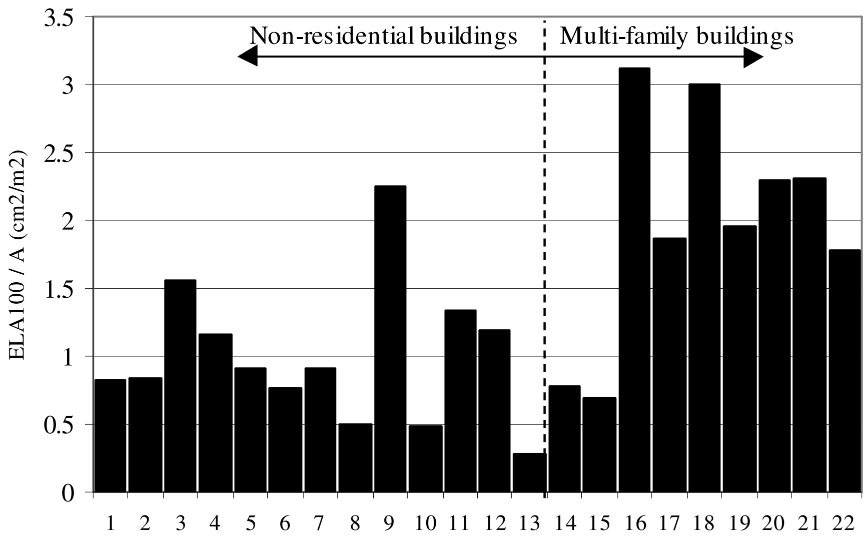


Figure 37: Duct leakage field measurements - ELA at 100 Pa normalised by the (tested) duct surface area.

6.6 Overview of duct leakage status in US buildings

Outside Europe, field studies have been conducted mainly in US residences. In the southern regions of this country, a typical residential forced-air distribution system has supply and return flexible plastic ducts in unconditioned spaces, but no outdoor air intake or exhaust (Figure 38). In the northern regions, rectangular sheet-metal trunk ducts with round sheet-metal branch ducts is most likely. The primary goal of these systems is to heat or cool the building spaces while fresh (ventilation) air is provided by other means (e.g. infiltration through the building shell or local exhaust).

Over the past ten years, effective leakage areas have been measured in many residences for certification, retrofit, or research purposes. According to Lawrence Berkeley National Laboratory field studies, effective leakage areas for plastic flexduct systems are found to be typically of the order of 1.3 cm^2 (ELA_{25}) per m^2 of floor area (Jump and Modera, 1996), which translates into about 5 cm^2 per m^2 of duct surface area (Modera, 1998) i.e. more than 12 times leakier than tightness Class A. Major deficiencies (worn tape, torn or damaged ducts) are frequently encountered. Moreover, the area-normalised leakage of typical sheet-metal duct systems in basements is approximately twice that which is found in plastic flexduct systems.

Research has quantified the impacts of US residential duct system leakage on HVAC energy consumption and peak electricity demand. A typical California house with ducts located in the attic or crawlspace wastes approximately 20 % of heating and cooling energy through leaks and draws approximately 0.5 kW more electricity during peak cooling periods (Modera, 1993). Therefore, significant efforts have been undertaken on retrofitting techniques (Jump *et al.*, 1996; see also aerosol-based technique in chapter 4).

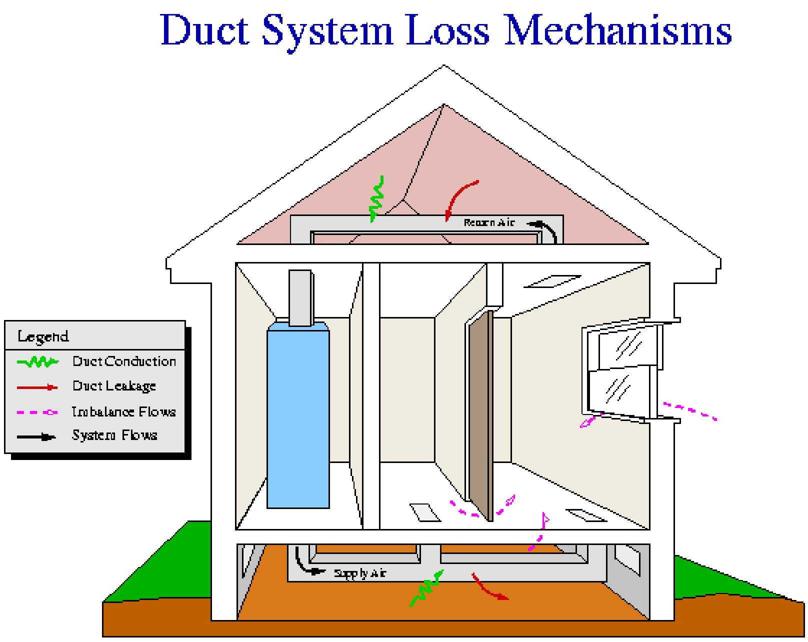


Figure 38: Typical US residential duct system (courtesy Lawrence Berkeley National Laboratory).

More recent research at LBNL has been focused on "light commercial buildings" - primarily one- and two-storey buildings with individual HVAC package roof-top units serving floor areas less than 1000 m^2 - that represent a large fraction of the building stock in the US (Delp *et al.*,1997). These systems use duct materials and construction techniques similar to residential systems. Although the ducts are most often located in a drop ceiling, the primary thermal barrier is frequently found at the ceiling tiles, in which case the ducts are entirely outside the conditioned space. However, little is known about the performance of these systems. Duct leakage measurements were performed in 43 buildings by the Florida Solar Energy Center (Cummings *et al.*, 1996) and on 15 systems by the Lawrence Berkeley National Laboratory (Delp *et al.*,1997). In both studies, effective leakage areas were found to be significantly greater than those for residential duct systems (Figure 39).

Field data from large commercial buildings is in very short supply, however, evidence suggests that they are leaky as well (Modera, 1998).

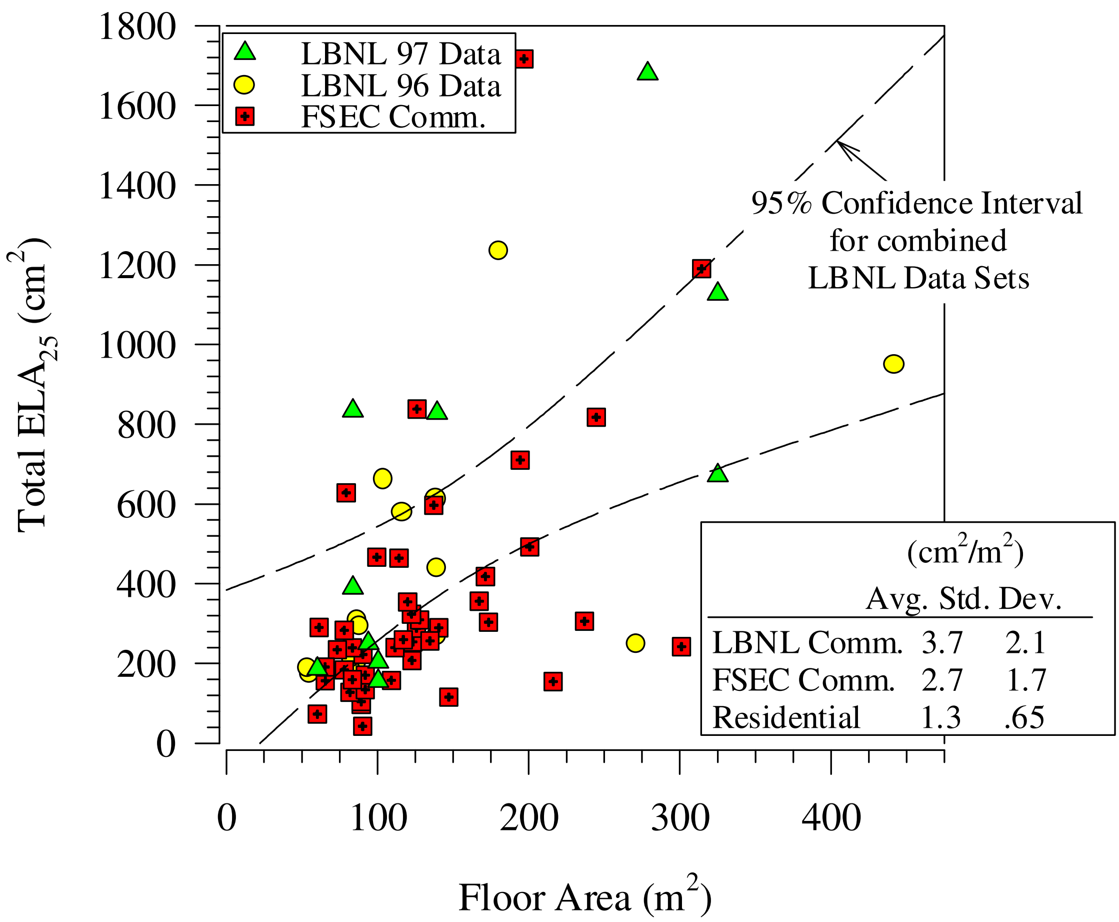


Figure 39: Combined leakage area (ELA_{25}) –vs- floor area using LBNL (Delp et al.,1997) and FSEC (Cummings et al., 1996) commercial data along with residential (Jump et al. 1996) summary information. Combined leakage areas includes both supply and return leakage. Graph from (Delp et al.,1997).

6.7 SAVE-DUCT measurements

In the framework of the SAVE-DUCT project the airtightness of 42 ductwork systems was measured in France (21) and Belgium (21). In Sweden, nearly all installations are leak-tested commissioning and as a consequence a lot of data is already available. Therefore, a randomly selected sample of 69 Swedish control measurements was collected.

6.7.1 Protocol

In Belgium and in France, the multi-point ductwork pressurisation method was used, i.e. the ductwork was pressurised at different pressure stations to calculate the leakage characteristics of the systems. The test was performed at pressures in the range of 50 % - 150 % of the operating pressure of the ductwork. In Sweden however, the measurement procedures are performed according to a different protocol. The one-point measurement method with an arbitrary flow exponent of 0.65 is used.

6.7.2 Belgium

Table 18 gives an overview of the 21 Belgian systems involved in the study and the results of the measurements. The sample included 12 ductwork systems in non-residential buildings, 5 in multi-family buildings, and 4 in single-family houses. The ductwork of all systems, except one (of concrete), consists of sheet-metal.

The results are represented in Figure 40, and summarised in Table 16. It appears that although the flow exponent has an average value close to 0.65 (0.64), it ranges from 0.55 to 0.73 and the standard deviation is large. It is clear that the majority of the systems have rather bad airtightness; only 4 systems fulfill the Class A requirement and one system reaches Class B. In Figure 40 a distinction is made between rectangular ductwork, circular ductwork, ductwork where a plenum is used for the connection at the registers and concrete ductwork. In this sample, rectangular ductwork is on average about 7 times leakier than circular ductwork. The positive effect of the use of circular ductwork seems to be partly lost if the registers are connected to the ductwork with plenums (see later in this chapter).

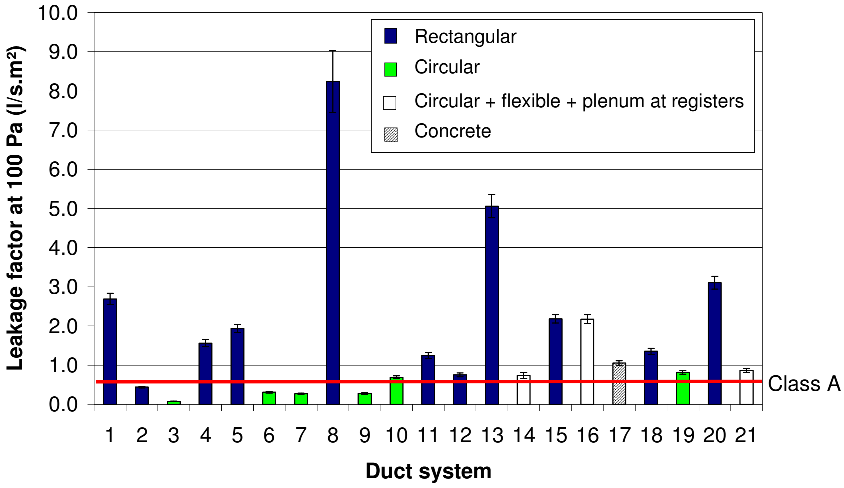


Figure 40: Leakage factor at 100 Pa for the investigated systems in Belgium.

	Flow exponent n (-)	f_{100} ($l\ s^{-1}\ m^{-2}$)
Non-residential buildings (12)	0.64 (0.05)	2.30 (2.34)
Multi-family buildings (5)	0.60 (0.05)	0.84 (0.40)
Single-family houses (4)	0.66 (0.03)	1.02 (0.86)

Table 16: Duct leakage field measurement results (Belgium only). Average values of n and f_{100}. The standard deviations are shown in parenthesis. Maximum f_{100} for Class A is 0.54 l/s per m^2.

6.7.3 France

Table 19 gives an overview of the 21 French systems involved in the study and the results of the measurements. The sample included 8 ductwork systems in non-residential buildings, 9 in multi-family buildings, 4 in single-family houses. The ductwork of all systems were made of sheet-metal.

The results are represented in Figure 41, and summarised in Table 17. The flow exponent ranges from 0.50[5] to 0.68. The average value is 0.60 with a standard deviation of 0.06. The airtightness of most of the systems did not meet Class A; only one system reaches Class B. The systems' airtightness in office buildings seems to be much better than that in multi-family buildings and single-family houses. This is probably due to the fact that, in the latter, the tested duct area is much smaller and, as a consequence, a small leak will have a larger impact on the leakage factor.

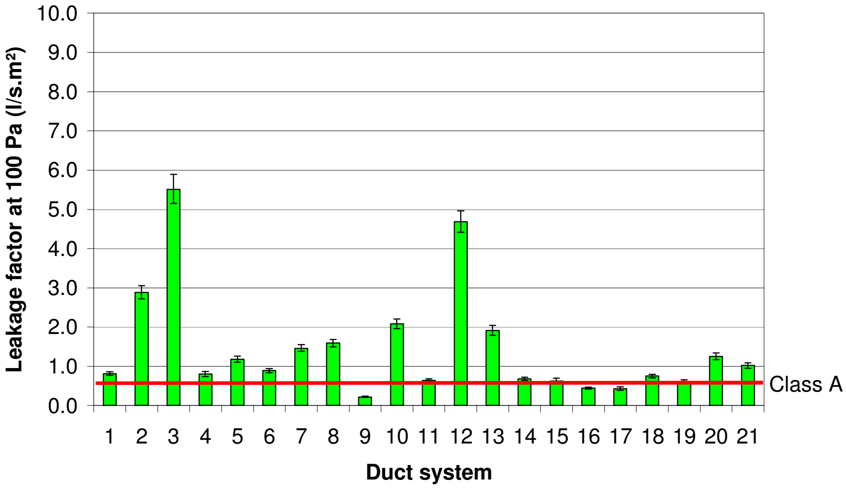


Figure 41: Leakage factor at 100 Pa for the investigated systems in France.

	Flow exponent n (-)	f_{100} ($l\ s^{-1}\ m^{-2}$)
Non-residential buildings (8)	0.59 (0.07)	0.72 (0.28)
Multi-family buildings (9)	0.58 (0.07)	1.73 (1.63)
Single-family houses (4)	0.63 (0.04)	2.36 (1.76)

Table 17: Duct leakage field measurement results (France only). Average values of n and f_{100}. The standard deviations are shown in parenthesis. Maximum f_{100} for Class A is 0.54 l/s per m^2.

[5] In two cases, a value lower than 0.50 was calculated, which is not physically possible. It is probably due to large measurement errors.

N°	Building type	Age of system	System type	∅ or R	Connections	Tested area (m²)	C (l/s per m²)	n (-)	f_{100} [(1)] (l/s per m²)	ELA_{100} (cm²/m²)	Design flow rate [(2)] in test section (l/s)
1	N	2 years	S (demand controlled)	R	F+G	64.0	0.102	0.71	7.20 (× ÷ 1.06)	2.09	180
2	N	2 years	S (demand controlled)	R	F+G+T	64.0	0.025	0.62	1.03 (× ÷ 1.05)	0.34	180
3	N	New	S (demand controlled)	∅	G	64.2	0.004	0.64	0.19 (× ÷ 1.06)	0.06	180
4	I	3 years	S	R	?	8.3	0.060	0.71	4.15 (× ÷ 1.06)	1.20	48
5	I	3 years	E	R	?	7.7	0.092	0.66	4.88 (× ÷ 1.06)	1.50	56
6	I	New	S	∅	S+T	13.0	0.016	0.64	0.74 (× ÷ 1.06)	0.17	27
7	I	New	E	∅	S+T	7.2	0.014	0.64	0.65 (× ÷ 1.06)	0.21	33
8	N	New	E	R	F+M	44.3	0.2873	0.73	22.46 (× ÷ 1.11)	6.33	392
9	M	New	E	∅ + F	S+T	5.3	0.011	0.67	0.65 (× ÷ 1.07)	0.20	150
10	M	New	E	∅	S+T	10.0	0.042	0.61	1.60 (× ÷ 1.06)	0.54	200
11	N	15 years	S	R	F+T	20.6	0.073	0.62	2.91 (× ÷ 1.06)	0.96	291
12	N	1 year	E	R	F+G	13.3	0.032	0.69	1.98 (× ÷ 1.07)	0.59	17
13	N	New	S	R + ∅	F+G (R) S+T (∅)	30.1	0.311	0.61	11.75 (× ÷ 1.06)	3.98	489
14	N	6 years	E	∅ + F	S+T	37.4	0.037	0.65	1.80 (× ÷ 1.11)	0.56	103
15	N	???	E	R	F+G	33.5	0.156	0.57	4.87 (× ÷ 1.05)	1.71	308
16	N	New	E	∅ + F	S+T	14.8	0.096	0.68	5.56 (× ÷ 1.06)	1.69	142
17	M	New	Smoke evacuation	R **concrete**	Cement	30.4	0.085	0.55	2.25 (× ÷ 1.05)	0.80	?
18	M	New	E	R	F+G	121.2	0.078	0.62	3.19 (× ÷ 1.06)	1.05	2275
19	M	New	E	∅	S+T	17.9	0.062	0.56	1.79 (× ÷ 1.07)	0.64	256
20	N	???	E	R + ∅	F+G	15.8	0.230	0.56	6.76 (× ÷ 1.06)	2.39	250
21	N	New	S	∅ + F	G (double)	21.2	0.056	0.60	1.98 (× ÷ 1.06)	0.67	78

[1] Measurement error calculated with Monte-Carlo analysis is shown in parenthesis. [2] May be operating airflow rate where design airflow is not available.

Table 18: Overview of Belgian sample. Building type: N = non-residential, M = multi-family, I = single-family. System type: E = exhaust, S = supply. ∅ or R: ∅ = circular, R = rectangular, F = flexible. Connections: S = screws, T = tape, G = gasket, F = flange, M = mastic.

N°	Building type	Age of system	System type	∅ or R	Connections	Tested area (m²)	C (l/s per m²)	n (-)	f_{100} [1] (l/s per m²)	ELA_{100} (cm²/m²)	Design flow rate [2] in test section (l/s)
1	M	New	E	∅ + F	S+M+T; S+T; T	14.8	0.049	0.61	0.81(× ÷ 1.06)	0.61	179
2	M	New	E	∅	S+M; M	2.9	0.210	0.57	2.88 (× ÷ 1.06)	2.17	83
3	M	New	E	∅	S+M+T; S+M; T	1.6	0.388	0.58	5.51 (× ÷ 1.07)	4.15	25
4	M	New	E	∅ + F	G; S+T; S+M; T	28.3	0.045	0.63	0.8 (× ÷ 1.08)	0.61	318
5	M	New	E	∅	S+M	14.1	0.052	0.68	1.18 (× ÷ 1.07)	0.89	125
6	M	New	E	∅	T; S+ T+M	6.2	0.045	0.65	0.89 (× ÷ 1.06)	0.68	83
7	M	New	E	∅	S+T	16.2	0.165	0.48	1.46 (× ÷ 1.06)	1.12	175
8	M	New	E	∅	S+T+M; S+T	23.2	0.113	0.58	1.59 (× ÷ 1.06)	1.22	125
9	M	New	E	∅	G; S+M	2.9	0.024	0.47	0.22 (× ÷ 1.08)	0.16	25
10	I	New	E	F	T	1.2	0.142	0.58	2.08 (× ÷ 1.06)	1.57	8
11	I	New	E	F	T	2.2	0.032	0.65	0.64 (× ÷ 1.06)	0.49	33
12	I	New	E	∅	G; S+M	1.5	0.253	0.64	4.68 (× ÷ 1.06)	3.57	46
13	I	New	E	∅	G; S+M	2.15	0.093	0.66	1.91 (× ÷ 1.07)	1.44	50
14	N	1 year	E	∅ + F	G; S+T; T	80.25	0.067	0.50	0.68 (× ÷ 1.06)	0.51	817
15	N	1 year	E	∅ + F	G; S+T; T	80.25	0.034	0.63	0.62 (× ÷ 1.12)	0.47	817
16	N	New	S	∅	G+C	35.4	0.028	0.60	0.44 (× ÷ 1.06)	0.33	833
17	N	1 year	E	∅ + F	S+T; S+M; T	57.9	0.025	0.62	0.43 (× ÷ 1.10)	0.33	211
18	N	1 year	E	∅ + F	M+T+S; T; S+M	36.3	0.055	0.56	0.75 (× ÷ 1.06)	0.56	294
19	N	1 year	E	∅ + F	T; S+T	31.2	0.026	0.68	0.61 (× ÷ 1.07)	0.46	31
20	N	1 year	E	∅ + F	S+T; T	54.7	0.119	0.51	1.25 (× ÷ 1.07)	0.95	667
21	N	New	E	∅ + F	C+T; M+T	34.2	0.051	0.65	1.02 (× ÷ 1.07)	0.77	181

[1] *Measurement error calculated with Monte-Carlo analysis is shown in parenthesis.* [2] *May be operating airflow rate where design airflow is not available.*

Table 19: Overview of French sample. Building type: N = non-residential, M = multi-family, I = single-family. System type: E = exhaust, S = supply. ∅ or R: ∅ = circular, R = rectangular, F = flexible. Connections: S = screws or rivets, T = tape, G = gasket, F = flange, M = mastic, C= Collar.

6.7.4 Sweden

As already mentioned before, the airtightness of new Swedish installations for air distribution has to be checked at commissioning (since the 1983 version of VVS AMA: see § 3.3.2). This means that many measurement data are available from Swedish installations. Therefore it was not necessary to perform additional measurements in the framework of the SAVE-DUCT project. The measurement results from a randomly selected group of 69 installations were collected. In Sweden, the one-point measurement procedure is used at commissioning. The reference pressure is usually set to 400 Pa and a flow exponent of 0.65 is assumed. Figure 42 represents the f_{400}-values of all selected duct systems.

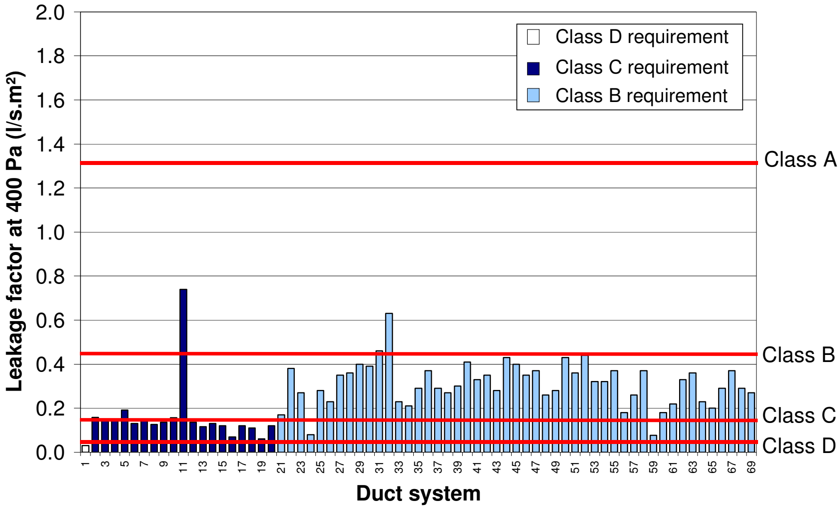


Figure 42: Leakage factor at 400 Pa for 69 duct systems in Sweden. Leak-tests performed at commissioning.

Nearly all new Swedish installations have to comply with airtightness requirements detailed in AMA 83 (see § 3.3.2) that depend on their type. In Figure 42 three groups of ductwork are represented: one system has to comply with Class D, 19 systems with Class C, and 49 with Class B. Most of the installations seem to meet the requirements, only 3 do not. It is noteworthy that installations that do not fulfil the requirements have to be tightened until they do; consequently, the 3 "bad" installations should eventually have at least the desired airtightness. In contrast with the Belgian measurements, which revealed that the airtightness of rectangular ductwork is generally worse than the airtightness of circular ductwork, there seems to be no significant difference between circular and rectangular ductwork in Sweden (Table 20).

Type of ductwork	Average f_{400} (l/s.m²)	
	Sweden	Belgium
Rectangular	0.30 (16)	6.47 (11)
Circular	0.26 (38)	0.94 (6)
Rectangular / circular	**1.15**	**6.90**

Table 20: Rectangular versus circular ductwork in Sweden and Belgium (the values between brackets represent the number of ductwork tested).

6.7.5 Comparison between the 3 countries involved in the study

➢ Leakage factors

The results from the different countries are compared in Figure 43. The determination of the classes was done on the basis of the f_{400}-value[6]. As the airtightness in France and Belgium is often much worse than Class A, additional classes were created based on the geometric progression of the existing classes (i.e. with a factor of 3).

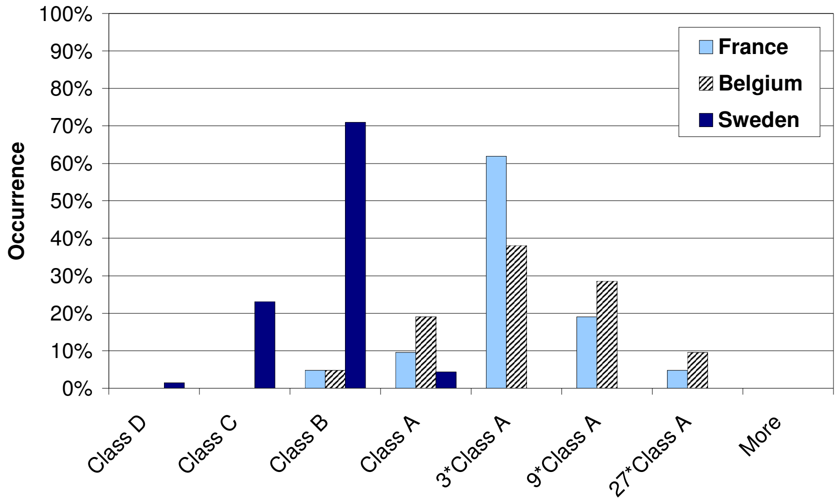


Figure 43: Occurrence of the different tightness classes. Based on 21 systems in Belgium, 21 in France, and 69 in Sweden. Each stack represents the relative number of systems that comply with the specified Class.

It is obvious that the situation in Sweden is by far the best: more than 95 % of the systems comply with Class B or better at commissioning; the remaining achieve Class B after improvement. The results from France and Belgium are comparable: most of the systems have an airtightness in the region of Class A to 9 * Class A. An airtightness better than Class A seems to be rather unusual in these countries. To give a better idea of the physical meaning of these results, the average leakage areas are represented in Figure 44. In Belgium and France the average ELA_{100} seems to be higher than 1 cm² per m², while in Sweden it is lower than 0.1 cm²/m².

[6] Belgian and French measurements were extrapolated to 400 Pa.

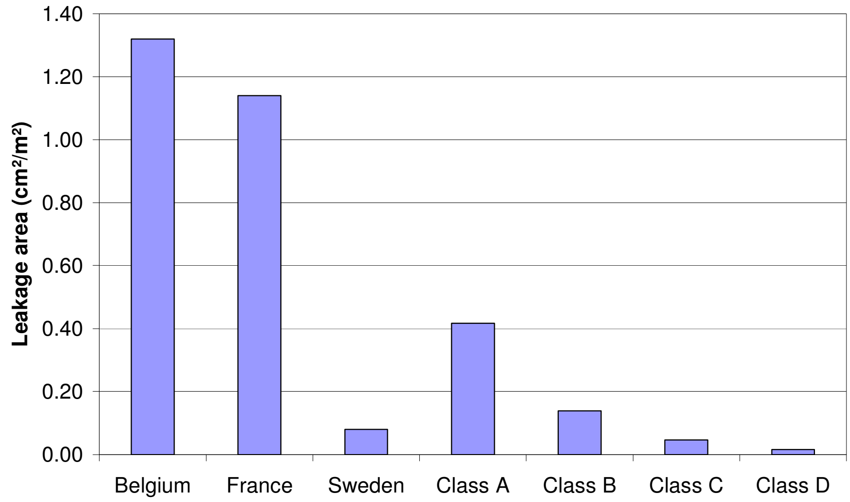


Figure 44: Average leakage area per m² (ELA_{100}/A) for the different countries and comparison with leakage area for the classes A, B, C and D.

➢Flow exponents

Figure 45 is a histogram representing the flow exponents of the Belgian and French results[7]. Although the average value is close to 0.65 (0.62), there is a significant spread in the data (standard deviation: 0.06).

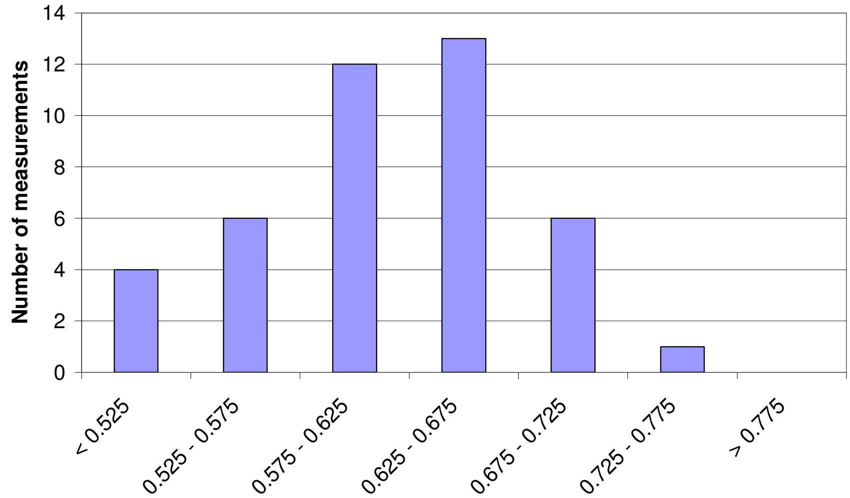


Figure 45: Histogram of the flow exponents of the Belgian and French measurements.

This can lead to significant errors when the test pressure is considerably different from the leakage factor reference pressure. In Figure 46 for instance, due to a flow exponent of 0.50, the installation does not comply with Class A at 10 Pa; the same installation complies with Class A at 1000 Pa.

[7] In Sweden the airtightness class is determined by a one-point measurement procedure, assuming a flow exponent of 0.65.

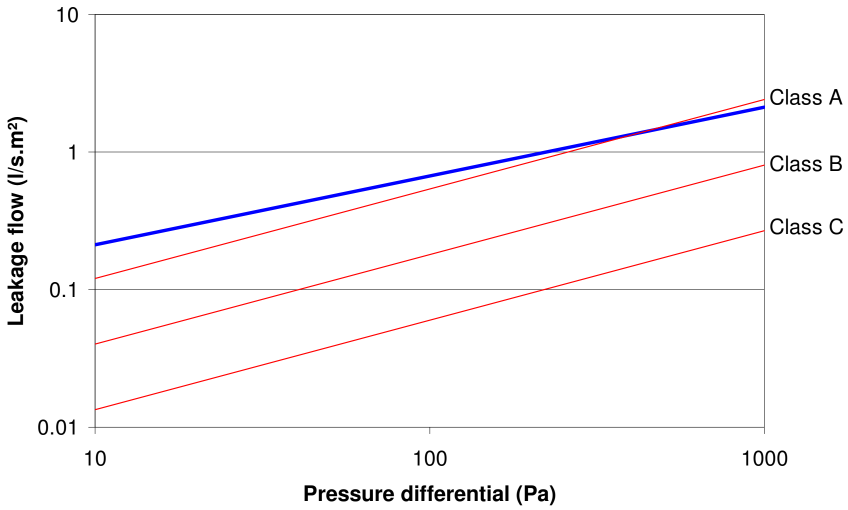


Figure 46: Influence of flow exponent on classification (building 14 of the French sample).

6.7.6 Air distribution impacts

Figure 47 shows the ratio of the leakage airflow rate (at 100 Pa [8]) to the design airflow rate[9], expressed as a function of the leakage factor (f_{100}).

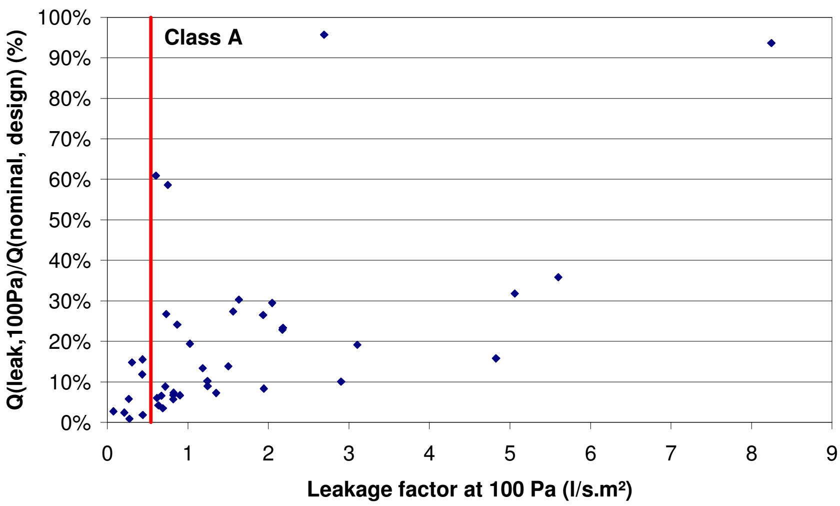


Figure 47: Ratio between leakage airflow rate (at 100 Pa) and design airflow rate as a function of f_{100} (l/s.m²).

The following conclusions can be drawn:

- In some cases the leakage airflow rate can be comparable to the design airflow rate (assuming a pressure of 100 Pa);
- On average, the leakage airflow rate is of about 20 % of the design airflow rate (again assuming an operating pressure of 100 Pa);

[8] Since the operating pressure could not be measured in some new installations, leakage flow rates are estimated at 100 Pa which is close to the design operating pressure of many European systems. The implications of this choice are discussed below.
[9] Where for some reason, the data is not available, the measured airflow rate is used.

- The effectiveness of the air distribution **does not depend uniquely on the leakage factor**. A system with an “acceptable” leakage factor can have a significant leakage airflow rate compared to the design airflow rate. In Figure 47, one can see a system case where Class A is achieved although the ratio is of 60 %. Conversely, some systems that do not comply with Class A can have a relatively low leakage flow rate;
- Other parameters should be taken into account to evaluate in more detail the air distribution impacts of leaky ducts, e.g. energy losses through increased fan and ventilation load. These include the type of system (heating, cooling or ventilating), the location of the leaks, the operating pressure and surface area of the ductwork, etc. (see chapter 7).

6.7.7 Sensitivity of leakage airflow rates to operating pressures

For the above calculations an operating pressure of 100 Pa was assumed. The magnitude of this pressure has a very important impact on the leakage airflow rate of a system. This is shown in Figure 48 where (for the Belgian and French results) the average of the ratio between the leakage airflow rate and the design airflow rate is calculated for different operating pressures.

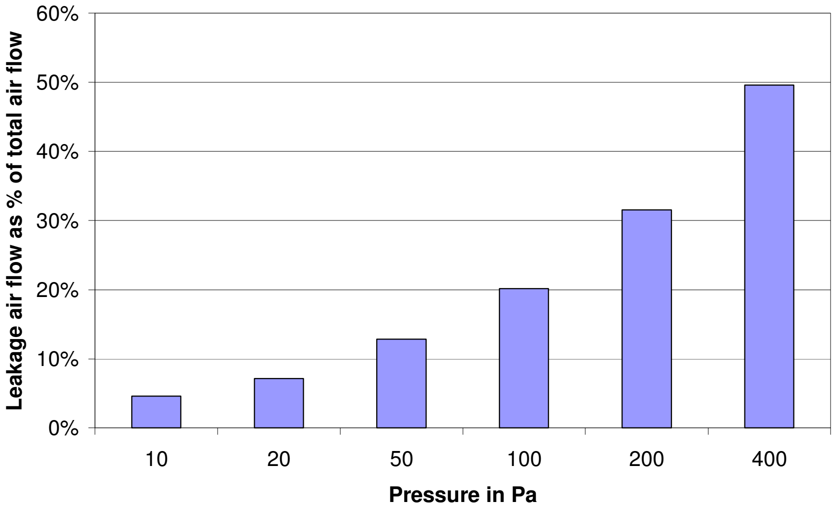


Figure 48: Influence of the operating pressure on the average ratio between leakage airflow rate and design airflow rate (for Belgian and French measurements).

Owing to this important impact, the requirement for ductwork airtightness depends on the operating pressure in some (national) standards (e.g. UK, Australia etc.). In some of the Belgian installations the operating pressure could be measured. Figure 49 shows the difference between the leakage airflow at 100 Pa and at the real operating pressure. Apparently, the pressure is lower than 100 Pa in most of the systems. In some cases the pressure is even lower than 10 Pa. This means that the leakage airflow rate was largely overestimated when a default 100 Pa operating pressure was taken. However, in such cases other issues, such as the problems to properly control the airflow rates at the registers, are likely to arise.

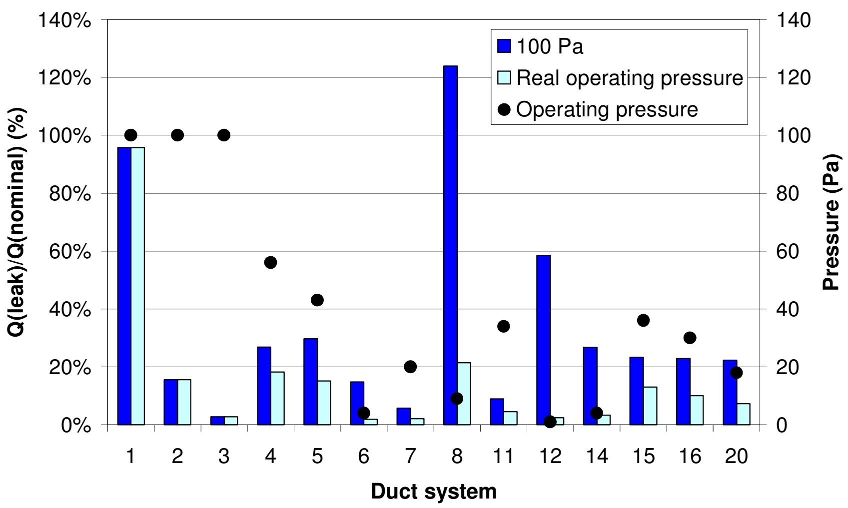


Figure 49: Comparison between leakage airflow rate at 100 Pa and at real operating pressure for some Belgian installations.

6.7.8 Some specific cases investigated in detail

➢Replacement of rectangular ductwork by circular ductwork

The Belgian field measurements revealed that rectangular ducts are generally much leakier than circular ones. However, the Swedish results showed that it is possible to achieve a similar airtightness with rectangular ductwork. It strongly depends upon the type of materials and the quality of the work. In the literature review, the steps towards the improvement of the airtightness of rectangular ductwork in a Belgian office building were explained (Ducarme *et al.*, 1995). After many person-hours of work, the leakage airflow rate could finally be reduced by a factor 6. As the leakage airflow rate still represented about 15 % of the nominal airflow rate, it was decided to replace the rectangular ductwork by circular ductwork on one of the two storeys of the building. The circular ducts had factory-fitted sealing gaskets (see chapter 4). Installation was fast and easy. Furthermore, the airtightness is excellent (Figure 50).

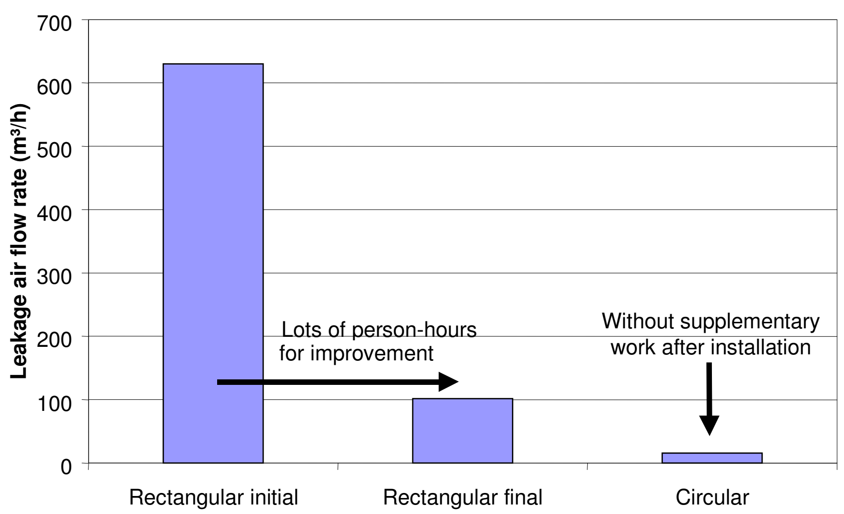


Figure 50: Impact of the replacement of rectangular ductwork by circular ductwork in a Belgian office building.

➢Influence of plenums on the airtightness

Sometimes plenums are used to make the connection between the registers and the ductwork. An example is shown in Figure 51. Usually the plenums are connected to the trunk ducts by flexible ductwork. In the Belgian sample, three duct systems of this kind were encountered. The measurements revealed that the airtightness of such installations is generally worse than duct systems without plenums.

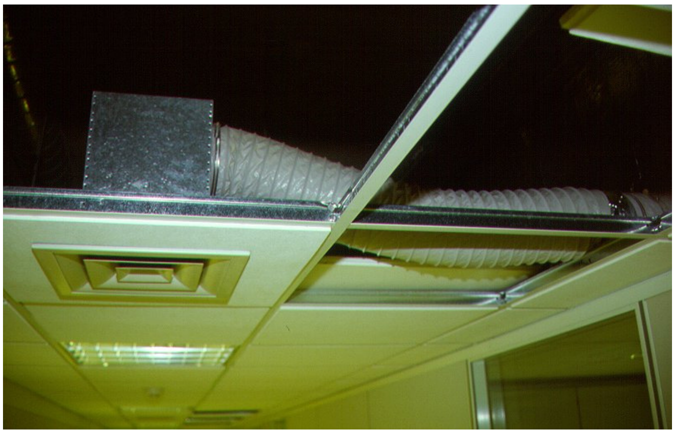


Figure 51: Registers connected to ductwork by plenums.

The contribution of the plenum on the total leakage was investigated in two systems of the Belgian sample. Two leakage measurements were performed: one with the plenums (by sealing the registers with tape) and without the plenums by disconnecting the flexible duct from the plenum and inflating a balloon at the end of the duct (see Figure 52).

Figure 52: Measurement with disconnected plenum (in this case plenum for linear register)

The results of both measurements are summarised in Table 21.

Building	ELA_{100} with plenums	ELA_{100} without plenums	Leakage of plenums (% of total)
16	24.8 cm²	5.4 cm²	78 %
21	14.2 cm²	4.8 cm²	66 %

Table 21: Contribution of plenums in total duct leakage. Leak tests performed with and without plenums in Belgian buildings.

It can be seen that, in both cases, most of the leaks are situated at the plenums. This could also be visualised using smoke. Leaks were encountered at the corners and the welds of the plenums. However, to evaluate the real contribution of the leaks at the plenums, the operating pressure in the plenums should be compared with the operating pressure in the trunk of the ductwork (see further).

➢Concrete ductwork

In Belgium, concrete ducts are regularly used for ventilation purposes, especially as exhaust ducts from “humid” rooms in apartments (shunt-type). In most of these cases ventilation is driven naturally, but sometimes a fan is connected to the ductwork on the top of the roof.
In the past, concrete ductwork seemed to have an unsatisfactory airtightness, mainly due to the fact that concrete ducts are constructed from small pre-fabricated concrete elements and, as a consequence, have many joints. The main advantage of small elements is the manageability, but to improve the airtightness there was a need for other installation techniques. It is clear that the leakage area can be decreased by reducing the number of joints or by assuring a better quality of the joints. A Belgian manufacturer of concrete duct elements opted for the last approach by starting the production of storey-high elements. Each element consists of several small elements which are put together in the factory. As opposed to the small pre-fabricated elements, it cannot be placed manually on site: a crane is needed. However, the airtightness of the pre-fabricated joints is much improved. Laboratory leakage tests on these storey-high elements showed that the airtightness seemed to be between Class A and Class B.

However, the small number of joints that have to be made at the building site are likely to have a major impact on the final airtightness. Indeed, a smoke test, which was performed on one system, showed that joints made on site were very leaky (unlike the prefabricated ones, see Figure 53). Furthermore, field measurements on this system showed that the concrete ducts were about 4 times leakier compared to laboratory measurement data (Table 22).

	Laboratory	Field measurement
f_{40} (l/s.m² at 40 Pa)	0.165	0.639
ELA_{40} (cm²)	6.1	23.8
Tightness Class (-)	Between A and B	Twice as leaky as Class A

Table 22: Comparison between laboratory test and field measurement for concrete ductwork. Test pressure for laboratory measurements was close to 40 Pa. A flow exponent of 0.65 is assumed to calculate f_{40} and ELA_{40}.

The presence of leaks at these joints may include:

- Use of inadequate material to make the joint on site;
- Bad instructions for the installers: e.g. elements placed too quickly on one another, yielding cracks in the joints during drying, etc.;
- Insufficient training of the installers, yielding bad application;
- Others.

Figure 53: Smoke visualisation of leaks in a concrete ductwork.

➢What should be taken as the reference pressure to evaluate duct leakage impacts?

The operating pressure in the ductwork plays a major role on the magnitude of duct leakage impact since it greatly affects the leakage flow rate (Figure 48). However, the determination of the operating pressure is not always trivial, because it depends strongly on where it is measured; it also requires a careful positioning of the probe in the air stream to avoid picking up some dynamic component. Therefore, one has to perform careful measurements at several places in the system, fairly close to the fan as well as at the end of the ductwork. If the pressure is relatively constant, the leakage airflow rate can be calculated using the average value.

When the pressure is not constant however, the determination of the leakage airflow rate becomes more complicated. As an example, in building 21 from the Belgian sample (Figure 40) in which the installation consists of circular sheet-metal ductwork with flexible ductwork for the shunts and plenums at the registers, a constant airflow regulator is included in the flexible duct. It is designed to ensure a constant airflow rate provided that the pressure drop across the device is kept within given limits. Typically, the operating pressure drop range for such device lies between 50 and 150 Pa. The actual measured pressure was:

- In the trunk duct: 160 Pa;
- In the plenums: ± 5 Pa.

As mentioned before, the airtightness of this installation was measured with and without the plenums and showed that most leaks were located at the plenums (Table 21). However, in this case, duct repairs at these locations will probably not improve the overall performance of the system as much as duct repairs in the rest of the system. Indeed, calculation of the "real" leakage airflow rates (at the operating pressures) shows that the plenums only have a limited impact i.e.:

- Leakage airflow main duct (at 160 Pa): 8 l/s (29 m³/h);
- Leakage airflow plenums (at 5 Pa): 1.9 l/s (7 m³/h) (approximately).

Thus, although 66 % of the total leakage area is located at the plenums, these leaks are responsible only for 20 % of the total leakage airflow! The total nominal airflow rate for the tested part of ductwork is 78 l/s (280 m³/h). This means that the leakage airflow of the main duct and the flexible connection represents about 10 % of the nominal airflow rate, while the leaks at the plenums only represent 2 % of the nominal airflow rate.

➢Comparison of the airtightness obtained with different connection systems

In a Belgian test house, a duct system was installed using different types of joints between the different elements. As the installer knew that airtightness measurements were planned, extra care was probably taken during the installation. Therefore the results are not included in the synthesis presented before. The ventilation installation consists of a mechanical supply in the "dry" rooms and a mechanical exhaust in the "humid" rooms. The unit consists of two fans and a heat exchanger. Three types of joints were used in the three different parts of ductwork:

- Fresh air intake: PVC-tape;
- Supply ductwork: rubber gasket;
- Exhaust ductwork: cold shrink tape.

An airtightness measurement was performed on each part. The results are represented in Table 23. It can be seen that the airtightness is rather good in all the cases. It is noteworthy that the airtightness is the best for PVC-tape sealed ducts. This can be explained by:

- The small tested area (only 2.5 m²), which makes it difficult to draw correct conclusions;
- The fact that the installer knew that tests were going to be performed, resulting in a better execution of the work.

About the same airtightness is achieved with cold shrink tape or pre-fitted rubber gaskets. It would be interesting to see how these results evolve in time. Also, it is important to note that for the interested parties, other aspects should be taken into account besides the airtightness performance alone, e.g.:

- Material cost;
- Labour cost;
- Life cycle cost.

Cost issues are discussed in chapter 7.

		Rubber gasket	Cold-shrink tape	PVC-tape
A	(m²)	10.2	6.4	2.5
Joints	(number)	25	18	5
C	(l/s.m² at 1 Pa)	0.0046	0.0042	0.0014
N	(-)	0.62	0.65	0.65[10]
Class	(at 400 Pa)	Class B	Class B	Class C
ELA_{100}	(cm²/m²)	0.062	0.067	0.022
ELA_{100}	(cm²/joint)	0.025	0.024	0.011

Table 23: Comparison of the airtightness obtained with different types of joints.

[10] This is an assumption; the leakage flow was measured at only one pressure station.

6.7.9 Conclusions from the SAVE-DUCT measurements

- Air distribution systems in Sweden seem remarkably tight compared to Belgian and French systems. This is probably due to the absence of performance requirements and control measurements in these countries. Since there is severe control in Sweden, most of the installations seem to comply with these stringent requirements at commissioning;
- Based on the Belgian measurements, it seems to be more difficult to obtain a good airtightness with rectangular ductwork. This does not seem to be the case in Sweden;
- The leakage factor normalised by the duct area is not sufficient to evaluate the air distribution impacts of leaky ducts. Among other important parameters are the operating pressure(s), the area of the ductwork and the ratio between the leakage airflow rate and the nominal airflow rate transported through the system;
- In Belgium and in France, the ratio between the average leakage airflow rate and the nominal airflow rate is of about 13 % at 50 Pa and 21 % at 100 Pa (both are pressures which are often found in European duct systems). There is room for improvement.

6.8 References

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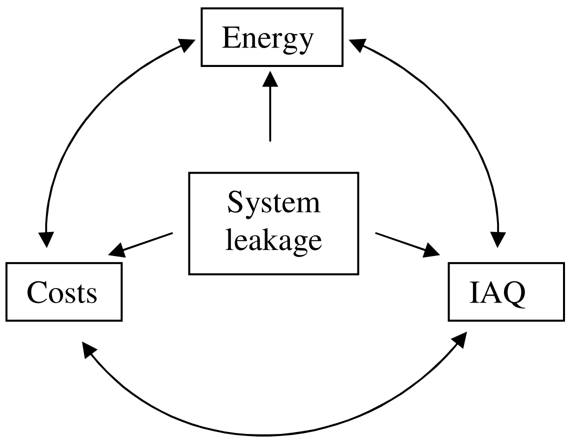
Chapter 7 Air distribution system leakage versus energy, indoor air quality and costs

Impact of duct leakage on ventilation rates

Peak load and energy use impacts

Indoor Air Quality

Costs



7.1 Summary and introduction

In general, designers, installers, building managers and building owners, mostly ignore the benefits of airtight duct systems. Field measurements suggest that over the years this has probably lead to very leaky systems in most European countries (see chapter 6). In fact, leakage rates up to 30 times greater than those of EUROVENT 2/2 Class C systems are commonly encountered. However, several studies have shown that duct leaks can significantly affect the ventilation rates in a building, which in turn modifies the amount of energy used for heating or cooling. Furthermore, as the fan power demand is a function of the airflow rate passing through it, additional energy losses may occur due to inadequate sizing and leakage airflow compensation. Poor airtightness can also contribute to the entry of pollutants and insufficient "effective" ventilation rates.

In summary, duct leakage is detrimental to energy efficiency, comfort effectiveness and indoor air quality. This chapter gives an overview of the methods that can be used to quantify those impacts. Several practical examples are discussed. Simple analyses on a balanced ventilation system with heat recovery show that the overall effectiveness of the system is reduced drastically when the ducts are leaky. Also, the cost implications of tight air ducts are discussed on an investment and Life Cycle Cost basis.

7.2 Impact of duct leakage on ventilation rates: some examples from the literature

Duct leakage can have a severe impact on the ventilation rates of a building, either directly when the desired airflow rates are not met at the registers, or indirectly, when the house pressure is affected (Figure 54).

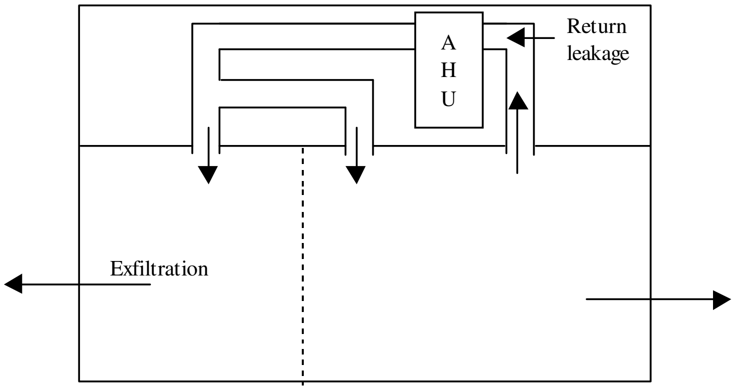


Figure 54: Effect of return leakage on exfiltration. Inversely, leaks on the supply side tend to de-pressurise the building.

In general, the infiltration rate can be estimated using the following equation (Sherman, 1980):

$$Q_{vent} = \sqrt{Q_{wind}^2 + Q_{stack}^2 + Q_{unbalanced}^2} + Q_{balanced} \qquad \textit{Equation 6}$$

where:

Q_{vent} is the total ventilation rate (m^3/s);
Q_{wind} is the wind-induced ventilation rate (m^3/s);
Q_{stack} is the stack-induced ventilation rate (m^3/s);
$Q_{balanced}$ is the balanced ventilation rate (m^3/s);
$Q_{unbalanced}$ is the unbalanced ventilation rate (m^3/s).

In the case described in Figure 54, this equation can be used to estimate the impact of leaky ducts. Then, $Q_{balanced}$ and $Q_{unbalanced}$ represent the balanced and unbalanced components of duct leakage, i.e.:

$$Q_{balanced} = \min\left(Q_{supply\ leakage}, Q_{return\ leakage}\right) \qquad \textit{Equation 7}$$

$$Q_{unbalanced} = \max\left(Q_{supply\ leakage}, Q_{return\ leakage}\right) - Q_{balanced}$$

Using Equation 6 for one residential forced-air heating system investigated in the UK, Babawale *et al.* (1993) found a significant contribution of the duct system leakage to the house infiltration:

- 0.1 air changes per hour (ach) when the ductwork is isolated from the house;
- 0.2 ach with ducting when the circulation fan is off;
- 0.5 ach with ducting when the circulation fan is on.

It should be noted that, in this system design, balanced leakage does not provide fresh air to the rooms. Thus, the total ventilation rate may be increased while the amount of fresh air delivered to the rooms decreases. In Belgium, Ducarme *et al.* (1995) monitored a demand controlled ventilation system (DCV) installed in an office building in 1993. Because of duct leakage, they observed large deviations between the measured and expected performances of the system.

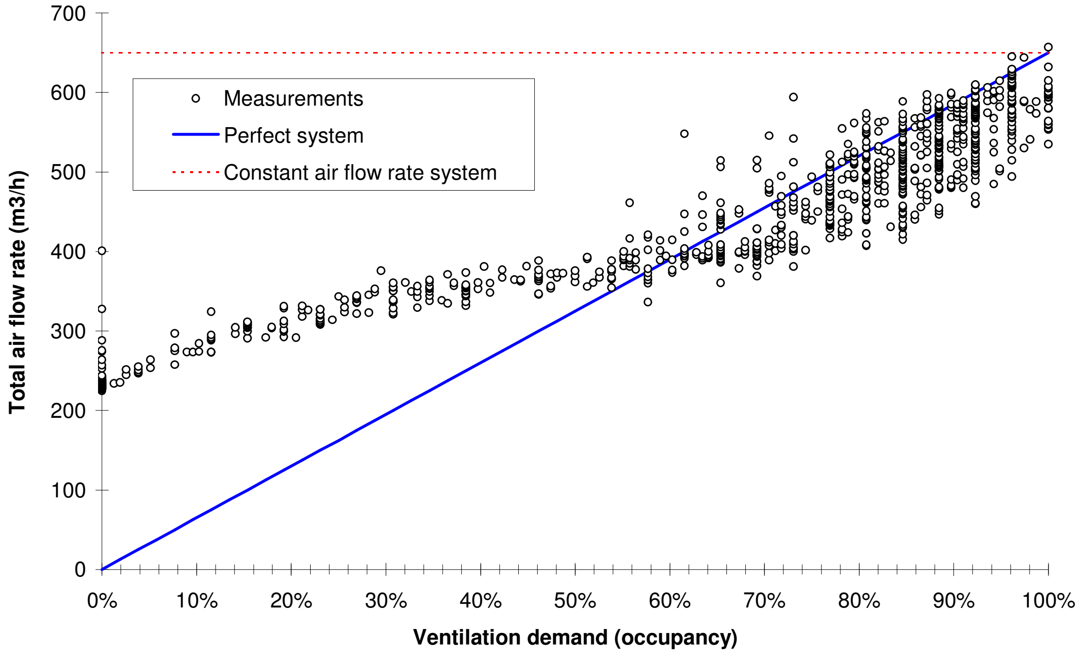


Figure 55: Airflow rate supplied as a function of the ventilation demand in a Belgian office building with demand-controlled ventilation.

As shown in Figure 55 the airflow rate is much higher than expected at low ventilation demands, which is due to a combination of incorrect pressure control (the system should keep the pressure between 70 Pa and 130 Pa, but values up to 180 Pa are measured) and ductwork leakage. The total airflow rate becomes closer to the expected airflow rate as the ventilation demand increases, which is due to a decreased pressure in the ductwork.

In France, Carrié *et al.* (1996) found that the ratio between the leakage airflow rates measured in 9 multi-family buildings and the minimum airflow rates set by the French regulation was an average of 13 % (Figure 56). Although they have not performed detailed ventilation measurements, these numbers suggest that the total ventilation rates of the buildings are affected.

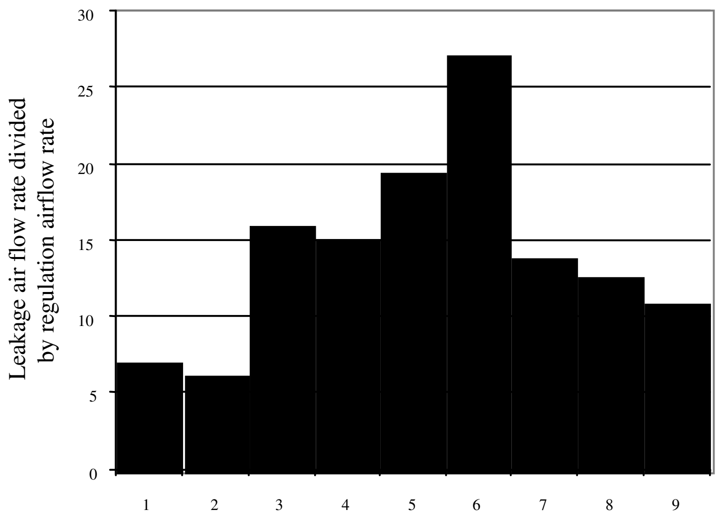


Figure 56: Leakage airflow rate at 100 Pa divided by regulation airflow rate in 9 multi-family buildings.

7.3 Peak load and energy use impacts

The energy loss linked to duct leakage may be itemised as follows:

- Fan power demand;
- Ventilation losses.

Conduction losses are, in general, highly correlated with duct leakage losses because they have a direct impact on the system's operation. In an air heating system, for example, transmission losses may imply a larger fractional on-time to maintain the desired temperature, thus resulting in increased fan energy use with potentially more ventilation losses. Equations are given hereafter to evaluate all of those losses assuming quasi-steady state conditions.

7.3.1 Fan power demand

Typically, the fan power demand lies between 1 W to 3 W to provide each l/s of air to a space. A commonly used fan law is that the power increases with the third power of the airflow rate.

$$P_{fan} \sim Q_{fan}^3 \qquad \textit{Equation 8}$$

This law is true only when the flow conditions stay similar as the fan speed changes. In particular, caution should be exercised when regulating devices are used.

The fan power demand can be calculated as follows:

$$\mathrm{P}_{fan} = \frac{Q_{fan}\ \Delta p_t}{\eta} \qquad \textit{Equation 9}$$

where:

P_{fan} is the fan power demand (W);
Q_{fan} is the airflow created by the fan (m^3/s);
Δp_t is the total pressure difference across the fan (Pa);
η is the global fan efficiency (-).

7.3.2 Ventilation losses

The energy loss associated with ventilation is due to the difference in enthalpy of the incoming and outgoing air streams. Thus, it will depend on where these streams come from.

The specific enthalpy of air is:

$$h = \underbrace{c_{pa}\,\theta + x\,c_{pw}\,\theta}_{\text{sensible heat}} + \underbrace{x\,L_0}_{\text{latent heat}} \qquad \textit{Equation 10}$$

where:

h is the specific enthalpy (J/kg);
c_{pa} is the specific heat capacity of dry air (J/kg K);
c_{pw} is the specific heat capacity of water vapour (J/kg K);
x is the water content of air (kg of water / kg of dry air);
θ is the air temperature (°C);
L_0 is the latent heat of vaporisation of water at 0°C (J/ kg of water).

For a circulation system, we obtain:

$$\begin{aligned} P_{vent} &= \rho Q_{vent}\left(h_{in} - h_{out}\right) + \underbrace{\rho Q_{leak,s}\left(h_s - h_{in}\right)}_{\text{return air lost in supply}} - \underbrace{\rho Q_{fan}\left(h_r - h_{out}\right)}_{\text{return air}} \\ &= \rho Q_{vent}\left(h_{in} - h_{out}\right) + \underbrace{\rho Q_{leak,s}\left(h_s - h_{in}\right)}_{\text{return air lost in supply}} - \underbrace{\rho Q_{-}\left(h_{in} - h_{out}\right) - \rho Q_{leak,r}\left(h_{rz} - h_{out}\right)}_{\text{return air}} \end{aligned} \qquad \textit{Equation 11}$$

where:

P_{vent} is the load due to ventilation (W);
Q_{fan} is the fan flow rate (m^3/s);
$Q_{leak,s}$ is the supply duct leakage flow rate (m^3/s);
$Q_{leak,r}$ is the return duct leakage flow rate (m^3/s);
h_r, h_s and h_{rz} represent the specific enthalpy of the air respectively in the return ducts (at the air handling plant), in the supply ducts, and in the zone where the return ducts are located.
The case of a balanced ventilation system with heat recovery is discussed below.

7.3.3 Conduction losses

When make-up air is transported in the ductwork, it has been shown that conduction losses can be substantial especially when the ducts pass through unconditioned spaces.
Interactions between transmission and duct leakage energy losses can be significant. These effects can be estimated through computer simulations.

Steady-state conduction losses can be calculated with the following equation:

$$P_{cl} = U\,A\,\Delta T_m \qquad \textit{Equation 12}$$

where:

P_{cl} is the conduction loss (W);
U is the estimated U-value of the ductwork ($W/m^2.K$);
A is the duct surface area (m^2);
ΔT_m is the logarithmic mean temperature difference (K), i.e.: $\dfrac{\Delta T_{beg} - \Delta T_{end}}{\ln\left(\dfrac{\Delta T_{beg}}{\Delta T_{end}}\right)}$

7.3.4 Simplified calculations

To evaluate these losses under quasi steady-state conditions at a given time *t*, the previous equations may be used.

➢Example 1: Multi-family building with exhaust ventilation system - Fan power demand

Using Equation 8, it is possible to estimate the fan power demand implications of duct leakage. The results presented in Table 24 and Figure 57 assume:

- A total airflow rate of about 209 l/s (750 m^3/h) delivered to 5 apartments;
- A mean fan power of 63 W per apartment (1.5 W per l/s) for a leakage coefficient $K = 0.12\ l\ s^{-1}\ m^{-2}\ Pa^{-0.65}$ (about 5 times worse than Class A);
- A (leakage) flow exponent of 0.65;
- An operating pressure of 100 Pa;
- A duct surface area of 15 m^2.

In this example it appears that it is beneficial to go to Class B on an electric energy use basis. Going to Class C or D does not change significantly the results in this case as the ratio of leakage flow rate to the nominal airflow rate stays within reasonable limits.

Ventilation losses are discussed in the following example.

				EUROVENT 2/2			
				Class A	Class B	Class C	Class D
K ($l\ s^{-1}\ m^{-2}\ Pa^{-0.65}$)	0.12	0.1	0.05	0.027	0.009	0.003	0.001
Total flow rate (l/s)	244	238	223	216	211	209	209
Fan power per apartment (W)	63	58	48	43	40	39	39

Table 24: Fan power demand per apartment versus leakage coefficient.

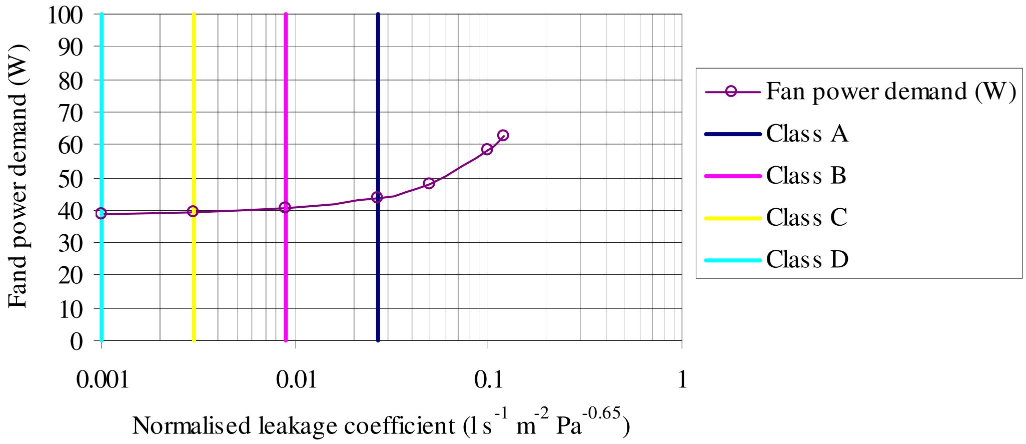


Figure 57: Fan power demand per apartment versus leakage coefficient.

➢Example 2: Office building with balanced ventilation system with heat recovery unit (HRU)

Assume the building described in Figure 58. In the analysis that follows, conduction losses are neglected.

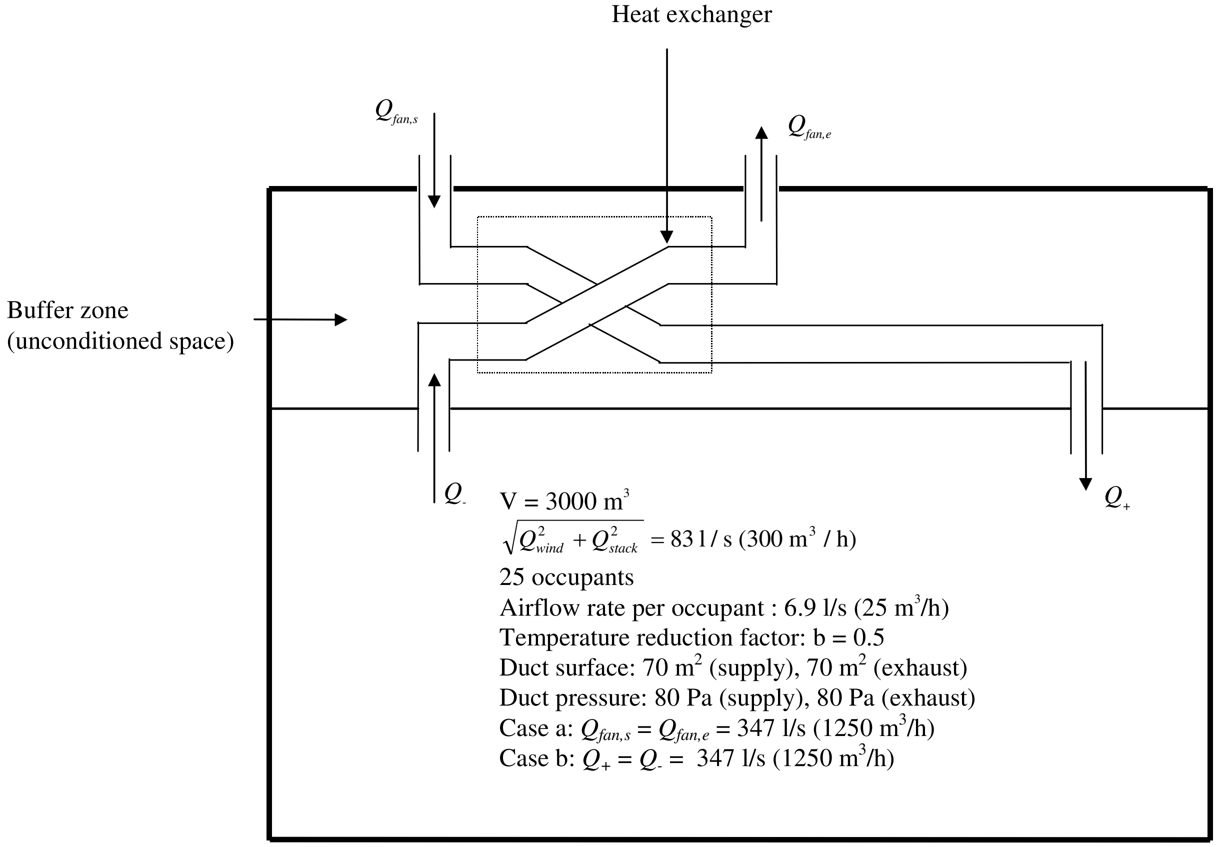


Figure 58: Schematic diagram of an office building equipped with a heat recovery system.

It can be seen in Figure 59, Figure 60, and Figure 61 that the effective heat recovery is severely affected by duct leakage. The ventilation rate and load as well as the fan power demand are normalised with respect the results of Class D. It can be seen that going to Class C or D does not change significantly the results as the leakage airflow rate becomes negligible compared to the nominal airflow rate as soon as Class B is achieved. It should be noted that if this ratio is made larger (e.g. by increasing the duct area), Class C or even Class D may be considered (Figure 62).

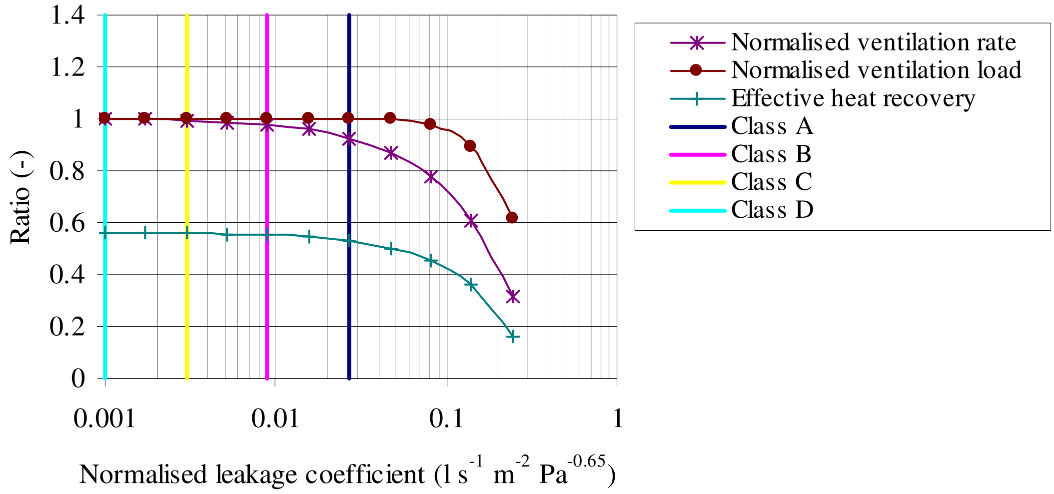


Figure 59: Ventilation rate and load impacts of duct leakage. The calculations are performed for the system described in Figure 58 - case a.

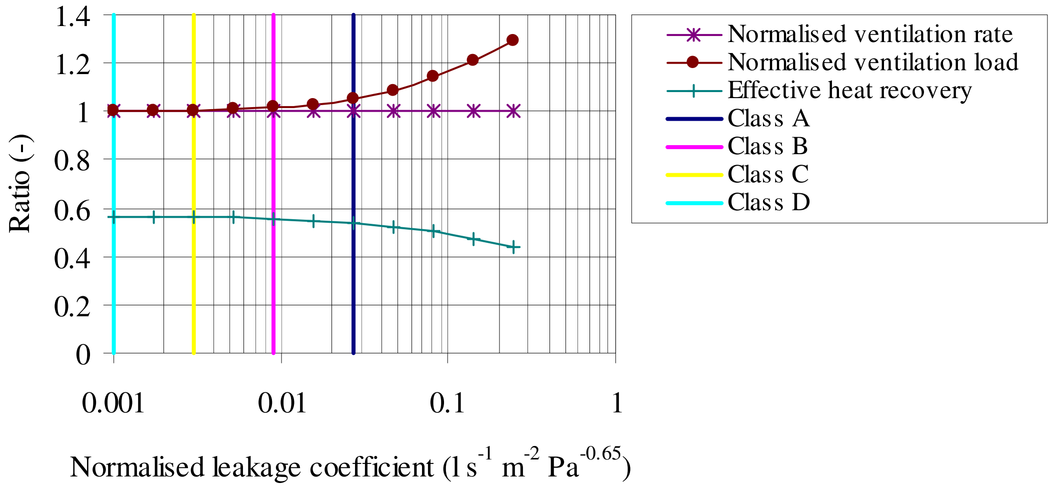


Figure 60: Ventilation rate and load impacts of duct leakage. The calculations are performed for the system described in Figure 58 - case b.

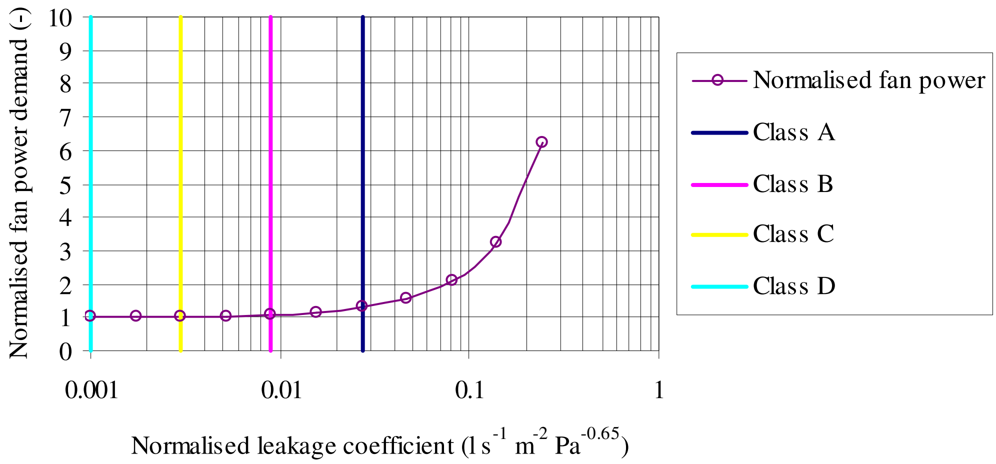


Figure 61: Fan power demand as a function of duct leakage. The calculations are performed for the system described in Figure 58- case b.

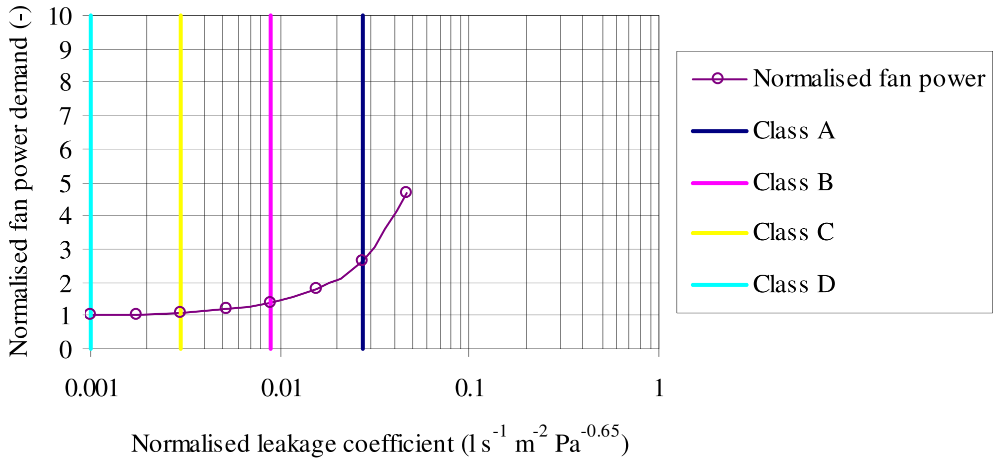


Figure 62: Fan power demand as a function of duct leakage. The calculations are performed for the system described in Figure 58- case b. The duct area is changed to 300 m^2.

The load due to ventilation can be computed by using the following equation:

$$\mathrm{P}_{\text{vent}} = \rho\, Q_{vent}\,(h_{in} - h_{out}) + \rho\, Q_{leak,s}\,(h_s - h_{out}) - \eta_v\, \rho\, Q_{fan,e}\,(h_e - h_{out})$$ *Equation 13*

outdoor air lost in supply heat recovery

where:

$Q_{fan,e}$ is the extract fan airflow rate (m^3/s);
h_e is the specific enthalpy of the extract air before entering the HRU (J / kg);
η_v is the efficiency of the HRU (-).
If we neglect the effect of the water vapour, this equation becomes:

$$\mathrm{P}_{vent} = \rho c_{pa}\left(Q_{vent} - \frac{Q_+}{Q_{fan,s}}\eta_v\,\left(b\,Q_{leak,e} + Q_-\right)\right)\Delta T$$ *Equation 14*

where:

b is the reduction factor in the unconditioned buffer zone (-) $\left(b = \frac{T_{buf} - T_{out}}{T_{in} - T_{out}}\right)$;
$Q_{fan,s}$ is the supply fan airflow rate (m^3/s);
ΔT is the temperature difference between inside and outside (K).

The effective heat recovery of the system is:

$$\eta_{v,eff} = 1 - \frac{\left(Q_{vent} - \frac{Q_+}{Q_{fan,s}}\eta_v\left(bQ_{leak,e} + Q_-\right)\right)}{Q_{vent}}$$ *Equation 15*

➢Detailed analyses through computer simulations

More detailed analyses can be performed using computer tools (Modera, 1993; Babawale *et al.*, 1993; Parker *et al,* 1993). The key advantage is to be able to take into account the interactions between energy loss mechanisms.

7.4 Indoor air quality

Added infiltration due to duct leakage is uncontrolled and does not mean that additional fresh air is delivered to the occupied rooms. Thus, it may be detrimental to comfort and indoor air quality. Also, if the fan is not properly sized to counteract the leaks, the building may be insufficiently ventilated. This means that the desired airflow rates will not be obtained at the registers, which can have a severe impact on the indoor climate.

Figure 63 displays the effect of duct leaks on the steady-state concentration of CO_2. It can be seen that in the extreme case the concentration of the pollutant is increased by about 30 %.

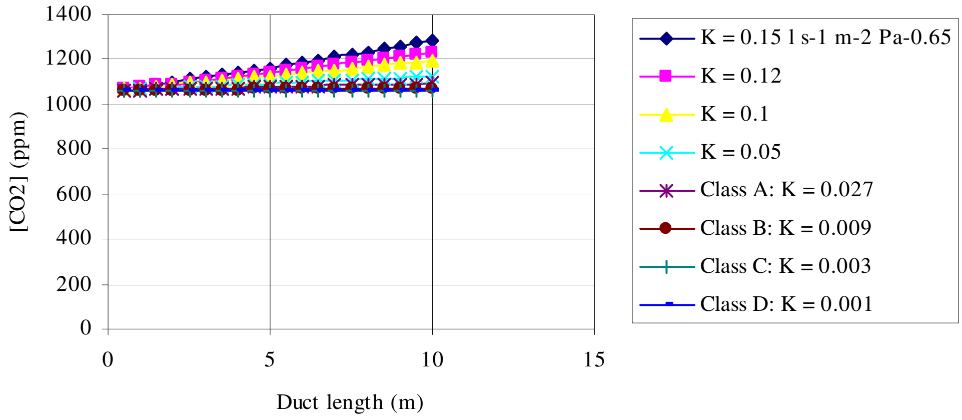


Figure 63: Room steady-state concentration of CO_2 versus duct length for various leakage coefficients. For these calculations, the initial airflow rate is 56 l/s (200 m^3/h) through a 0.16 m diameter duct. The initial pressure is equal to 100 Pa and the pressure drop is of 0.7 Pa/m. Source strength of CO_2 is based on 8 persons (i.e. about $7.1*10^{-5}$ kg/s).

7.5 Costs

The cost of an air distribution system can be divided into 3 major components:

- Capital or initial costs;
- Operating costs;
- Replacement costs.

The last item goes beyond the scope of this handbook.

7.5.1 Initial costs

In general, many parameters have to be considered when comparing costs between two options For example, for two installations with round and rectangular ducts respectively, special attention should be paid to the following items:

- Material cost for round ductwork, factory price;
- Material cost for rectangular ductwork, factory price;
- Transport cost factor, factory to site. Cost difference round vs. rectangular ductwork due to larger transport volume for rectangular ducts than round (normal volume ratio 3:1);
- Packing cost factor for transport factory to site. Cost difference round vs. rectangular ductwork due to larger transport volume for rectangular ducts than round (normal volume ratio 3:1), and rectangular ducts (flanges) being more sensitive to transport damages;
- Waste cost factor due to alterations, adjustment and wrongly measured duct lengths. Cost difference round vs. rectangular ductwork due to the fact that the rectangular ducts have to be made exactly to measure while the round ducts can be adjusted on site to correct length. Wasted rectangular ducts can normally not be used at other locations due to the tailor made dimensions while round ducts and components normally can be re-used;
- Normal installation time for round ductwork installation as calculated. The time includes moving of necessary scaffolding etc.;
- Normal installation time for rectangular ductwork installation as calculated. The time includes moving of necessary scaffolding etc.;

- Basic wage cost (net wage) per hour;
- Social cost factor based on net wage;
- Cost factor for tools, machines, huts, scaffolding, etc., based on net wage;
- Costs factor for insurance, fees, site cleaning, etc., based on net wage;
- Cost factor for site organisation, administration, profit, based on net wage;
- Inspection and supervision time factor based on installation time. Time factor difference round vs. rectangular ductwork due to the fact that the rectangular ducts have to be made exactly to measure while the round ducts can be adjusted on site to correct length. The rectangular duct installation thus needs more supervision than the round one. Rectangular ducts are normally more difficult to inspect due to less free space around ducts, e.g. when mounted tight to the ceiling in narrow corridors;
- Testing (airflow measurements and adjustments, duct tightness testing) time factor based on installation time. Time factor difference round vs. rectangular ductwork due to the fact that the rectangular ducts are less dimension standardised and normally more difficult to test due to less free space around ducts, e.g. when mounted tight to the ceiling in narrow corridors;
- Waiting time factor based on installation time. Part of the installation time is non-productive and used in waiting for missing parts, etc.;
- Building cost time factor based on ductwork installation time. This factor includes higher building site costs due to the fact that round ducts are more close-fitting to holes in walls and need less tightening after the installation of the duct (the tightening is especially needed when ducts pass through fire-classed walls but normally also in ordinary walls to reduce noise transmission). This factor also includes higher building site costs due to the fact that rectangular ducts often need more tight time schedule coupled to other building works (e.g. corridor walls can not be installed before the rectangular ducts' top flanges have been mounted) and to the testing and commissioning of the ductwork installation.

All these expenditures vary from one country to another, even from one city to another and especially from one time to another. Therefore, the only accurate method to compare initial costs is to ask for prices for the building in question.

In Table 25, we have itemised the cost of a balanced ventilation system with heat recovery in a small office building in France. In the base case, it is assumed to be sealed on site. Then, it is possible to perform sensitivity analyses to evaluate the cost implications of different options. For this, weight factors were applied separately to the labour and the ductwork components (ducts and accessories). Assuming that using accessories with pre-fitted sealing devices implies an additional cost of 20 % to 30 %, and that the labour cost can be reduced by 25 % (which is claimed by some manufacturers), Table 25 shows that the capital cost remains equivalent to the base case.

	Base case			
Additional cost for ducts and components (in %)	0 %	+20 %	+30 %	0 %
Additional cost for labour (in %)	0 %	-25 %	-25 %	+10 %
Airflow rate (m^3/h)	300 / 240	300 / 240	300 / 240	300 / 240
Surface of ventilation system (m^2)	50	50	50	50
Air handling unit (EURO)	2582	2582	2582	2582
Ducts accessories (EURO)	593	712	771	593
Registers (EURO)	642	770	834	642
Margin (EURO)	763	813	837	763
Labour (EURO)	1432	1074	1074	1575
Insulation (EURO)	162	162	162	162
Total ADS (EURO)	6174	6112	6261	6317
Normalised cost of ADS (EURO/m^2)	123	122	125	126
Cost percentage for ducts and accessories (%)	9.6 %	11.6 %	12.3 %	9.4 %
Normalised cost of ducts and accessories (EURO/m^2)	12	14	15	12
Normalised cost of registers (EURO/m^2)	13	15	17	13
Relative cost (compared to base case) (in %)	0.0 %	-1.0 %	+1.4 %	+2.3 %
Additional cost (EURO)	0	-62	87	143
Normalised additional cost (EURO/m2)	0	-1	2	3

Table 25: Capital cost comparisons on a balanced ventilation system with heat recovery (real case).

7.5.2 Operating costs

These options should not be compared on an initial cost basis alone. For example, the ductwork airtightness should be considered if it has an impact on energy use, thus on operating costs. Life Cycle Costing is a useful tool for such comparisons as it brings the different cost components together. In such studies, it is common to express a stream of expenditure over a number of years in terms of its Net Present Value (i.e. it is brought back to its value in year 0). Calculations were carried out in the case described in Figure 58. The cost performance of a leaky and a tight system (Class D) are compared in figure 64. The results are based the following figures:

Normalised cost of the system:	120 EURO/m^2
Cost for heating energy:	0.03 EURO/kWh
Cost for electric (fan) energy:	0.105 EURO/kWh
Additional initial cost of tight system:	10 %
Fractional on-time:	0.75
Discount rate:	5 %
Interest rate for energy:	1 %

Table 26: Input parameters for life-cycle cost calculations.

Figure 64 clearly shows the key role of the ductwork airtightness.

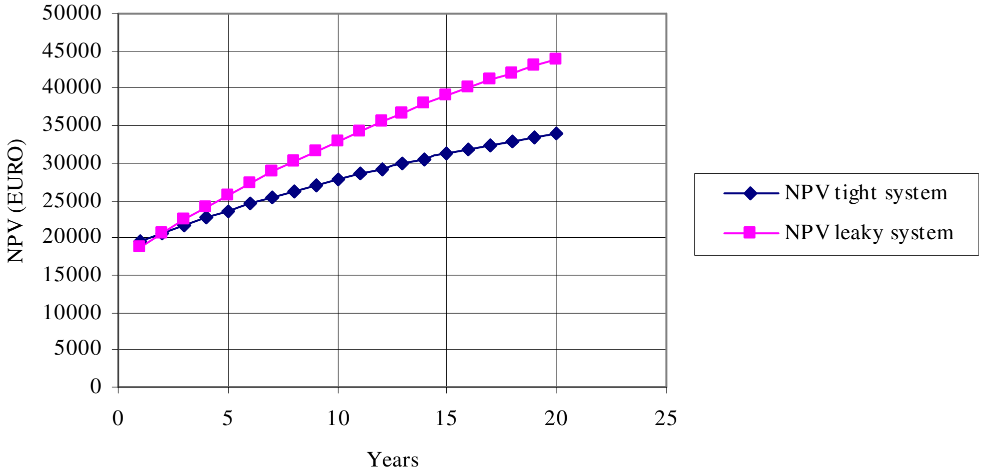


Figure 64: Comparisons of Net Present Values of a leaky and an airtight duct system. Calculations are based on the system described in Figure 58 and Table 26.

$$NPV = CC + OC \times \sum_{k=1}^{n} \left(\frac{1+j}{1+i}\right)^{k} + RC \times \sum_{p} \left(\frac{1+j}{1+i}\right)^{n_p}$$

Equation 16

where:

NPV is the Net Present Value (currency);
CC is the capital cost (currency);
OC is the operating cost (currency);
RC is the replacement cost (currency);
i is the discount rate (-);
j is the interest rate (-);
n is the number of years over which the analysis is performed (-);
and each n_p is a year during which a replacement cost is foreseen.

7.6 Nomenclature for chapter 7

A	duct surface area (m^2)
b	reduction factor in the unconditioned buffer zone (-) $\left(b = \frac{T_{buf} - T_{out}}{T_{in} - T_{out}} \right)$
c_{pa}	specific heat capacity of dry air (J/ kg K)
c_{pw}	specific heat capacity of water vapour (J/ kg K)
h	specific enthalpy (J / kg)
h_{in}	specific enthalpy of the inside air (J / kg)
h_e	specific enthalpy of the extract air (J / kg)
h_r	specific enthalpy of the air in the return ducts (J / kg)
h_{rz}	specific enthalpy of the air in the zone where the return ducts are located (J / kg)
h_{out}	specific enthalpy of the outside air (J / kg)
h_s	specific enthalpy of the air in the supply ducts (J / kg)
L_0	latent heat of vaporisation of water at 0°C (J / kg of water)
P_{cl}	conduction loss (W)
P_{fan}	fan power demand (W)
P_{vent}	ventilation load (W)
Q_+	sum of the airflow rates at the supply registers (m^3/s)
$Q_{balanced}$	balanced ventilation rate (m^3/s)
Q_{fan}	fan flow rate (m^3/s)
$Q_{fan,e}$	extract fan airflow rate (m^3/s)
$Q_{leak,r}$	return duct leakage flow rate (m^3/s)
$Q_{leak,s}$	supply duct leakage flow rate (m^3/s)
Q_{stack}	stack-induced ventilation rate (m^3/s)
$Q_{unbalanced}$	unbalanced ventilation rate (m^3/s)
Q_{vent}	total ventilation rate (m^3/s)
Q_{wind}	wind-induced ventilation rate (m^3/s)
Q-	sum of the airflow rates at the exhaust registers (m^3/s)
T_{buf}	temperature of unconditioned (buffer) zone (K)
T_{in}	inside temperature (K)
T_{out}	outside temperature (K)
U	estimated U-value of the ductwork (W/m^2K)
x	water content of air (kg of water / kg of dry air)
Δp_t	total pressure drop across the fan (Pa)
ΔT	temperature difference between inside and outside (K)
ΔT_m	logarithmic mean temperature difference (K) i.e.: $\frac{\Delta T_{beg} - \Delta T_{end}}{\ln\left(\frac{\Delta T_{beg}}{\Delta T_{end}}\right)}$
η	global fan efficiency (-)
η_v	efficiency of the HRU (-)
$\eta_{v,eff}$	effective heat recovery of the system (-)
ρ	density of air (kg/m^3)
θ	air temperature (°C)

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Chapter 8 Potential energy impacts of a tight air duct policy at the European level

Potential savings in Belgium

Potential savings in Europe (exc. FSU)

Assumptions about market penetration

8.1 Introduction

This chapter aims at making very approximate estimates of the order of magnitude of the energy wastage and supplementary peak power demand due to the duct leakage at the European level (excluding the Former Soviet Union - FSU). First calculations are made for Belgium and afterwards these are extrapolated to the whole of Europe (excluding the FSU). The savings potential of an airtight duct policy is calculated a) assuming that all buildings are equipped with mechanical ventilation systems; b) based on estimates of the number of buildings equipped with mechanical ventilation systems; c) assuming market penetration scenarios of rehabilitation techniques.

8.2 General assumptions

1. The air leaving the ductwork through leaks (in false ceilings, technical rooms, attics etc.) does not contribute to the indoor air quality. Therefore, air leakage from ductwork results in higher airflow rates through the air handling unit and through outdoor air intakes. This implies a higher fan power and more energy for air treatment;
2. A specific fan energy of 1.5 W per l/s is assumed;
3. The leakage airflow rate is set to 15 % of the nominal airflow rate (this can be roughly concluded from field measurements in Belgium and in France, see chapter 6);
4. The figures assumed for number of employees, total energy consumption, number of degree days, etc. (see below) are only orders of magnitude;
5. There is no heat recovery from exhaust air.

8.3 Potential savings in Belgium

8.3.1 Offices

The following assumptions are made:

- 1 million office workers (total population of 10 million);
- Required airflow rate: 7 l/s per person;
- Total energy consumption for heating for all office buildings together: 5 TWh/year (18 PJ/year), from:
  - 200 kWh/m² *(BRE, 1991);*
  - Available surface per worker: 25 m²;
- 1400 degree days during working hours;
- year-round efficiency of heating system: 70 %;
- available electrical power (peak-value) in Belgium: 15 GW.

This gives the following results for mechanical ventilation in all buildings:

⇨ Nominal airflow rate for all office workers: 7 million l/s;
⇨ Total air leakage rate: 1.05 million l/s;
⇨ Heating energy consumption due to leaks: 60.5 GWh/year (0.22 PJ/year);
⇨ Share of leaks in total heating energy: 1.2 %;
⇨ Required additional fan power: 1.57 MW;
⇨ The additional fan power corresponds to about 0.01 % of the available electrical power.

Assuming that 25 % of the workplaces in Belgian office buildings are mechanically ventilated, this becomes:

⇨ **Heating energy consumption due to leaks: 15 GWh/year (0.054 PJ/year);**
⇨ **Share of leaks in total heating energy: 0.30 %;**
⇨ **Required additional fan power: 0.4 MW;**
⇨ **The additional fan power corresponds to about 0.003 % of the available electrical power.**

8.3.2 Dwellings

The following assumptions are made:

- Nominal airflow rate (supply) per dwelling is about 80 l/s *(BBRI, 1998);*
- Year-round efficiency of the heating system is about 70 %;
- 2000 degree days;
- Total energy consumption for heating for all Belgian dwellings together: 90 TWh/year (324 PJ/year) , from:
  - typical average heating energy consumption for a Belgian dwelling: 30 000 kWh/year *(BBRI, 1998) (figure typical for new single-family dwelling)*;
  - about 3 million dwellings.

This gives the following results in the case where all buildings are assumed to be mechanically ventilated:

- ⇨ Total nominal airflow rate: 240 million l/s;
- ⇨ Total air leakage rate: 36 million l/s (this is probably an overestimation: the duct surface in dwellings is normally a lot smaller than the duct surface in office buildings);
- ⇨ Heating energy consumption due to leaks: 3.0 TWh/year (10.8 PJ/year);
- ⇨ Share of leaks in total heating energy: 3.3 %;
- ⇨ Required additional fan power: 54 MW;
- ⇨ The additional fan power corresponds with about 0.36 % of the available electrical power

The number of dwellings with a permanent mechanical ventilation (supply or exhaust or both) is very limited in Belgium. Assuming that 5 % of the Belgian dwellings are equipped with permanently working mechanical ventilation devices, this brings us to:

- ⇨ **Heating energy consumption due to leaks: 150 GWh/year (0.54 PJ/year);**
- ⇨ **Share of leaks in total heating energy: 0.16 %;**
- ⇨ **Required additional fan power: 2.7 MW;**
- ⇨ **The additional fan power corresponds with about 0.02 % of the available electrical power.**

8.4 Potential savings in Europe (exc. FSU)

The previous results are extrapolated to the rest of Europe. However, the reader should keep in mind that the Belgian estimates apply to the Belgian climate, and the number of dwellings situated in the Mediterranean area is bigger than the number of Scandinavian dwellings. Moreover, the leakage flow rate is probably much smaller in Scandinavian countries (see chapter 6). Therefore, caution should be exercised when interpreting the savings estimates calculated below.

The following assumptions are made:

- 50 million office workers;
- 150 million dwellings (University of Oxford, 1998);
- the loss of cooling energy due to leaky ductwork is not taken into account.

These assumptions give the following results, assuming that all buildings are mechanically ventilated:

- ⇨ Heating energy consumption due to leaks in offices: 3 TWh/year (10.8 PJ/year);
- ⇨ Heating energy consumption due to leaks in dwellings: 150 TWh/year (540 PJ/year).

Making the same assumptions for the occurrence of mechanical ventilation as for the Belgian situation (i.e. 5%), this brings us to:

- ⇨ **Heating energy consumption due to leaks in offices: 0.75 TWh/year (2.7 PJ/year);**
- ⇨ **Heating energy consumption due to leaks in dwellings: 7.5 TWh/year (27 PJ/year).**

8.5 Assumptions on the market penetration

In the previous calculations the energy savings were estimated assuming that all new and existing ductwork systems were airtight. This market transformation can occur only step by step, especially for existing buildings. In order to give an idea of the potential savings in the short term, new calculations were performed for dwellings.

The assumptions were the following:

- The total number of existing dwellings at the European level is about 150 million;
- The heating loss by leaks in ductwork is 1000 kWh/year (from the previous calculations);
- The number of newly constructed dwellings is 1.7% of the existing dwellings (according to the Belgian situation) (BBRI, 1998);
- 5% of the dwellings are equipped with a permanently operating mechanical ventilation system;
- Airtight ducts are placed in all new and rehabilitated dwellings.

With these assumptions, the energy savings of tight air ducts were calculated for different rehabilitation scenarios (market penetration: 0.0%, 0.1%, 0.5%, 1.0% and 2.0%). The results are presented in Figure 65.

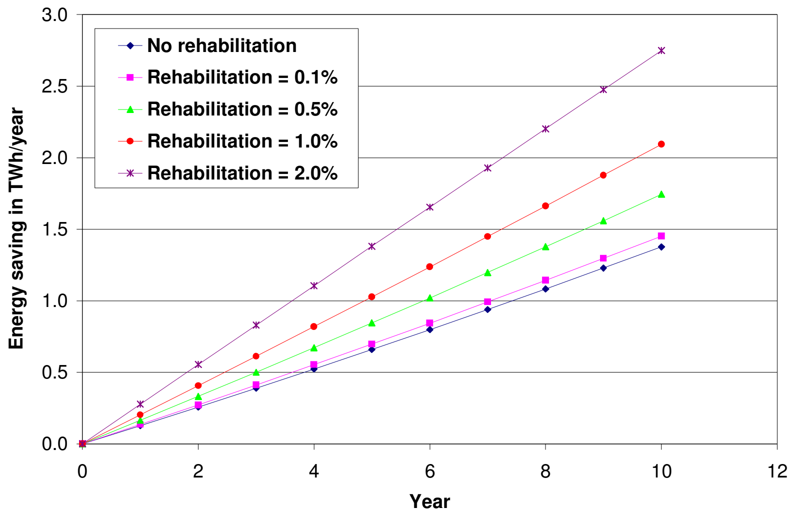

Figure 65: Energy savings per year due to the installation of airtight ductwork in new and rehabilitated dwellings.

In Figure 66 the cumulative energy savings over the first 10 years are represented for the same conditions.

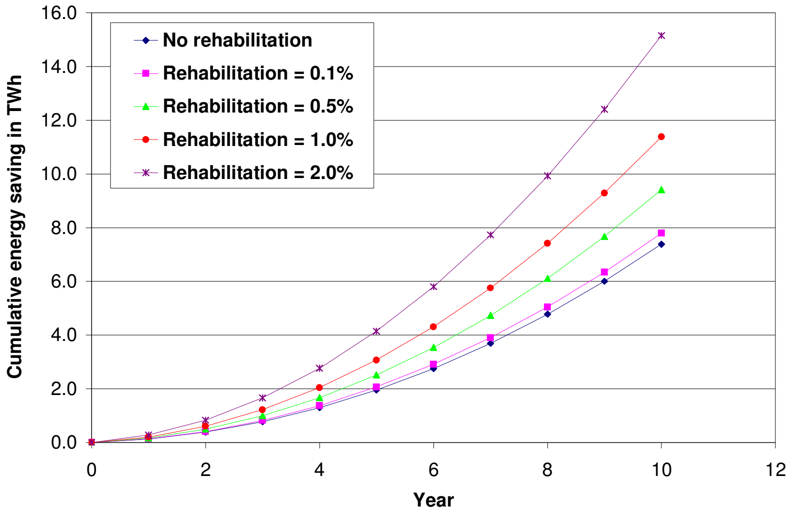

Figure 66: Cumulative energy savings due to the installation of airtight ductwork in new and rehabilitated dwellings.

8.6 Key conclusions and remarks

- These results are very approximate estimates, based on simple calculations, but they demonstrate clearly that significant energy savings can be achieved by installing airtight ductwork. **The order of magnitude of the energy savings that can be achieved by using airtight ductwork in Europe is probably in the region of 1 to 10 TWh/year (3.6 to 36 PJ/year).** This is between 0.007 % and 0.07 % of the total European energy consumption per year (about 14000 TWh (50400 PJ) **-** figure from 1992 (EC DGXVII, 1994));
- It is important to mention that these savings cannot be obtained at once. It is very much dependent upon the market penetration scenario of rehabilitation techniques. Probably, the cumulated energy saving over a period of 10 years would be in the region of 10 TWh;
- One has to keep in mind that the use of ductwork will probably increase in the future, mainly due to:
  - the increasing importance of ventilation in the total energy consumption due to a better thermal insulation of the dwellings, which makes it feasible to install balanced ventilation (and thus ductwork) with a (recovery) heat exchanger;
  - the increasing number of active cooling installations in offices and dwellings, for which it is critical to have airtight ducts;
- A leakage airflow ratio of 15 % is based on results of measurements in France and Belgium. It is clear that this figure is an overestimation for a country such as Sweden. However, it is probably representative for the European situation as a whole, because in most countries there is nearly no control and as a consequence, the performances are probably comparable to those in Belgium and France;
- The share of duct leakage in the annual heating energy consumption is valid for typical dwellings and offices (according to the existing Belgian situation). For highly insulated buildings the energy loss due to ventilation will have a higher relative impact on the total energy use.

8.7 References

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Chapter 9 Outcome of the international SAVE-DUCT seminar in Brussels, June 1998

9.1 Introduction

An international seminar was organised by BBRI in Brussels (June 10-11 1998) in the framework of the European project SAVE-DUCT. Its main purpose was to inform the industry as well as the standardisation and governmental bodies of the recent findings in this project, and discuss measures that could be implemented to remedy the energy use and ventilation rate implications of duct leakage. Fourteen presentations were given. Most of the information is integrated in the various chapters of the handbook. The key findings and conclusions of the seminar that are not handled clearly in the handbook are described in this chapter.

A variety of people and institutes participated in this seminar, these included:

- SAVE-DUCT project partners: BBRI, ENTPE, Scandiaconsult, Aldes;
- Ductwork manufacturers and installers: Stork, Bergschenhoek, Lindab, ABB, Flanders Air Technique, LPS Klimatechniek;
- Research and/or technical institutes: BSRIA, AIVC, CETIAT, TNO;
- Government: Boverket (Sweden), Ministry of the Flemish Community (Belgium), Regie der Gebouwen (Belgium);
- Members of CEN TC 156, WG 3 (Ductwork);
- Architects, engineers, etc.

9.2 Ductwork in relation to indoor air quality and energy

Presentation given by M. Liddament from AIVC, UK

In his presentation, M. Liddament described the reference framework for a discussion on ductwork performances. The achievement of an acceptable indoor air quality is the first priority, ventilation being essential in most circumstances. A limited energy use is an important boundary condition. Poor ductwork performances will have a negative influence on both the indoor air quality and the energy use of the building.

9.3 Experiences from Sweden

9.3.1 Progress in ductwork design over the last 25 years

Presentation given by K. Lennertsson from Lindab, Sweden

An overview was given of the evolution in ductwork design in Europe, with special attention to airtightness. The most important points were the following:

<u>1970's:</u>

- Rectangular ductwork is used more frequently, but there is an increasing use of circular ductwork;
- First use of rubber gaskets;
- Change of the manufacturing process;
- Growing attention for cleaning and inspection of ductwork.

<u>1980's:</u>

- The Swedish guideline AMA 83 requires Class C for some applications in Sweden;
- Increasing use of circular ducts, especially in Northern Europe;
- Northern Europe 90 % circular ducts with 100 % rubber gaskets;
- Middle Europe 30 % circular ducts with 20 % rubber gaskets;
- Southern Europe < 30 % circular ducts without rubber gaskets;
- Increasing use of seam-welded products.

<u>1990's:</u>

- Development of CEN standards;
- Introduction of Class D in VVS AMA in Sweden;
- Increasing use of circular ductwork in Middle Europe: 50 % circular with 60 % rubber gaskets;
- Clean ducts and fittings at delivery (supplied with covers at the ends).

<u>Future developments:</u>

- ♦ Adoption of the CEN standards;
- ♦ More attention to:
  - ⇨ Airtightness;
  - ⇨ Easy to clean solutions;
  - ⇨ Noise attenuation;
  - ⇨ Pressure drops;
  - ⇨ Environmental impacts.

9.3.2 The Swedish experience with inspection protocols

Presentation given by B. Lindström from Boverket, Sweden

In 1992 a regulation came into force in Sweden, requiring performance checks of ventilation installations according to Table 27. Results from the first checks were presented by Boverket (Swedish National Board of Housing, Building and Planning) during the seminar.

Buildings	Last date for first inspections of existing building	Inspection intervals	Inspector qualifications class
Day-care centres, schools, health care centres, etc.	31 Dec. 1993	2 years	K
Blocks of flats, office buildings, etc. with balanced ventilation	31 Dec. 1994	3 years	K
Blocks of flats, office buildings, etc. with mechanical exhaust ventilation	31 Dec. 1995	6 years	N
Blocks of flats, office buildings, etc. with natural ventilation	31 Dec. 1995	9 years	N
One- and two-family houses with balanced ventilation	31 Dec. 1995	9 years	N

Table 27: Requirements for performance checks of ventilation systems in Sweden. Class N qualified inspectors can investigate only simple installations; Class K qualified inspectors can investigate all types of installations.

The following activities are always included in a ventilation performance check: check of availability of operation/maintenance instruction manual, airflow rate measurement, humidity, fans and air handling units, recirculated air, radon, deposits in ventilation ductwork, noise and eventually a more detailed inspection.

Analysis of more than 8000 reports shows that only 37 % of the systems have been approved. The following distribution of approved systems is found for the different types of buildings:

- Apartment building: 25 %;
- Office building: 43 %;
- Schools: 37 %;
- Day-care centres: 51 %;
- Health-care centres: 32 %.

The most common defaults are summarised in Table 28:

Wrong airflow rate	61 %
Missing maintenance manuals	48 %
Deposits in fans	40 %
Deposits in ducts	37 %
Defects in fans	30 %
Control and guidance equipment	27 %
Deposits in filters	25 %
Defects in supply and exhaust devices	23 %
Deposits in supply air devices	22 %
Defects in filters	20 %

Table 28: Most common defaults found during inspection of Swedish ventilation systems.

9.4 Status in the USA

Presentation given by M. Modera from LBNL and Aeroseal Inc., USA

M. Modera gave an overview of the duct leakage status in US buildings. Considerable work has been undertaken over many years on the performance of residential air distribution (heating or cooling) systems. A major conclusion is that ductwork airtightness is very poor and that this results in very significant energy wastage, especially because in more than 50 % of the cases, the ducts are located in unconditioned spaces. More recent studies were also presented, namely:

- Measuring and improving the performance of commercial-building duct systems (see chapter 6);
- Aerosol-based duct sealing (that is increasingly used in the US, see chapter 4);
- Standards for duct efficiency (ASHRAE standard 152 P, see chapter 3).

9.5 Standards and regulations: CEN TC 156 WG3

Presentation given by B. Göstring from the Swedish Association of Air Handling Industries, Sweden

The work programme of CEN TC 156 / WG 3 (Ductwork) was presented in detail, with special attention to the most recent decisions of WG3 for the different work items.

- ENV 12097: Requirements for ductwork components to facilitate maintenance of ductwork systems;
- EN 1505: Sheet metal air ducts and fittings with rectangular cross section – dimensions;
- EN 1506: Sheet metal air ducts and fittings with circular cross section – dimensions;
- EN 12220: Dimensions of circular flanges for general ventilation;
- prEN 12236: Supports for ductwork, requirements for strength;
- prEN 1507: Strength and leakage of sheet metal air ducts and fittings with rectangular cross section;
- prEN 12237: Strength and leakage of sheet metal air ducts and fittings with circular cross section;
- prEN 13180: Dimensions and mechanical requirements for flexible ducts;
- WG3 N147: Measurement of duct surface area;
- WG3 N207: Ductwork made of insulation ductboards;
- WG3 N204: Identification of ductwork.

prEN 1507 and prEN 12237 that are detailed in chapter 3 have to be submitted to a new public inquiry as a result of the large number of comments on the initial documents.

9.6 Testing ductwork according to prEN 12237

Presentation given by W. F. de Gids from TNO, the Netherlands

TNO carried out a number of laboratory measurements to determine the airtightness of ductwork according to prEN 12237 (November 1995 version). It is likely that this standard will be modified in the future.

Tests were performed on round ductwork, for 10 different diameters (ranging from 125 to 1250 mm). All tested ducts were from the same company. The following measurements were performed:

- <u>Air leakage:</u>

  For all diameters, the airtightness was measured for the following 4 sets of conditions:

Pressure in the ductwork	External loading
Overpressure	Yes
Underpressure	No
Overpressure	Yes
Underpressure	No

Although prEN 12237 only requires a single-point measurement procedure to determine the airtightness, the leakage flow rate was measured at several pressure stations at TNO to be able to determine the flow exponent. The pressure in the ductwork was always in the region of 50 to 750 Pa;

The following conclusions could be drawn:

- ⇨ In all cases the airtightness in the laboratory was better (up to a factor of 5) than the best class in prEN 12237 (which is Class C). This indicates that for laboratory tests an additional class (Class D) should be introduced;
- ⇨ The flow exponent is in the region of 0.51 to 0.84, with an average of 0.76. This indicates that the one-point measurement procedure can cause significant errors when the test pressure is significantly different from the reference pressure at which the leakage flow rate is calculated. Therefore the application of a multi-point measurement procedure should be considered in prEN 12237;
- ⇨ Performing the tests in underpressure always leads to the best result from the point of view of airtightness. This is probably caused by the fact that seams and joints are pressed open in the case of an overpressure in the ductwork;
- ⇨ External loading of the ductwork does not seem to affect considerably the airtightness in the case of underpressure. However, in the case of a positive pressure in the ductwork the loading can have a significant influence;

- <u>Deflection:</u>

  The deflection was determined with a positive pressure in the ductwork and an external loading (1.5 times the weight of the tested ductwork). The deflection of the different ducts were between a factor of 4 to 120 better than the requirement in the standard;

- Ovality

The ovality was also determined with a positive pressure in the ductwork and an external loading (1.5 times the weight of the tested ductwork). The ovality of the different ducts were between a factor of 2 to 25 better than the best class in the standard.

Chapter 10 Recommendations for future technical and governmental measures

10.1 The Swedish experience: an interesting concept for other countries

The measurements and literature review performed within the SAVE-DUCT project suggest that duct systems are very leaky in Belgium and in France. Conversely, the installation of high-quality airtight (Class C or better) systems prevails in Sweden. One reason for this lies, most likely, in the fact that the need for tight systems has been identified in this country since the early sixties. This has resulted in a series of quality-requirements now detailed in the VVS AMA 98 guideline (1998) (see also chapter 3). 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.

AMA requires that all ventilation and air conditioning systems be carefully commissioned. The procedures include:

- Measurement and adjustment of all supplied or extracted airflows at the registers. The result should be within ± 15 % including the measurement error. The result is to be presented on standard AMA protocols;
- The duct system leakage has to be verified, normally by the contractor as part of the contract. This is undertaken as a spot check where the parts to be checked are chosen by the owner's consultant. For round duct systems 10 % and for rectangular ducts 20 %, of the total duct surface has to be verified. In case the system is found to be leakier than required, the tested system shall be tightened and another, equally sized, part of the system shall be verified in the same manner. Should this part also be found to leak more than accepted the complete installation has to be leak tested and tightened until the requirements are fulfilled.

Class C was introduced in 1983 and is required for duct systems with a surface larger than 50 m^2. This met resistance from the contractors who considered that is was too high a demand. However, one year later it was found that the AMA requirements were easier to fulfil than first thought, so the opposition died and the demands were accepted.

Furthermore, the concern about an increasing part of the Swedish population becoming allergic and asthmatic, often due to “sick buildings” and inadequate dilution of indoor emissions by inferior ventilation systems, lead the Swedish Parliament and Government to decide on compulsory inspection of ventilation systems (Government Bill 1990/91:145, and Ordinance SFS 1991:1273, about the performance checks on ventilation systems). The rules for the inspection were issued by the Swedish National Board of Housing, Building and Planning (General Guidelines 1992 : 3 “Checking the performance of ventilation systems” based on BFS 1992 : 15 “Regulations about performance checks on ventilation systems”). The intervals between the checks depend on how sensitive the building occupants are and how complicated the ventilation system is. The intervals range from 2 years for day-care centres, schools, health care centres, etc., up to 9 years for one- and two-dwelling houses with balanced ventilation. The performance checks are to be carried out by an inspector who is authorised either nationally by the Swedish National Board of Housing, Building and Planning or locally by the municipal committee(s) responsible for planning and building matters. The inspector qualifications differ between these different buildings and systems and whether the authorisation is local or national.

10.2 Integrated ductwork performance in an energy performance concept

In the past, many building regulations focused on the thermal insulation level of buildings or the net heating demand. Since the beginning of the nineties, several countries have developed a so-called energy performance standardisation concept. The aim is to have a requirement on the total energy consumption of the building for standardised boundary conditions (external climate, indoor climate) and the energy analysis includes the energy demand for heating and cooling, the efficiency of the heating and cooling systems, the energy for hot water production, fans, pumps, humidification, etc.

Examples of such an approach are the Dutch energy performance standardisation (NEN 5128 for dwellings, NEN 2916 for utility buildings), the French global thermal performance calculation method (ANFNOR DTU P 50-708 (1988), règles Th-C, under revision), the German Energiesparverordnung (which is revised every three years).

In order to stimulate the construction of buildings with improved energy efficiency, it is important that the ventilation system receives appropriate attention. Demand controlled ventilation concepts, heat recovery, etc. should be included in the energy performance calculation as well as the airtightness performances of the ductwork. The better the performance of these components, the lower the normalised energy performance index. To be most effective, the airtightness of ductwork should probably be included only if the final calculation of the energy performance index can be undertaken at the end of the works (i.e. after commissioning). In most countries, the legislation requires proof of performances at the granting or issuing of the building permit (i.e. before the performance of the ductwork can be tested). Therefore, it is important that the regulations foresee the possibility of performance calculation after commissioning. This concept is illustrated in Figure 67. The constraints apply to the sum of the energy flows and the ductwork airtightness item appears under the ventilation related issues. There are two options at this level:

1. The ductwork airtightness is tested on site. Then the values determined on site may be used in the energy calculations;
2. The ductwork airtightness is **not** tested on site. Then default (typical) values are used in the energy calculations.

Because the energy impact of duct leakage is expected to be large, severe requirements on the ductwork airtightness appear to be a cost effective solution compared to increasing the insulation level or improving the efficiency of thermal systems. This should be a great incentive to use airtight ducts. Finally, this approach is compatible with specific duct leakage requirements that are not related to energy issues.

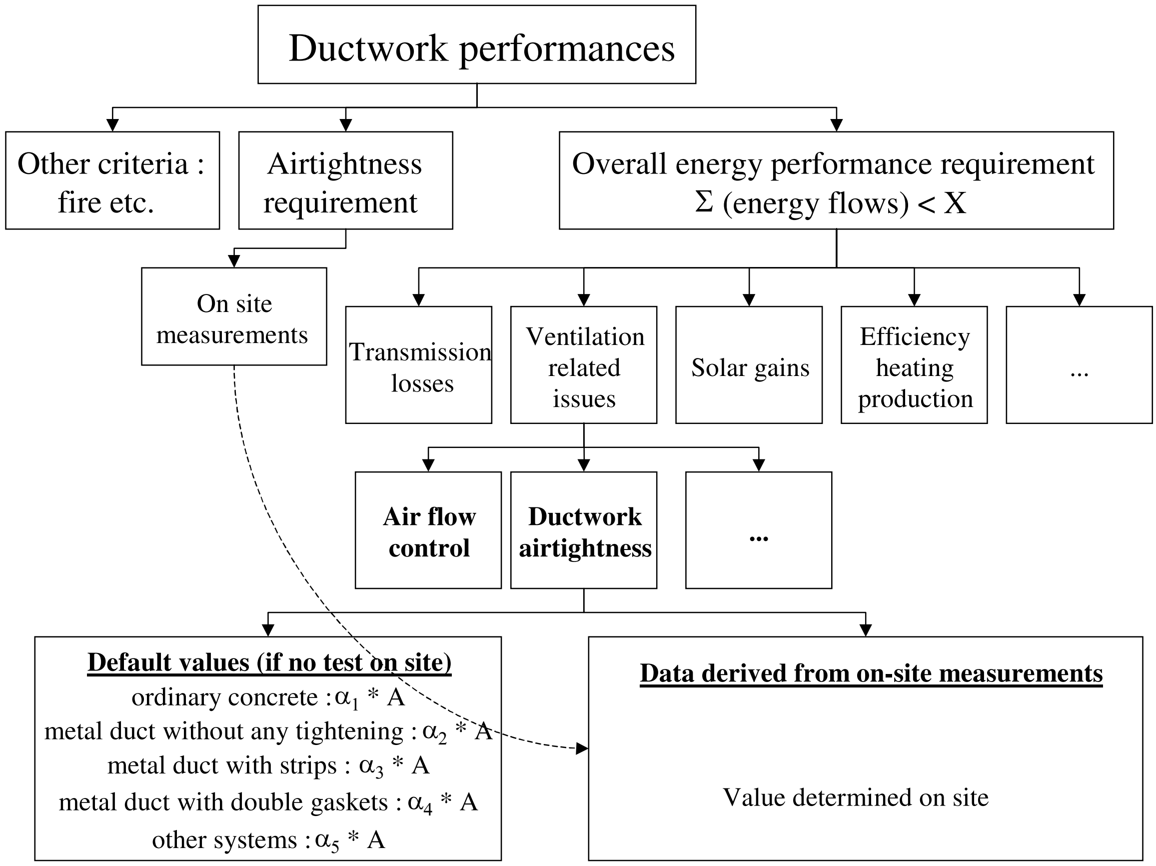

Figure 67: Flow chart of the philosophy of the integration ductwork performances in an energy performance concept.

10.3 Integrating the ductwork airtightness in the system performance

Although some adjustments are needed (see § 10.7.3), currently used leakage tests that express requirements in terms of the leakage factor appear satisfactory for industry standards for sheet-metal ducts as they are compatible with product certification constraints and may be checked on site.

However, integrating ductwork leakage in the system performance goes beyond performing "classical" leakage tests as the way the whole system operates should be taken into account. In principle, performance tests should apply to all types of systems (sheet-metal, fibre-glass board, etc.). It appears natural to express leakage flows as a percentage of the delivered airflow. This system performance approach appears as a very attractive measure towards energy efficiency.

Duct leakage requirements could be as follows:

System class	Maximum value of leakage flow divided by delivered airflow (%)	Increase of fan power demand (%) (assuming cube law, see chapter 7)
I	6 %	20 %
II	2 %	6 %
III	$\frac{2}{3}$ %	2 %
IV	$\frac{2}{9}$ %	0.7 %

Table 29: Proposal for system classes. Requirements are expressed in terms of a maximum value of leakage flow divided by delivered airflow.

It should be noted that as there is no direct relationship between the delivered airflow rate and the system's surface area, the leakage factor concept (on which are based EUROVENT tightness classes) cannot be directly utilised. At the design stage however, a leakage factor class requirement can easily be derived from the desired system class. Thus, there should not be any difficulties to go back and forth between leakage factor and system classes.

Given the commercially-available airflow measurement devices that are practical for in-situ applications, it seems reasonable to require to demonstrate that the leakage airflow rate of the whole system measured by fan-pressurisation at the operating pressure be determined with an accuracy of 0.3 l/s (1 m^3/h) or 10 %, whichever is the greater. Leakage flow rates lower than 0.3 l/s for a typical system should not have a significant impact on its performance. Therefore, the tested area should be chosen such that it is large enough to enable the test apparatus to register a measurable flow with the required accuracy. Large tight systems may require that the whole plant be leak-tested.

10.4 Installation

The issue of proper installation of duct systems is often thought to be linked to the installers' competence. This is certainly true for cleanliness aspects and some components that require careful on-site adjustments. For instance, particular attention should be paid to the connections at the registers (to the ducts and to the building) and at the air handling unit. To obtain improved results with this site work, installation procedures should be well documented and installers should be well trained.

Today, manufacturers propose pre-clean systems that are delivered on site with end-caps to give protection from pollutants (airborne particles, water, etc.). Therefore, it is no longer difficult to obtain clean systems at installation provided that simple rules be observed. Namely, on-site cutting of ducts should be performed with shears as opposed to hacksaws (that produce dust).

The ductwork airtightness is also very sensitive to the workers' skills and the sealing media when conventional sealing techniques are used. However, today's commercially-available products considerably reduce the human factor (chapter 4). In addition to reduced installation time (about 25 % according to the manufacturers), these products are cost-effective both on an investment and on Life Cycle Cost basis despite their initial higher purchase cost[11].

[11] These analyses are presented in Chapter 7 on a real duct system in France. The results are certainly very sensitive to the type of system and the local cost of labour.

10.5 Commissioning

Evidence suggests that commissioning and maintenance plays a major role in securing optimum system performance. Special care should be given to:

- The cleanliness of the system;
- Damaged ducts;
- The airflows at the registers;
- Ductwork airtightness;
- Accessibility (e.g. for filters or cleaning procedures);
- Documentation (detailed drawings of the system, specifications for the materials and devices, instructions for the maintenance) that shall be provided to the building owner or manager;
- The correct functioning of the whole system.

Detailed commissioning protocols can be found in e.g. VVS AMA 83 (1984).

10.6 Operation and maintenance

The management of an air distribution system is a serious task that involves some knowledge on health, and technical background on the operation and maintenance of such systems. Therefore, it certainly deserves a higher status than at present. Also, the technicians whose task is to ensure the proper functioning of these systems should be trained adequately.

10.7 Further work

10.7.1 Rehabilitation

Field measurements performed in Belgium and in France suggest that there is a large building stock that needs rehabilitation. However, as discussed in chapter 4, retrofitting with conventional external-access techniques is tedious, time-consuming, possibly unhealthy, and sometimes even inefficient. Internal-access techniques seem more appropriate for such work. However, very few internal-access sealing techniques are available. The Rolyner® developed by Bergschenhoek seems to be adequate for concrete ducts. The aerosol-based technique commercialised by Aeroseal seems to be promising for other types of ductwork systems, although some development is necessary to adapt it to the European market.

10.7.2 Better knowledge of duct leakage status in Europe

Our knowledge of duct leakage in Europe (except Sweden) relies on about 60 field measurements on a variety of buildings (residential, office, schools, etc.) in Belgium and in France. Whereas the systems were consistently poor as regards airtightness, more leakage measurement data is needed in these countries and in the other member states to enable definite conclusions about the duct leakage status in Europe.

10.7.3 Duct leakage testing

EUROVENT 2/2 guidelines and similar documents have been used for a number of years in Europe for testing ductwork airtightness. However, some aspects of the test procedures need to be clarified. Furthermore, a different protocol should be used if tests are to be performed according to § 10.3.

➢System part to be tested

In the system performance approach, the requirements should not be based uniquely on the air distribution system between the air handling plant and the air terminal devices as it is in most standards. They should be based on the system as a whole. AMA includes the possibility to test a part of a system with most types of equipment, however, the owner decides whether these components shall be part of the leakage test or not. Given the sensitivity of the plant performance to these parts (chapter 6), it appears necessary to give precise requirements on this issue.

➢Test pressure

The reference test pressure varies considerably between different standards. For instance, EUROVENT 2/2 is based on a mean operating pressure of the duct system, whereas in the European pre-standard 12599, Δp_{ref} should be adjusted to 200, 400, or 1000 Pa, whichever is closest to the mean operating pressure of the system. As for DW/143, recommended test pressures are given although “the choice of test pressure shall be at the discretion of the test operator”. Although this may not look like major differences, the extrapolation of a leak flow to a pressure different from the test pressure can lead to large uncertainties in the final results.

Therefore, the test pressures should be well-defined and harmonised. For best results in a system performance test, the test pressure should be set to the operating pressure. For industry standards however, tests should be performed at different pressure stations to ease the comparison between the products. The pressure stations should be representative of the range of operating pressures to which the products will be subjected.

➢Surface area calculation

Most ductwork airtightness standards do not give guidelines on how to calculate the surface area of all parts of an air distribution system. This makes them inappropriate to test systems that include air handling equipment such as a heat exchanger. These calculations are detailed in AMA in which these components are sometimes given a “surface bonus” due to the difficulties to get these parts as tight as the connecting ducts.

This can have a considerable impact on the leakage factor as it is inversely proportional to the tested surface area. Therefore, surface area calculation procedures should be harmonised.

➢Uncertainty analyses

It should be clear how to calculate the uncertainty of the measurements and how to include them in the test report. Uncertainties shall include both bias errors (due to the instruments) and random errors (noise). This remains an area where scientific work is needed.

➢Ready-to-use leakage testers

Ready-to-use duct leakage testers developed by US companies do not seem appropriate for the European market (chapter 6). This is unfortunate as they would be very useful for commissioning or certification purposes in the member states.

10.7.4 Going towards Class D ?

Work has been undertaken for the next AMA generation (AMA 98). Class D (3 times tighter than Class C) is introduced as an option for large circular duct systems.
Indeed, given today’s technology, it seems reasonable to include Class D in CEN ductwork airtightness industry standards.

It also seems reasonable to give incentives for people to require the proposed system Class IV (Table 29). The energy performance approach (§ 10.2) could be an incentive by itself if it includes duct leakage, since severe requirements on airtight ducts appear to be a cost effective solution compared to increasing the insulation level or the efficiency of thermal systems.

10.7.5 Products

Although quality products that quasi-ensure airtight (Class C or D) systems are already commercially-available, research and development in the manufacturing industry would be useful to ease installation, reduce further the human error factor, and obtain even better systems. Namely, the quality of the register–envelope fitting is still quite sensitive to the workers' skills. Also, air handling equipment such as heat exchangers, dampers, etc. should be tighter. Work should be undertaken to get systems with lower pressure drops and thus lower fan energy use. Noisy systems constitute a major source of complaints. In this area, as well, research and development is needed to minimise the noise transmission and generation in duct systems. The design of ventilation products should take into account the cleaning access of the components, as well as the dirt accumulation factor.

Finally, further research is needed to lower the environmental impacts of the manufacturing process of, and the materials used for, air handling equipment.

10.8 Reaching the target

Attractive seminars aimed at HVAC professionals with product demonstrations and case studies could constitute a great complement to this handbook. Original information media should be sought out to reach designers, installers, building managers and building owners, who mostly ignore the benefits of airtight duct systems.

10.9 Cost issues: a major barrier

Any measure for improvement should take into account the fact that a major barrier towards tighter air ducts lies in the cost issues as investment and operating budgets are evaluated sequentially and almost never globally.

10.10 Implications of market transformation

The requirement of tight systems is likely to lead to an increasing use of high-quality ductwork with rubber-seals at the joints. This technology is not straightforward to implement and implies heavy machine-tools investments. However, at present, there exist many small sheet-metal ductwork manufacturers who rely on simple and relatively inexpensive machine-tools to produce their components. These will probably not be able to follow the market as it evolves towards higher technology standards.

10.11 References

1. EUROVENT 2/2. Air leakage rate in sheet metal air distribution systems. EUROVENT / CECOMAF. 1996.
2. HVCA. DW 143 - A practical guide to ductwork leakage testing. Heating and Ventilating Contractor's Association, London, 1994. Copyright 1983.
3. PrEN 12599. CEN pre-standard. Ventilation for buildings – Test procedures and measuring methods for handing over installed ventilation and air conditioning systems. Draft. October 1997.
4. VVS AMA 83. Allmän material- och arbetsbeskrivning för VVS-tekniska arbeten. AB Svensk Byggtjänst. Stockholm 1995. Copyright 1984.

5. VVS AMA 98. Allmän material- och arbetsbeskrivning för VVS-tekniska arbeten. AB Svensk Byggtjänst. Stockholm 1998. Copyright 1998.

Chapter 11 Conclusions

Duct leakage is detrimental to energy efficiency, comfort effectiveness, indoor air quality, and sometimes even to health. However, in most countries designers, installers, building managers and building owners, ignore the benefits of airtight duct systems. Furthermore, as there are no incentives in most countries, over the years, this has (probably) lead to poor ductwork installations in a large fraction of the building stock. In these countries, installation is (probably) often undertaken using conventional *in situ* sealing techniques (e.g. tape or mastic), and therefore the ductwork airtightness is very much dependent upon the workers' skills. Field studies suggests duct systems in Belgium and in France are typically 3 times leakier than EUROVENT Class A (chapter 6).

Simple analyses on specific cases can be made to show that the overall performance of the systems is drastically affected when the ducts are that leaky (chapter 7). Furthermore, projections at the European level, based on available measurement data, suggest potentially large energy impacts of duct leakage (chapter 8). However, it is possible and easy to install tight duct systems with quality commercially-available products. In Sweden, where factory-fitted sealing gaskets are widely used, airtightness Class C is commonly required and fulfilled (chapter 6). Furthermore, the additional investment cost (if any) for these products is probably not very significant since the labour cost is considerably reduced. In addition, the duct systems installed today are likely to be used for at least the next twenty to fifty years. A possibly higher investment cost for a higher quality duct system should be considered on a Life Cycle Cost (LCC) basis and not just on the first cost (chapter 7).

Although the situation appears to be quite satisfactory in Sweden compared to other countries, even tighter requirements are being considered. Today's technology, and the increasing concern for energy conservation and environmental impacts are among the reasons that are raised for this step. In summary, the investigations presented in this handbook lead to the conclusion that the ventilation and energy use implications of leaky ducts are large and merit further examination. Namely:

1. Field work seems to be necessary to better evaluate the extent of duct leakage in the building stock;
2. There is a need for harmonised ductwork airtightness test and analysis protocols for all types of ductwork. Ready-to-use duct leakage testers should be designed accordingly;
3. Retrofitting of poor installations should be seriously considered. Further research and development work in this area seems to be necessary;
4. Cost analyses were performed on one real system. As the results are sensitive to many local parameters, such as the cost of labour, further analyses would be useful to better evaluate the cost implications of different options;
5. However, since it can be safely stated that quality products are very efficient and reasonably expensive, they have probably not been marketed correctly. Significant efforts should be made by the manufacturing industry in this area;
6. Finally, in the context of energy conservation, governmental measures such as those proposed in chapter 10 should probably be considered to promote tight air duct systems.

Appendices

Appendix A: Overview of the SAVE-DUCT project

Scope of SAVE-DUCT project

Since the efficient use of energy reduces the emission of pollutants to the atmosphere, it has been hailed as the single most important policy objective towards attaining the EU's stated goal of stabilising CO_2 emissions. In recognition of this fact, the SAVE programme (“Specific Action on Vigorous Energy Efficiency” - Directorate-General for Energy (DG XVII)) has been recognised by the Commission as a cornerstone of the Community's CO_2 reduction strategy.

SAVE is the European Union non-technological programme aimed at promoting the rational use of energy within the Union. SAVE II is the follow-up to the original SAVE which ran from 1 January 1991 to 31 December 1995. The SAVE II programme was adopted by the Council of Ministers on 16 December 1996 and will run until 31 December 2000 (Council decision 86/737/EC, OJ No L 335/ 24 12 96 p. 50).

The completion of this handbook depended upon investigations carried out within the framework of the DUCT project (1997-1998) that was funded in part by the SAVE II programme. The objectives of DUCT may be summarised as follows:

1. Quantify duct leakage impacts;
2. Identify and analyse ductwork deficiencies;
3. Propose and quantify improvements;
4. Propose modifications to existing standards.

DUCT involved five teams representing three different countries:

- Ecole Nationale des Travaux Publics de l'Etat, Lyon, France;
- Belgian Building Research Institute, Brussels, Belgium;
- ALDES Aéraulique, Lyon, France;
- SCANDIACONSULT, Stockholm, Sweden;
- Centre d'Etudes Techniques de l'Equipement, Lyon, France.

The following persons have contributed to DUCT :

François Rémi Carrié (ENTPE, co-ordinator), Johnny Andersson (SCANDIACONSULT), Emmanuel Balas (CETE), Emmanuel Berthier (CETE), Serge Buseyne (Quiétude Ingénierie), Alain Bossaer (BBRI), Pierre Chaffois (ALDES), David Ducarme (BBRI), Jean-Claude Faÿsse (ALDES), Olivier Faure (ALDES), Marc Kilberger (CETE), Vincent Patriarca (CETE), Peter Wouters (BBRI).

Kenneth Lennartsson (Lindab Ventilation AB) and Peter Bulsing (Bergschenhoek B.V.) are greatly acknowledged for his interest in the project and valuable input.

Tasks and tasks allocations

DUCT was divided in four phases:

1. State of the art;
    1.1 Codes and standards (Task 1);
    1.2 Duct leakage data and rehabilitation techniques (Task 2);
    1.3 Survey of HVAC manufacturers and contractors (Task 3);
2. Field measurements (Task 4);
3. Data analysis (Task 5);
4. Implementing the results;
    4.1 International seminar on air distribution in buildings: airtightness aspects (Task 6);
    4.2 Publication (Task 7).

Description	Task Leaders
1. Codes and standards	BBRI
2. Existing duct leakage data and rehabilitation techniques	SCANDIACONSULT
3. Survey of HVAC manufacturers and contractors	ALDES
4. Field measurements	CETE
5. Data analysis	ENTPE
6. Seminar in Brussels	BBRI
7. Publication/final report	ENTPE

SAVE-DUCT project participants

Designation	Address	Tel / Fax / http	Contact person
Ecole Nationale des Travaux Publics de l'Etat Département Génie Civil et Bâtiment URA CNRS 1652 Laboratoire des Sciences de l'Habitat (LASH)	2 rue Maurice Audin F - 69518 Vaulx en Velin Cedex France	Tel : (+33) 4 72 04 70 31 Fax : (+33) 4 72 04 70 41 http://www.entpe.fr	François Rémi Carrié (Remi.Carrie@entpe.fr)
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ALDES Aéraulique	20 Blvd Joliot Curie F - 69200 Vénissieux France	Tel : (+33) 4 78 77 15 15 Fax : (+33) 4 78 76 15 97	Jean-Claude Faÿsse
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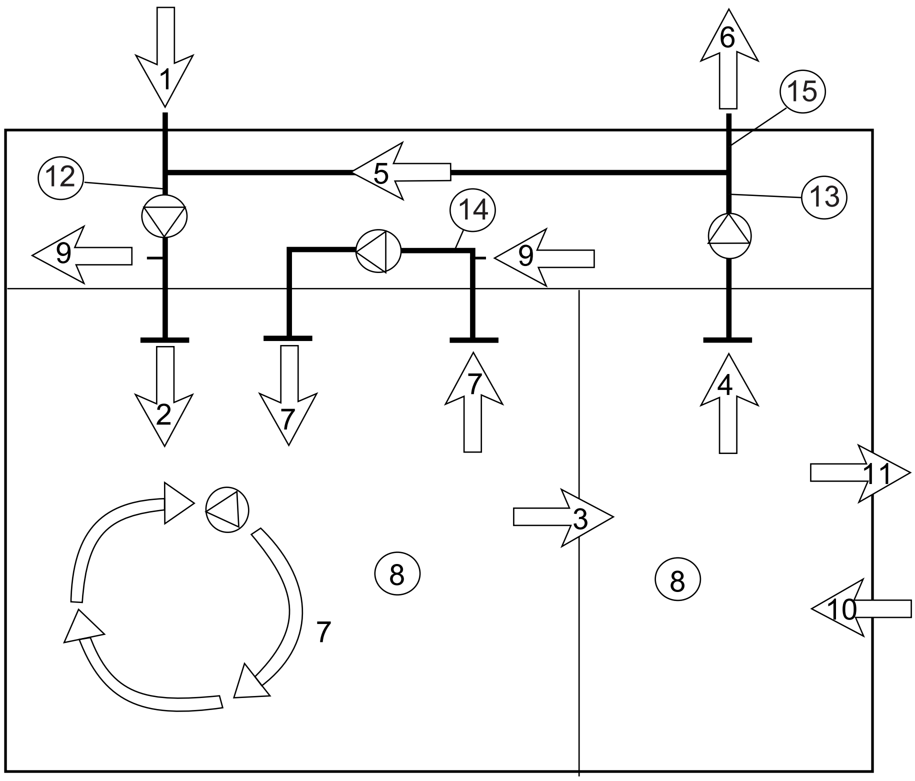
Appendix B: Terminology, symbols, and useful constants

Terminology



1.	Outdoor air	
2.	Supply air	Air brought to a room. Can be a mixture of outdoor air, circulated air, return air, or transferred air
3.	Transferred air	Air transferred from room to room
4.	Extract air	Air taken out of a room
5.	Return air	Extract air returned to a group of rooms
6.	Exhaust air	Extract air delivered to the outside
7.	Circulated air	Air circulated in a room
8.	Inside air	
9.	Duct leakage	Unintended inward or outward airflow through duct leaks
10.	Infiltration	Air leakage into the building through leakage paths in the structure separating it from external air
11.	Exfiltration	Air leakage out of the building through leakage paths in the structure separating it from external air
12.	Supply duct	Duct that carries supply air
13.	Extract duct	Duct that carries extract air
14.	Return duct	Duct that carries return air
15.	Exhaust duct	Duct that carries exhaust air

Quantities and Units

Symbol	Quantity	Units	
Δp	pressure difference	Pa	(N/m^2)
Δp_{ref}	reference pressure difference	Pa	(N/m^2)
A	surface area	m^2	
C	leakage coefficient	$m^3\ s^{-1}\ Pa^{-n}$	
C_d	discharge coefficient	-	
c_p	specific heat capacity at constant pressure	$J\ kg^{-1}\ K^{-1}$	($kJ\ kg^{-1}\ K^{-1}$)
E	energy	J	(N m)
ELA_{ref}	effective leakage area at Δp_{ref}	m^2	
f_{ref}	leakage factor at Δp_{ref}	$m^3\ s^{-1} m^{-2}$	($l\ s^{-1}\ m^2$)
h	specific enthalpy	J/kg	
K	leakage coefficient normalised by duct surface area	$m^3\ s^{-1} m^{-2}\ Pa^{-n}$	($l\ s^{-1}\ m^2\ Pa^{-n}$)
l, L	length	m	
L_θ	latent heat of vaporisation at temperature θ	J/kg	(kJ/kg)
m	mass	kg	
n	flow exponent	-	
p	pressure	Pa	(N/m^2)
P	power	W	(J/s)
q, Q	airflow	m^3/s	(l/s)
t	time	s	
T	thermodynamic temperature	K	
U	estimated U-value	$W\ m^{-2}\ K^{-1}$	
x	vapour ratio	kg/kg	(g/kg)
θ	Celsius temperature	^oC	
ρ	density	kg/m^3	

Useful constants

1 atmosphere = 1.01325 10^5 Pa
Density of air at 20°C = 1.205 kg/m^3
Density of water at 20°C = 1000 kg/m^3
Latent heat of vaporisation of water at 0°C = 2490 kJ/kg
Specific heat capacity at constant pressure of air = 1.002 $kJ\ kg^{-1}\ K^{-1}$
Specific heat capacity at constant pressure of liquid water = 4.187 $kJ\ kg^{-1}\ K^{-1}$
Specific heat capacity at constant pressure of water vapour = 1.86 $kJ\ kg^{-1}\ K^{-1}$

Since the efficient use of energy reduces the emission of pollutants to the atmosphere, it has been hailed as the single most important policy objective towards attaining the EU's stated goal of stabilising CO_2 emissions. In recognition of this fact, the **SAVE programme** ("Specific Action on Vigorous Energy Efficiency" - Directorate-General for Energy (DG XVII)) has been recognised by the Commission as a cornerstone of the Community's CO_2 reduction strategy.

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The **Air Infiltration and Ventilation Centre** was inaugurated through the International Energy Agency and is funded by the following twelve countries:

Belgium, Denmark, Finland, France, Germany, Greece, Netherlands, New Zealand, Norway, Sweden, United Kingdom, United States of America.

The Air Infiltration and Ventilation Centre provides technical support in air infiltration and ventilation research and application. The aim is to provide an understanding of the complex behaviour of the air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

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Fax: +44 (0)24 7641 6306
Email: airvent@aivc.org
Web: http://www.aivc.org/

EVENTS AND WEBINARS

International workshop on

"Large scale national implementation plans for building airtightness assessment : a must for 2020!"

"We should start now to be ready in 2020"

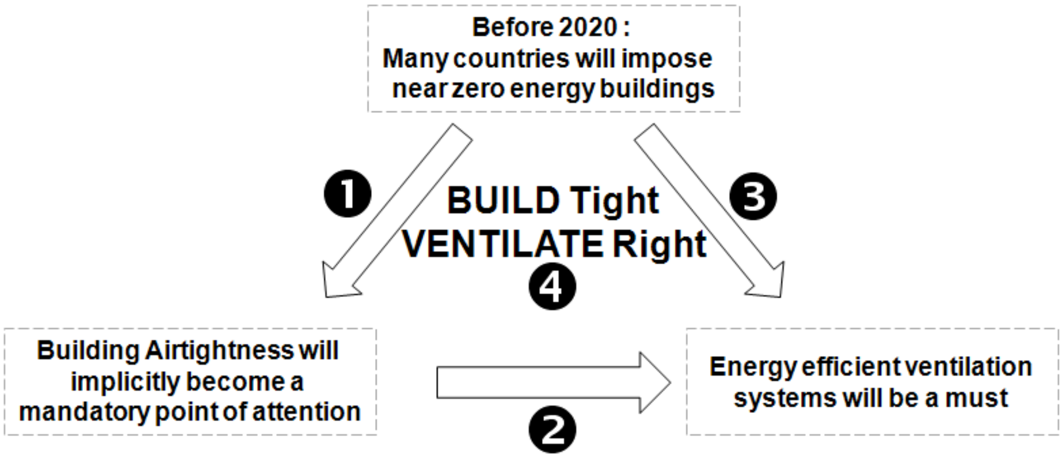
June 14-15 2010 in Hotel Crowne Plaza – Brussels (Belgium)

An initiative of AIVC and INIVE

Context for the workshop

It is expected that many countries will between 2015 and 2020 have regulations imposing requirements for new buildings which are **near-zero energy targets**. This has major consequences:

– Such strategies will for most climates automatically lead to specific attention to **building airtightness** (❶), including large scale measurements, challenges in terms of design and execution, quality issues, long term performances, ... This is a tremendous challenge.
– As a result of the increased attention for building airtightness, the need for appropriate, energy efficient, **ventilation systems** (❷)will grow. Issues as correct air flow rates, air quality, acoustics, draught, energy optimisation, economics, ... will have to be handled at large scale. At present, we know that many countries are faced with poor performances of most systems.
– So, indirectly, the move towards near-zero energy buildings will lead to a greater need for ventilation systems (❸).
– As a result, the expression already used in the eighties, i.e. 'Build Tight – Ventilate Right' is becoming a big reality(❹).



– In addition, there are the tremendous challenges for the existing building stock. Although there will be in most countries more time for implementation and, in absolute terms, probably less severe targets, more or less similar challenges are found for the existing building stock.

This international workshop aims to give a good overview of all the issues involved in building airtightness, with specific attention to planning aspects (session 2), execution (session 3) and evaluation (session 4).In session 5, attention will be given to the point of view of key stakeholders.

During the workshop, the European Platform on Building Airtightness will be launched and it is planned to have follow-up sessions on specific topics.

Dates

The workshop will start on Monday June 14 at 13.30 (registration and welcome coffee at 12.30) and will end on Tuesday June 15 at 17.00

Location

Crowne Plaza Brussels Le Palace
Rue Gineste 3, BE-1210 Brussels, Belgium
Website : http://www.crowneplazabrussels.be

Hotel reservation

A contingent of rooms in hotel Crowne Plaza Brussels Le Palace has been taken until 21 May 2010. To benefit of the preferential rate of 159 € (breakfast excluded, taxes and wireless internet connection included), **Click here** to proceed directly to the reservation desk.

Crowne Plaza Brussels City Centre Le Palace
Rue Gineste 3, BE-1210 Brussels, Belgium
☎+32.2.203.62.00 - 🖷 +32.2.203.55.55
E-mail : reservations@cpbxl.be – info@cpbxl.be
Website : http://www.crowneplazabrussels.be

Language

The workshop will be held in English. No translation is foreseen.

Fee

The workshop fee is 363 € (VAT included). This fee includes participation to the workshop, documentation, the walking dinner on Monday evening, the lunch on Tuesday and coffee breaks.

Registration

Participants should enrol by returning the registration form available on the AIVC website and pay the registration fee before June 1st, 2010.

More information

For any information, please contact Stéphane Degauquier at INIVE EEIG (Belgian Building Research Institute - BBRI):
Avenue P. Holoffe 21, BE-1342 Limelette, Belgium
☎+32.2.655.77.11 - 🖷 +32.2.653.07.29
E-mail : sd@bbri.be

Sponsoring

In order to allow a large number of interested parties to participate at this workshop and to have an efficient follow-up of this initiative, sponsoring is foreseen:

– There is financial support by Eurima, Lindab, Proclima, Soudal and Tremco Illbruck. REHVA supports the workshop as well.

– The workshop receives support from the Brussels Region (“Technological guidance actions eco-construction”), the Flemish Region (Flemish Energy Agency and the Technological guidance actions Sustainable Building Envelope) and the Walloon Region (Support to the participation in the AIVC).

Programme

Monday June 14 2010

12.30 Opening of registration

13.30 session 1 : Welcome and context for building airtightness

1. General welcome and context of this workshop (including some data on European building market)
   P. Wouters, INIVE, Belgium
2. EU IEE activities on energy efficiency in buildings
   G. Sutherland, EACI project officer
3. Importance of building airtightness in overall energy efficiency strategies
   R. Carrié, CETE de Lyon, France
4. Experiences from practice
   a. Experiences from the USA
      M. Sherman, LBL, USA
   b. Meaning of the envelope airtightness in cold and mild climate regions under wider perspectives for energy conservation in residential buildings
      T. Sawachi, BRI, Japan
   c. The change and course in airtightness levels of Dutch dwellings over the last 60 years – reasons behind and measures taken
      W. de Gids, TNO, Netherlands

15.30 break

16.00 Session 2 : PLANNING of airtight envelopes

1. Intro by the session chairmen
2. Importance of careful airtightness design to avoid improvised solutions on site – the Passive House approach
   M. Bodem, ING + ARCH partnership, Nürnberg, Germany
3. Design, market transformation and cost considerations in Norway
   P.G. Schild (SINTEF), S. Holøs (SINTEF), T. Aurlien (UMB), T-O. Relander (NTNU), Norway
4. Long term performance and durability of seals and bonds
   R. Gross, Center for conservation-conscious building, Kassel, Germany
5. Airtightness prediction
   N. Van den Bossche (UGent) and J. Langmans (KU Leuven), Belgium
6. Importance of a correct overall performance assessment – probability assessment of performance and costs
   C.-E. Hagentoft, operating Agent IEA ECBCS Annex 55, Sweden
7. Cost considerations
   A. Zhivov, USACE, USA

18.00 End

19.30 Walking Dinner with keynote in hotel Crowne Plaza

Tuesday June 15 2010

9.00 Session 3 : EXECUTION of airtight envelopes

1. Intro by the session chairmen
2. Overview of available technologies for building airtightness
   General introduction (W. de Gids, TNO, Netherlands) with specific solutions from industry representatives
3. The need for quality management – overview of possible instruments and practical examples
   P. Wouters

10.30 break

11:00 Session 4 : EVALUATION of the airtightness

1. Intro by the session chairmen
2. The role of the ISO standard - Revision of ISO 9972/EN 13829
   Hiroshi Yoshino, ISO Convenor, Japan
3. Fan pressurisation measurements; what kind of uncertainties? Round Robin tests
   Max Sherman, LBL, USA
4. Qualification of airtightness measurers and framework of quality management- the French approach
   R. Carrié, CETE de Lyon, France
5. Practical experience on large buildings
   a. Ian Mawditt, Building Sciences, UK

12:30 Lunch

13.30 Session 5: Challenges and opportunities for the stakeholders

Panel 1 :**Governments and clients**
- W. Roelens, Flemish Energy Agency, Belgium
- S. Alvarez, University of Seville, Spain
- B. Wallyn, CECODHAS (The European liaison committee for social housing)
- A. Zhivov, USACE, USA
- T. Sawachi, Building Research Institute, Japan

Panel 2 : **Suppliers and executers**
- Pekka Vuorinen, FIEC (European federation of Building contractors)
- Representative from consulting engineers (EFCA)
- Representative from CEPMC (European federation of Building material suppliers)
- Representative from architects

15:00 Break

15:30 Closing session
- Lessons learned & summing up : Martin Liddament, International Journal on Ventilation
- The need for a platform approach - The role of AIVC - Launch of the European Platform on Building Airtightness
- Conclusions and next steps

17:00 End of workshop

Envelope airtightness measurement method and equipment
Building preparation and uncertainty estimation

Webinar
17 September 2010 08.30-10.30

Envelope airtightness is an important feature for low-energy, well-ventilated buildings. With the objective to generalize zero-energy buildings by 2020, several countries have to stimulate a market transformation for better envelope airtightness. This has been identified as a major challenge in the ASIEPI project, with several underlying issues to resolve, among them, the need to clarify the measurement protocol to complete legally robust airtightness rewards and penalties.

The objective of this webinar were to discuss proposals:
- to better define the building preparation ;
- to estimate the uncertainty in the derived quantities which are used as a reference versus a minimum requirement and/or in energy performance calculation methods.

This Webinar was a follow up of the ASIEPI project (www.asiepi.eu) funded under the Intelligent Energy Europe programme. It was an initiative of the Building Airtightness Platform Europe whose aim is to be the central European information point on all aspects related to Building Airtightness.
Visit us at http://www.buildup.eu/communities/airtightness and http://www.asiepi.eu/wp-5-airtightness.html .

Programme

Click on the presentation title to access the recording of the presentation, available on internet!

INTRODUCTION OF THE EVENT AND OBJECTIVES

Speaker : Rémi Carrié, CETE de Lyon, France & Willem de Gids, TNO, The Netherlands
Duration : 3 minutes

ESTIMATING THE UNCERTAINTIES OF AN AIRTIGHTNESS MEASUREMENT

Speaker : Max Sherman, Lawrence Berkeley National Laboratory, USA
Duration : 17 minutes

THE ISO 9972 REVISION PROCESS

Speaker : Hiroshi Yoshino, Tohoku University, Japan
Duration : 19 minutes

Exchanges with participants

Chairman : Rémi Carrié, CETE de Lyon, France
Duration : 16 minutes

LESSONS LEARNT FROM PRACTICE ON BUILDING PREPARATION IN GERMANY
+ Exchanges with participants

Speaker : Stefanie Rolfsmeier, BlowerDoor Gmbh, Germany
Duration : 27 minutes

STATING NON-COMPLIANCE AND ITS LEGAL CONSEQUENCES : THE UK EXPERIENCE

Speaker : David Unwin, Tom Jones, BSRIA, UK
Duration : 19 minutes

General discussion – Conclusion – Polling

Chairman : Rémi Carrié, CETE de Lyon, France
Duration : 35 minutes

What is a webinar?
A webinar is a conference broadcasted on internet.

Hardware, software
Our webinars are powered by WebEx Event Center. The only thing you need is a computer with a sound card and speakers. Before you can watch the recordings, WebEx will install the required application.

ASIEPI web event 1

Ways to stimulate a market transformation of envelope airtightness - Analysis of on-going developments and success stories in 5 European countries

Date: 12 December 2008, 10:00-12:00 GMT+1 (Paris time)

Envelope airtightness is an important feature for low-energy, well-ventilated buildings. Germany has produced a continuous effort on this issue during the past two decades. More recently, there has been an increasing interest for this issue in some other European countries, with interesting developments to further stimulate the market.

The objective of this WebEvent is to give you :

- an overview of those interesting developments in Belgium, France, Finland, and Norway;
- feed-back on the German experience;
- an opportunity to give your point of view.

Event page: http://www.asiepi.eu/wp-5-airtightness/web-events/web-event-1.html

Ways to stimulate a market transformation of envelope airtightness - Analysis of on-going developments and success stories in 5 European countries
Brief presentation of the ASIEPI project *by Rémi Carrié, CETE de Lyon, WP5 leader*
Introduction in the building airtightness issue bridges as covered in ASIEPI *by Rémi Carrié, CETE de Lyon*
Airtightness revival in Norway *by Aurlien Tormod, SINTEF*
Recent steps towards the generalization of airtight buildings in France *by Rémi Carrié, CETE de Lyon*
Recent market trends in Belgium *by Nicolas Heijmans, BBRI*
Over two decades of experience with airtight buildings in Germnay *by Bernd Rosenthal, E-U-Z*
Questions
Conclusion and closure *by Rémi Carrié, CETE de Lyon, WP5 leader*

ASIEPI web event 7

How to improve ductwork airtightness – Ongoing developments and success stories in Europe

Date: 16 December 2009, 10:00-12:00 GMT+1 (Brussels time)

Several studies have shown that ductwork air leakage can significantly affect the energy performance and indoor air quality in buildings. Scandinavian countries identified this issue over 50 years ago. For example, the first requirements on ductwork airtightness were introduced in Sweden in 1950, and the use of components with certified pre-fitted seals is now in standard use. Other countries are now tackling the same problems, due to increased use of ducted ventilation systems, some with heat recovery, heating or cooling. Despite this, the interest for airtight ducts in most European countries has remained low until now.

The objective of this WebEvent is to give you :

- an overview of energy impacts and calculation procedures;
- an overview of duct leakage measurement methods;
- a feed-back on the Scandinavian experience and how it can be applied in your country;
- an opportunity to give your point of view and ask questions.

Event page: http://www.asiepi.eu/wp-5-airtightness/web-events.html

How to improve ductwork airtightness – Ongoing developments and success stories in Europe
Introduction to the event *by Dr. Peter Schild, SINTEF Buildings & Infrastructure, Norway*
Duct leakage problems & consequences in EU *by Samuel Caillou, BBRI, Belgium*
Including leakage in energy calculations *by Dr. Jean-Robert Millet, CSTB, France*
Leakage testing methods/requirements *by Dr. Peter Schild, SINTEF Buildings & Infrastructure, Norway*
Practical solutions for airtight ductwork *by Lars Åke Mattsson, Lindab, Sweden*
The Scandinavian success story *by Jorma Railio, FAMBSI, Finland*
Questions, open exchanges on success stories
Conclusion and closure *by Dr. Peter Schild, SINTEF Buildings & Infrastructure, Norway*

TIGHTVENT PARTNERS

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PARTNER PRESENTATION

The Buildings Performance Institute Europe (BPIE) is an independent, non-profit organisation based in Brussels and has been in operation since February 2010. It was created following the acknowledgment of the need for initiative and strengthened action to improve energy performance in buildings in a currently dynamic EU energy policy environment. BPIE is dedicated to improving the energy performance of buildings across Europe, and thereby helping to reduce CO_2 emissions from the energy used by buildings.

BPIE acts as a strong European centre of promoting energy efficiency in buildings, and thereby contributing to the reduction of CO_2 emission levels both at EU and Member State level. Specifically, BPIE acts as:

- a reference point in Europe for credible and structured information about developments, trends, barriers and solutions for improving energy efficiency in buildings;
- a centre for European-wide dissemination of best available technologies and practices;
- a centre for promotion of global cooperation in the energy performance of buildings.

BPIE's mission is to support the development of ambitious but pragmatic building-related policies and programs at both EU and Member State levels, and timely drive the efficient implementation of these policies by teaming up with relevant stakeholders from the building industry, consumer bodies, policy and research communities.

MOTIVATIONS FOR TIGHTVENT

Meeting the 2020 targets requires major actions from all stakeholders at both EU and Member State levels. In the building sector, there are two main challenges ahead. The first one is associated with the realisation of nearly zero-energy buildings and what these actually mean in different regions of Europe. The rehabilitation of existing buildings with poor performance levels is the second but most important challenge both in terms of scale and complexity.

Building solutions for both new and existing buildings must be a holistic effort integrating a number of elements. Airtightness is one of them. Although airtightness currently receives low attention around the EU, it will become increasingly important both in the discussion of nearly zero-energy buildings, as well as in the efforts to transform EU's existing stock into high energy efficient buildings. The first and most apparent reason is related to environmental benefits as leakier buildings emit higher CO_2 levels. Airtightness also affects the indoor air quality and can be a key ingredient to healthy buildings. This is why airtightness must always be considered in parallel with adequate ventilation.

As the pressure for more stringent building regulations will increase, so will the demand for airtightness and ventilation measures. Information on available solutions, tests and issues related to airtightness measures will be of increasing demand. So will the issue of ventilation. The TightVent platform can play a key role in facilitating the information exchange necessary to support this process. BPIE strongly supports the TightVent objectives and its activities.

RELEVANT PROJECTS

The BPIE project on nearly zero-energy buildings aims to support the discussion of mandatory low-energy buildings from 2020. To make concrete steps into this direction, a common and cross-national understanding of the potential principles of such buildings and their market implications will be identified. Technical solutions will require, inter alia, the inclusion of airtightness and ventilation measures.

BPIE is currently undertaking a project on the European buildings and buildings policies across all 27 Member States. This is one of the most thorough studies ever undertaken in Europe on the building sector gathering data (including airtightness) that has never been done before and collating a lot of policy information as well. The study is realised together with industry: EuroACE, Eurima, PU Europe and Glass for Europe.

For more information about the BPIE projects, please visit www.bpie.eu

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PARTNER PRESENTATION

The European Climate Foundation (ECF) aims to promote climate and energy policies that greatly reduce Europe's greenhouse gas emissions and help Europe play an even stronger international leadership role in mitigating climate change. The ECF has identified four main areas for intervention in Europe: Energy Efficiency in Buildings and Industry, Low-Carbon power generation, Transportation, and EU Climate Policies and Diplomacy.

HOW WE WORK

The European Climate Foundation is dedicated to supporting the development and implementation of well-crafted climate and energy policies that greatly reduce Europe's global greenhouse gas emissions. ECF builds alliances among a wide range of partners in government, business and the NGO sector.

The majority of the European Climate Foundation's funds are re-granted to organisations engaged in trying to bring about meaningful policy change. The ECF is, however, also engaged in direct initiatives, such as commissioning of papers, convening of meetings and the launching of new organisations.

MOTIVATIONS FOR TIGHTVENT

In the buildings sector, our goal is to ensure a meaningful improvement in the energy efficiency of both new and existing buildings. While the newly recasted Energy Performance of Buildings Directive (EPBD) creates a strong incentive towards 'near zero-energy' new buildings by the end of the decade, the progress regarding existing buildings has been slower. What is clear is that, for both new and renovated buildings, new energy efficiency requirements will require, for most climates, an increase in building airtightness, which will in turn require improved ventilation systems. ECF supports the TightVent platform in its mission to create support for proper implementation of the EPBD recast and to help policy makers, industry, developers and other stakeholders in the deployment of low-energy buildings.

RELEVANT PROJECTS

For the last couple of years, the ECF has been helping build the groundwork of technical analysis and advocacy support that can help translate closed-door technical discussions among energy efficiency experts into a high-level political debate. The ECF supports technical and advocacy capacity and the establishment of multi-stakeholder coalitions. In doing so ECF is building coalitions with industries both in Brussels and in many European countries, and awarded several grants to NGOs to advocate for strong national and EU buildings energy efficiency policies.

Below we describe a few examples of buildings efficiency-related research and projects supported by the ECF:

- The ECF supported in 2009 the Institute of International and European Affairs (IIEA) in Ireland to examine the feasibility of a national building energy efficiency retrofit programme in the country, including the potential for hypothecating revenue from a national carbon tax towards the programme.
- In early 2010, the ECF supported the Central European University (CEU) to carry out a study on the employment impacts of a large-scale deep building energy efficiency retrofit programme in Hungary. The study demonstrated the double benefit of radically improving energy efficiency in buildings as well as creating a significant number of new jobs.
    - In 2010, ECF supported analysis and activities around a proposed Green Investment Bank and Green Energy Deal for the UK. The Green Deal energy efficiency policy is a flagship programme for the UK's coalition Government, aiming to create a framework to enable households and smaller business to make energy efficiency investments with no upfront cost, by attaching the loan to the property and not to the individual. In March 2011 the UK Government announced that the Green Investment Bank (GIB) would receive £3bn in start-up funding, beginning in 2012.

A full list of projects supported by the ECF can be found at www.europeanclimate.org.

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PARTNER PRESENTATION

Eurima is the European Insulation Manufacturers Association. Eurima members manufacture mineral wool insulation products. These products are used in residential and commercial buildings as well as in industrial facilities. Glass and stone wool insulation secure a high level of comfort, low energy costs and minimised CO_2 emissions. Mineral wool insulation prevents heat loss through roofs, walls, floors, pipes and boilers, reduces noise pollution and protects homes and industrial facilities from the risk of fire.

THE EURIMA ECOFYS STUDIES

Since 2002, Eurima has been working with Ecofys, an independent and international consultancy specialised in energy saving and renewable energy solutions, to develop a deeper understanding of the energy savings and climate change mitigation potential of buildings.

EURIMA AND TIGHVENT

The recast of the EBPD (2010/30/EU) makes nearly zero-energy buildings (NZEB) compulsory in the near future. That requires a good coordination between strong insulation and good functioning ventilation in order to guarantee both energy efficiency and good indoor air quality. TightVent seeks such solutions, develops the thinking about it and should provide increasing insight.

AIRTIGHTNESS SOLUTIONS

Insulation is not a specific airtightness solution. But calculation methods, as well as, installation practice need updating in view of the double aim of good energy efficiency and good indoor air quality in residential buildings.

RELEVANT PROJECTS

The ASIEPI project (www.asiepi.eu) was closely followed by Eurima's Technical Committee (TC). Eurima's TC gave feedback to the consortium on the documents produced. The members appreciated the work done with regard to airtightness and the ability of ASIEPI documents to explain complex technical issues in an understandable language.

EURIMA CORPORATE MEMBERS ARE:

FIBRAN S.A - Insulating Materials Industry, FLUMROC AG, GLAVA AS, IZOCAM TICARET VE SANAYI A.S, KNAUF INSULATION HOLDING GmbH, ODE Yalıtım A.S., PAROC Group Holding Oy, ROCKWOOL INTERNATIONAL A/S, SAGER AG, SAINT-GOBAIN ISOVER FRANCE S.A., SCHWENK DÄMMTECHNIK GMBH & CO. KG, URSA INSULATION S.A. - GRUPO URALITA

EURIMA AFFILIATED MEMBERS:

Eurima has 18 affiliated members (Mineral Wool National Associations) throughout Europe.

EUROPE MUST GO

→ **Deep Renovation** of the EU building stock **must become a priority**. The potential of an **80% reduction of energy consumption** in buildings **by 2050**, will be a key enabler for the EU to meet its long-term climate goals, reduce the need for energy imports and eliminate fuel poverty

→ **Europe's Energy Policy** should include an ambitious plan to increase **quantity** and **quality** in building renovation. The current **annual renovation rate must be at least tripled** whilst ensuring that each refurbishment brings **significant improvement of energy performance**

→ **Energy efficiency** and deep renovation of buildings through measures such as **mineral wool insulation**, will create European **sustainable jobs, boost higher and professional education** and above all will help citizens **save billions of Euro** annually

→ **Partial**/sub-optimal renovation of buildings **will not deliver** to the EU its environmental objective of cutting **80%-95%** of its **CO_2 emissions** by 2050. Buildings are responsible for **40%** of the total EU energy consumption and **36%** of CO_2 emissions. Deep renovation of an existing building can improve its energy performance by up to **85% to 90%**

DEEP Renovation is the motto for Europe, with a **new focus** on **existing buildings.**
Europeans are counting on policy makers to act!

SUSTAINABLE ENERGY EUROPE

www.eurima.org

eurima
European Insulation Manufacturers Association

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PARTNER PRESENTATION

INIVE (International Network for Information on Ventilation and Energy Performance) is a registered European Economic Interest Grouping (EEIG), whereby from a legal viewpoint its members act together as a single organisation and bring together the best available knowledge from its member organisations. The present members are:

- BBRI - Belgian Building Research Institute, Belgium
- CETIAT - Centre Technique des Industries Aérauliques et Thermiques, France
- CIMNE - International Center for Numerical Methods in Engineering, Spain
- CSTB - Centre Scientifique et Technique du Bâtiment, France
- eERG - End-use Efficiency Research Group, Politecnico di Milano, Italy
- ENTPE - Ecole Nationale des Travaux Publics de l'Etat, Vaulx en Velin, France
- IBP - Fraunhofer Institute for Building Physics, Germany
- SINTEF - SINTEF Building and Infrastructure, Norway
- NKUA - National & Kapodistrian University of Athens, Greece
- TMT US - Grupo Termotecnia, Universidad de Sevilla, Spain
- TNO - TNO Built Environment and Geosciences, business unit Building and Construction – The Netherlands

These organisations cover a wide range of expertise in building technology, human sciences and dissemination/publishing of information. They also actively conduct research in this field - the development of new knowledge will always be important for INIVE members.

INIVE has multiple aims, including the collection and efficient storage of relevant information, providing guidance and identifying major trends, developing intelligent systems to provide the world of construction with useful knowledge in the area of energy efficiency, indoor climate and ventilation. Building energy-performance regulations are another major area of interest for the INIVE members, especially the implementation of the European Energy Performance of Buildings Directive (EPBD) and its recast.

With respect to the dissemination of information, INIVE EEIG aims for the widest possible distribution of information.

MOTIVATIONS FOR TIGHTVENT

Building and ductwork airtightness represent a key challenge towards very low-energy buildings and therefore towards the ambitious 2020 targets set in the EPBD recast. The TightVent Europe platform aims at meeting the obvious need for a strong and concerted initiative to overcome this challenge.

The target audience of the TightVent Europe activities is wide and ranges from the research community over designers, practitioners and the supply industry to European governmental policy makers. It is clear that awareness raising is key in the start-up phase, whereas in time the emphasis should move to providing the appropriate support tools and getting the knowledge into the market.

Since this action clearly fits within the objectives of INIVE, i.e. collection and dissemination of knowledge on energy efficiency and ventilation in buildings, INIVE strongly supports and acts as the facilitator of TightVent Europe. INIVE is strongly interested to gather knowledge through TightVent for actions such as raising the awareness of all building professionals, developing improved training courses, or helping professionals in the development of quality management approaches. INIVE also believes that there are areas that need to be investigated (for example, the durability of seals, the integration of airtightness and ventilation issues in renovation projects, the variability of the energy impact with climate, etc.) where TightVent can play a major role, both in terms of research development and dissemination.

RELEVANT PROJECTS

■ INIVE and THE AIVC (*www.aivc.org*)

Since its creation in 2001, a major activity of INIVE EEIG has been the Operating Agent for the Air Infiltration and Ventilation Centre (AIVC). AIVC is one of the International Energy Agency's information centres, and is organised under the IEA's Implementing Agreement on Energy Conservation in Buildings and Community Systems (ECBCS). AIVC's main focus is on ventilation, indoor climate, energy in buildings and related building technology & physics.

■ INIVE and BUILD UP (*www.buildup.eu*)

The BUILD UP initiative was established by the European Commission in 2009 to support EU Member States in implementing the Energy Performance of Buildings Directive (EPBD). INIVE EEIG is the lead service provider for this project.

■ INIVE and the SAVE ASIEPI PROJECT (*www.asiepi.eu*)

The ASIEPI project (01/10/2007 - 31/03/2010) was coordinated by INIVE EEIG. It dealt with the implementation of the EU EPBD directive in the Member States, including:

- the impact of the directive on the requirements defined in the Member States;
- the comparison of the requirements between Member States;
- the handling of specific issues such as thermal bridges, airtightness, summer comfort, innovation; and
- the control and compliance schemes.

In addition to the traditional reports, publications, contributions to workshops and conferences, ASIEPI has also disseminated its results through web events and presentations on-demand.

■ INIVE and the DYNASTEE NETWORK (*www.dynastee.info*)

DYNASTEE (DYNamic Analysis, Simulation and Testing applied to the Energy and Environmental performance of buildings) is an informal grouping of organisations actively involved in the application of tools and methodologies relative to this field. DYNASTEE functions under the auspices of INIVE EEIG and constitutes a sustainable informal networking mechanism, which is intended for those who are involved in research and applications related to energy performance assessment of buildings.

Real experimental set-up for outdoor testing of building components provided high quality data series for estimation of thermal characteristic parameters. The objective of DYNASTEE is to provide a multidisciplinary environment for a cohesive approach to the research work related to the energy performance assessment of buildings in relation to the EPBD.

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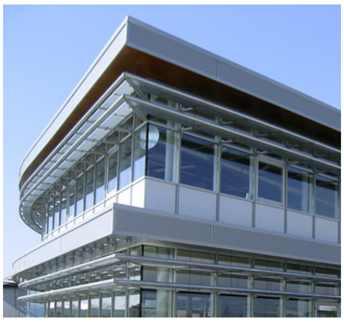
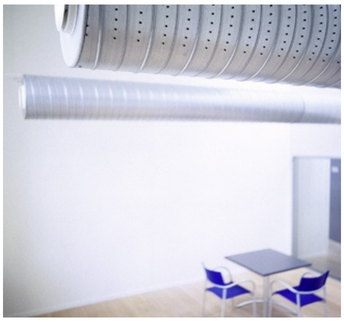
PARTNER PRESENTATION

Lindab is an international Group that develops, manufactures, markets and distributes products and system solutions, primarily in steel, for buildings and indoor climate. The business is carried out within three business areas, Ventilation, Building Components and Building Systems.





MOTIVATIONS FOR TIGHTVENT

Lindab is a high quality producer of building components such as ventilation products and components for walls and roofs. Our effort to offer these products focusses genuinely in ensuring a better and more sustainable world by using renewable materials and striving to use less material. By using our product it is possible to lower the energy consumption in the long term running of the building.

By participating in TightVent we believe we can learn more about the process of building airtight, energy efficient buildings and fine-tune our product template by networking with suppliers working with the same issues. Our ambition is to transfer this knowledge all the way through the building owner, the architects/consultants, the construction companies and to all their workers.

AIRTIGHTNESS SOLUTIONS

A non-tight ventilation system leads to an "over-dimensioning" of components such as:

- fans
- filters
- heating and cooling surfaces
- heat exchangers

If you do not compensate for the leakage with a larger airflow you get reduced comfort (air quality, temperature, etc.) All this leads to increased energy consumption, increased costs and larger impact on the atmosphere (CO_2).

Tight duct systems are one way to improve the energy efficiency of buildings. Therefore Lindab offers different solutions such as:

■ Lindab Safe and Lindab Safe Click

Lindab Safe is a complete range of circular ducts, fittings, silencers, t-pieces etc. The system is based on a double, factory-installed seal made of EPDM rubber. This seal makes the system quick and easy to mount. The system is type approved to tightness class D.

Lindab Safe provides a duct system with low energy usage, simplicity when balancing the airflow and simple maintenance. Lindab Safe Click is based on Lindab Safe but does not require any screws or rivets, which makes the system even tighter.

■ Leakage Tester; the complete equipment for field measuring of leakage in duct systems

The Lindab Leakage Tester measures the leakage of duct work installations by measuring the leakage airflow required to maintain a wanted pressure level.

The leakage measurements make it easier to agree upon a level of quality for the duct system and also to educate the worker to do a better job.

■ Membrane lead-through, MG and MGL

Is used for sealing of the building envelope for all types of pipes and ducts, which is lead through a vapour barrier of roofing underlay and thereby making the building tighter.

The products can be used as a roofing underlay transition or as a vapour barrier sheet, in the ridge, as well as on the inclined roof area.

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PARTNER PRESENTATION

Soudal NV is Europe's leading independent manufacturer of sealants, PU-Foams and adhesives. The company, established in 1966, proudly remains family-owned. Soudal serves professionals in construction, retail channels and industrial assembly and has 45 years of experience with end-users in over 100 countries worldwide. Since sealing, bonding and insulating are our business, we actively support the Tightvent platform. And with 7 manufacturing sites on 4 continents and 35 subsidiaries worldwide, we hope to contribute to a wide-scale implementation of nearly zero-energy buildings.

MOTIVATIONS FOR TIGHTVENT

There is a wide array of measures that can be taken to improve the energy performance level of a dwelling, including advanced, but often expensive technical solutions. However the starting point for improving the energy performance of any construction should be the building envelope, the outer skin, which ideally is very well insulated without interruptions, and is airtight. This is also what is incorporated within several EPB-regulations, such as the Flemish one, where distinction is made between K and E level. Building airtight and free of thermal bridges does not involve complicated and expensive products. It can be done by using small quantities of basic products such as sealants, adhesives and PU-foams from a manufacturer that is committed to airtightness, marketing easy-to-use quality products.

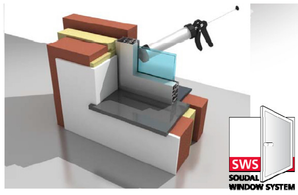
Building airtight therefore is one of the best cost effective ways to reach certain energy performance levels, but it starts with the building design, involves careful planning and coordination on the building site and most importantly careful execution. However, looking at building practices throughout Europe as they are today, Soudal is a strong believer in action plans and schemes to train blue collar workers on one hand, and setting-up a quality framework on the other. TightVent can certainly play an important role in raising awareness in both fields.

Soudal has a long tradition of focus on innovation and adaptation to local market needs. This long standing vision has now resulted in the erection of a brand-new Research and Development (R&D) facility in Turnhout, Belgium, situated next to Soudal headquarters. It underlines the innovative spirit of Soudal. The new R&D centre also features training, presentation and reception facilities for employees, professional end-users and commercial partners. Through the TightVent platform the company hopes to improve its understanding of market needs, so that product development can be stepped-up towards durable airtight products and solutions.

AIRTIGHTNESS SOLUTIONS

Soudal provides a wide array of individual products to build airtight envelopes:

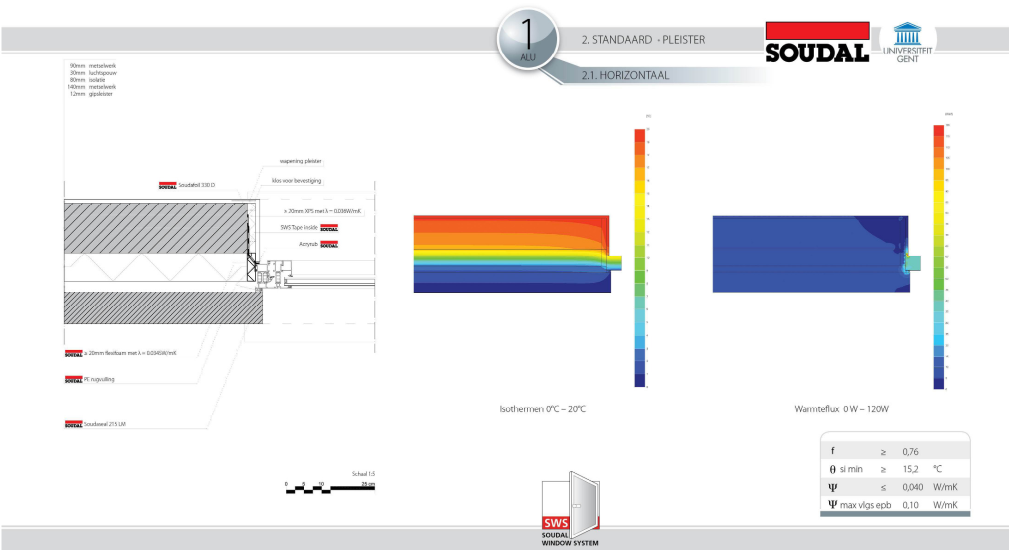
- Hybrid sealants: permanently elastic
  - Excellent adhesion on almost any substrate, even if damp.
  - Diverse, low modulus and high modulus.
  - High movement capacity (20-25LM or 20-25HM – ISO11600).
  - No cracks under UV-radiation.
- Silicone sealants: permanently elastic
  - Excellent adhesion on glass and metals.
  - Ideal for airtight glass sealing.
  - High movement capacity (20LM – 25LM).
  - Very resistant to UV.
- Acrylic sealants
  - Mainly interior use/finishing.
  - Paintable, "elastic and airtight extension of plaster".
  - Prevents cracks between window frame and plaster.
  - New development: meets with ISO 11600 12,5E.
- Adhesives
  - Vapour barrier adhesive.
  - Membrane adhesives.



Airtightness and avoiding thermal bridges can be particularly tricky when it comes to installing windows. Soudal Window System (SWS) is designed to exactly fulfil in this need. It is capable of bringing a solution for proper window installation in both new constructions and refurbishment. SWS is a clever combination of easy-to-use products in order to meet the highest standards in insulation and airtightness in the connection joint between window frame and brickwork/wall. SWS as a system was subjected to tests and simulations at the University of Ghent (Belgium) and IFT (Germany) with regards to airtightness, insulation and weatherproofing. Products used are: Soudaseal 215LM, Acryrub, SWS tapes (inside and outside), Soudafoil 330D and 360H and Flexifoam.

RELEVANT PROJECTS

Soudal conducted further internal and external research with regard to using sprayable PU-foam not only as an insulator but also as an airtight barrier. Flexifoam, an elastic PU-foam was examined for two academic years at the High School of Ghent. Airtightness was proven even after ageing.



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PARTNER PRESENTATION

Tremco illbruck has a leadership position in the sealants and building protection market throughout Europe, Africa and the Middle East. Our efforts are focused on Window, Façade, Coatings, Fire Protection, Insulating Glass and non-construction industries.

With nearly 80 years of experience, we possess an unrivalled understanding of our customers' business – which empowers us to provide a broad range of reliable and truly efficient products under strong premium brands such as Tremco, illbruck, Nullifire and Pactan. We actively incorporate customer feedback so that we are able to meet and exceed our customers' requirements to offer tailored solutions that ensure our customers' on-going success in every project.

Our strong local presence means we are on the ground daily, helping our customers make the most of our products and responding rapidly to their questions. We thoroughly understand the specific local markets, standards and regulations. Our well-trained staff partner with customers to get the best application results.

Tremco illbruck is headquartered in Cologne, Germany, and employs close to 1,000 people in 19 countries. It is part of RPM International Inc., a world leader in specialty coatings.

MOTIVATIONS FOR TIGHTVENT

To reach the goals for 2020 set in the EPBD recast throughout Europe, a holistic approach of Airtightness, Insulation and Ventilation is mandatory. For Tremco illbruck, TightVent is the platform that shows this approach on a European level and that gives the opportunity of raising the awareness for airtight buildings. We want to share our experience and expertise in the airtight connection of building components to reach the ambitious goal and to improve knowledge of building professionals by implementing training programs in the EU. Tremco illbruck wants to initiate future developments regarding Airtightness and Ventilation. We want to generate information about possibilities of Airtight Buildings in Europe and share this information with the local authorities and all people involved in construction.

NATIONAL CONTACT INFORMATION

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Czech Rep.	http://www.tremco-illbruck.cz	Slovakia	http://www.tremco-illbruck.sk
Denmark	http://www.tremco-illbruck.se	Russia	http://www.tremco-illbruck.ru
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Netherlands	http://www.tremco-illbruck.nl	UK, Ireland	http://www.tremco-llbruck.co.uk

AIRTIGHTNESS SOLUTIONS

Tremco illbruck is one of the leading companies for airtight and weather sealing solutions for door and window installation. We are also well-known as a specialist for facade solutions, flooring and passive fire protection in the market:

Impregnated tapes

- Driving rain tight to 600 Pa
- Airtight
- Breathable
- One tape for both interior and exterior sealing

Membranes

- Airtight
- One membrane for both interior and exterior sealing
- Intelligent moisture management

Sealants and PU Foams

- Acrylics
- Silicones
- Hybrid sealants
- PU Sealants
- PU Foams for thermal and sound insulation
- PU Foams for bonding

Adhesives

- Several types of construction adhesives based on PU and Hybrid technology

For further information please join our website www.tremco-illbruck.com.

RELEVANT PROJECTS

Tremco illbruck is an active part in many countries throughout Europe in committees for norms and standards regarding the proper, airtight installation and energy efficiency of doors, windows and façades.

We are also known as a reliable partner in developing solutions for building projects, e.g. the Southend Passiv Project (http://91.186.180.41/uk/news/news/03720/index.html) or the One Brighton Project (http://www.onebrighton.co.uk/index.aspx) and in raising the awareness of airtight building by implementing local quality standards.

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PARTNER PRESENTATION

Founded in 1819 in Vienna and traded since 1869 on the Vienna Stock Exchange, Wienerberger is the world's largest producer of bricks and No. 1 on the clay roof tiles market in Europe with 245 plants in 27 countries. Wienerberger also holds leading positions in concrete pavers in Central and East Europe. Some of the Wienerberger Group's well-known brand names include Porotherm, Terca, Heylen, Desimpel and Koramic.

Under the name Porotherm and Desimpel, Wienerberger offers a qualitatively optimised and complete range of clay blocks. Under the brand Terca, Heylen and Desimpel, Wienerberger offers a diverse range of facing bricks and pavers. Wienerberger clay roof tiles are sold under the Koramic brand and offer a wide range of different shapes, colours and surface structures.

As a manufacturer of ceramic building products and solutions, Wienerberger is continuously concerned with sustainable production, construction and living. In the area of construction, Wienerberger has developed some sustainable and innovative alternatives for new construction, as well as for the renovation of solid-construction buildings with long service lives.

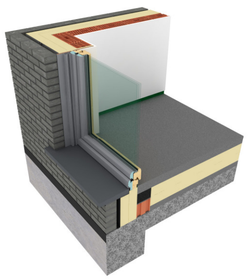
Wienerberger is convinced that, if we want to achieve the objectives for 2020 set in the EPBD recast throughout Europe, we may not hesitate to make accelerated use of building envelopes which guarantee an energetic optimum, such as low-energy, passive and zero-energy houses.

MOTIVATIONS FOR TIGHTVENT

Building and ductwork airtightness represent a key challenge towards the ambitious 2020 European objectives. In the scope of our concern about sustainable production, construction and living, we believe that, by participating in TightVent, we can learn more about the process of airtight construction and energy efficient building envelopes.
We are convinced that this knowledge will enable us to further develop and optimise the sustainable building solutions we offer to our customers. Moreover, we have also the ambition to transfer this knowledge through our customers (both builders, renovators and building professionals such as architects, engineering agencies, contractors, etc.) by means of theoretically- and practically-oriented training courses, seminars, workbooks, etc.

AIRTIGHTNESS SOLUTIONS

Wienerberger has done and is still doing a lot of research on solutions for airtight construction. The solutions that Wienerberger is striving for, should remain in line with current building traditions and be cost-effective.



- As to the airtightness of the walls of a building, Wienerberger has done a lot of tests and measurements to conclude that by applying a finishing layer of plaster on the inside of the inner leaf of cavity walls composed out of clay blocks and the use of an airtight foil at some connection points, more than sufficient airtightness, more particularly a value of 0.04 m^3 hr / m^2, can be achieved to comply with the standards for passive construction. This simple solution is also very safe since it concerns the interior envelope of the building, which is less vulnerable and at the same time more accessible. This method is also cost effective, as it is the traditional way of finishing of inner wall leafs, so no extra costs are linked to this method.

- As to the airtightness of the pitched roof of a building, Wienerberger has set up a collaboration with the Catholic University of Leuven in Belgium, Laboratory of Building Physics under the direction of prof. dr. ir. Arch Staf Roels, to study the optimum way to reach wind and airtightness at the level of three typical connection points of the pitched roof: connection to the wall plate, connection to the ridge and connection to the side wall. Goal of the study, which is still on-going, is to achieve for each of these connections a solid and practically feasible airtight solution. In order to evaluate possible solutions, laboratory measurements are being done.

RELEVANT PROJECTS

As a result of the airtightness solution for walls by using a finishing layer of plaster on the inside of the inner leave of the cavity wall, three massive passive projects have been realised in Belgium which were approved and certified by the Passive House Platform – www.massiefpassief.be.

ABOUT ASIEPI

The Intelligent Energy – Europe supported project ASIEPI, as part of a suite of policy support actions, has provided valuable insight into pragmatic solutions for improving the impact of our existing building codes, as well as those being prepared for the future. It has been instrumental in demonstrating the benefits of an ambitious and effective implementation of the legislation. Only by sharing its knowledge on these issues can Europe as a whole reap the benefits of a sustainable economy based on knowledge and innovation. Likewise, building cleaner, greener buildings in Europe requires the commitment and the expertise of a variety of actors. This is why the European Commission has launched an initiative like BUILD UP which provides building professionals, public authorities, owners and tenants with a common (web) platform to start working today for the buildings of tomorrow.

Patrick Lambert, Director EACI

General project description

INTRODUCTION

WHAT IS THE ASIEPI PROJECT

ASIEPI is the acronym of the full project name:

ASsessment and **I**mprovement
of the **EP**BD **I**mpact
(for new buildings and building renovation)

The project took two and a half years and was completed in March 2010.

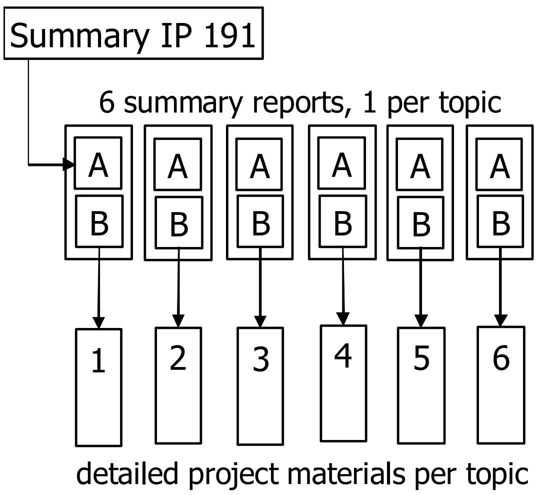
The main objective of the ASIEPI project has been to formulate suggestions to policy makers on how to improve the quality and the impact of the regulations on the energy performance of buildings with respect to 6 specific topics:

- intercomparison of the levels of the EP-requirements
- impact, compliance and control of legislation
- effective handling of thermal bridges
- stimulation of good building and ductwork airtightness
- support for the market uptake for innovative systems
- stimulation of better summer comfort and efficient cooling

Several major aspects of each of the topics have been analysed. The results are documented in a full suite of project data. Among others, these data provide insight in the potential problems and give guidance with respect to possible solutions. However, as the project had to conform to the objectives of the IEE-SAVE programme, no new, ready-to-use methods were developed, but instead awareness of the challenges was raised and existing best practice to achieve more effective EPB-regulations were highlighted.

PROJECT MATERIALS

The ASIEPI project has produced a broad set of dissemination materials.



As illustrated in the figure, the project results are structured as follows:

- An information paper (IP191) briefly summarises the main conclusions and constitutes the gateway to the project.
- 6 summary reports are each dealing with 1 of the topics listed above. The summary reports all consist of a Part A which describes the major findings and the final recommendations on the topic and a Part B that gives a synthetic overview of all the other information that the project has made available on that topic.

- Finally, a wide range of information materials provide a more comprehensive, in-depth coverage of many different aspects of each of the topics.

The different project outcomes come in a variety of electronic formats:

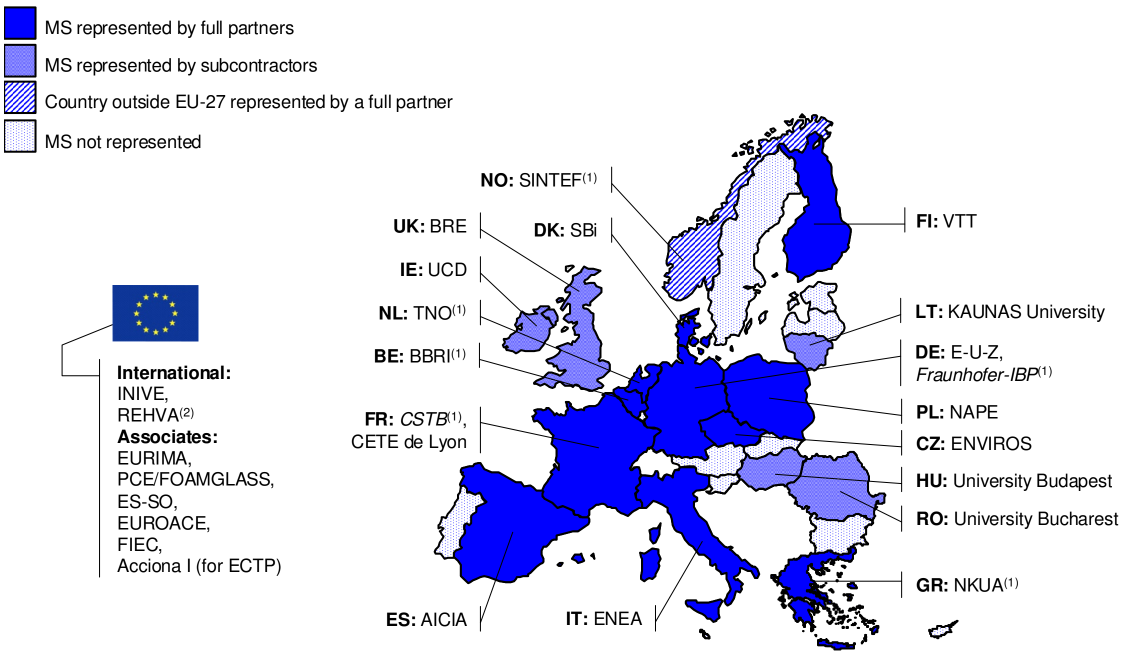
- summary reports
- detailed technical reports
- information papers
- recordings of internet information seminars
- presentations-on-demand
- conference abstracts and papers
- other related material, such as documents supplied by third parties

All materials are available on the project website www.asiepi.eu.

PROJECT PARTNERS

As shown in the figure, the project had full partners in 12 countries and subcontractors in 5 more countries. Furthermore, there were 6 Europe-wide associations acting as associated partners.

Through this large number of countries involved, a good reflection was obtained of the EPB-practices across all of Europe at the time of the project. For most topics, surveys have been made in these countries in order to see how the EPB-regulations deal with each of the issues.



(1) INIVE member
In the MS where there are two participants, the national contact point is in *italic*.

ASIEPI has received funding from the Community's Intelligent Energy Europe programme under the contract EIE/07/169/SI2.466278.

The following organisations have contributed to ASIEPI:

- **International Network for Information on Ventilation and Energy Performance EEIG** (INIVE), project coordinator. The following INIVE members are participating in ASIEPI:
    - **Belgian Building Research Institute** (BBRI), Belgium, WP1 leader, WP6 leader, WP9 leader,
    - **National and Kapodestrian University of Athens** (NKUA), Greece, WP1 leader, WP7 leader,
    - **Netherlands Organisation for Applied Scientific Research** (TNO), Netherlands, WP2 leader,
    - **Fraunhofer Institute of Building Physics** (IBP), Germany, WP4 leader,
    - **Stiftelsen for Industriell Teknisk Forskning ved Norges Tekniske Høgskole as legal entity acting for its institute SINTEF Buildings & Infrastructure** (SINTEF), Norway,
    - **Centre Scientifique et Technique du Bâtiment** (CSTB), France,
- **Centre d'Etudes Techniques de l'Equipement de Lyon** (CETE de Lyon), France, WP5 leader,
- **Federation of European Heating and Air-conditioning Associations** (REHVA), WP8 leader,
- **Ente per le Nuove Tecnologie l'Energia e l'Ambiente** (ENEA), Italy,
- **Asociacion de Investigacion y Cooperacion Industrial de Andalucia** (AICIA), Spain,
- **Narodowa Agencja Poszanowania Energii** (NAPE), Poland,
- **Technical Research Centre of Finland** (VTT), Finland,
- **Energie- und Umweltzentrum am Deister e.V.** (E-U-Z), Germany,
- **ENVIROS, s.r.o.** (ENVIROS), Czech Republic,
- **Danish Building Research Institute** (SBi), Denmark.

ASIEPI has used the service of four subcontractors, to cover five more Member States:

- **Budapest University of Technology and Economics**, Hungary
- **University College Dublin**, Ireland
- **Institute of Architecture and Construction of Kaunas University of Technology**, Lithuania
- **Civil Engineering University of Bucharest**, Romania
- **British Research Establishment**, United Kingdom

Sponsors and associates

ASIEPI is financially supported by four umbrella organisations:

- **European Association of Insulation Manufacturers** (EURIMA);
- **Pittsburgh Corning Europe** (PCE);
- **European Solar-Shading Organization** (ES-SO);
- **European Alliance of Companies for Energy Efficiency in Buildings** (EuroACE).

ASIEPI is also supported by two other umbrella organisations:

- **European Construction Industry Federation** (FIEC);
- **Acciona Infraestructuras** *(as co-leader (together with Saint Gobain) of the Focus Area Cities and Buildings of the European Construction Technology Platform)*.

TightVent Europe

BUILDING AND DUCTWORK AIRTIGHTNESS PLATFORM

Partners

The **Buildings Performance Institute Europe (BPIE)** is an independent, non-profit organisation based in Brussels. BPIE supports the development of ambitious but pragmatic building-related policies and programs at both EU and Member State levels. We timely drive the implementation of these policies by teaming up with relevant stakeholders from the building industry, consumer bodies, policy and research communities. With the TightVent Europe Platform, our ambition is to play a key role in implementing policies on building and ductwork airtightness, bearing in mind ventilation needs.

The **European Climate Foundation** aims to promote climate and energy policies that greatly reduce Europe's greenhouse gas emissions and helps Europe play an even stronger international leadership role in mitigating climate change. ECF supports the TightVent platform in its mission to create support for proper implementation of the new Energy Performance of Buildings Directive (EPBD) and to help policy makers, industry, developers and other stakeholders in the deployment of low-energy buildings.

Eurima is the European Insulation Manufacturers Association. Eurima members manufacture mineral wool insulation products. We actively support TightVent to develop knowledge and application of efficient airtightness solution for a successful implementation of the recast of the EPBD. This requires a good coordination between strong insulation and well-functioning ventilation in order to guarantee both energy efficiency and good indoor air quality.

INIVE is a registered European Economic Interest Grouping (EEIG) that brings together the best available knowledge from its member organisations in the area of energy efficiency, indoor climate and ventilation. INIVE strongly supports and acts as facilitator of TightVent Europe because it clearly fits within the objectives of our grouping, namely, fostering and structuring RTD and field implementation of energy-efficient solutions and good indoor climate in new and existing buildings.

Lindab is an international group that develops, manufactures, markets and distributes products and system solutions primarily in steel for buildings and indoor climate. With TightVent Europe, we learn more about the process of building airtight and energy efficient buildings; we fine-tune our product range by networking with suppliers confronted with the same issues. Our ambition is to transfer this knowledge all the way to building owners, architects/consultants, construction companies and workers.

Soudal NV is Europe's leading independent manufacturer of sealants, PU-Foams and adhesives. The company, established in 1966, proudly remains family owned. Soudal serves professionals in construction, retail channels and industrial assembly and has 45 years of experience with end-users in over 100 countries worldwide. Since sealing, bonding and insulating is our business, we actively support the Tightvent platform. And with 7 manufacturing sites on 4 continents and 35 subsidiaries worldwide, we hope to contribute to a wide-scale implementation of nearly-zero energy buildings

Tremco illbruck has a leadership position in the sealants and building protection market throughout Europe, Africa and the Middle East. Our efforts are focused on Window, Façade, Coatings, Fire Protection, Insulating Glass and non-construction industries. Through TightVent Europe, we share our experience and expertise in the airtight connection of building components to reach ambitious goals and to improve knowledge of building professionals by implementing training programs in the EU.

Wienerberger is the world's largest producer of bricks and No. 1 on the clay roof tiles market in Europe with 245 plants in 27 countries. TightVent Europe enables us to further develop and optimize the sustainable building solutions we offer to our customers. Moreover, we want to transfer knowledge to our customers (both builders, renovators and building professionals such as architects, engineering agencies, contractors, etc.) by means of theory- and practice-oriented training courses, seminars, workbooks, etc

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