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AIRWAYS

Source book for efficient air duct systems in Europe




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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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More information on AIRWAYS partners

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Link to an other document

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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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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).

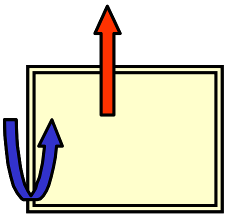


Figure 1. Schematic representation of a typical natural stack ventilation system. In this figure, the air comes naturally into the building through cracks, slots, trickle ventilators, or other devices, and exits naturally through vertical ducts. The air motion is due to temperature differences or wind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

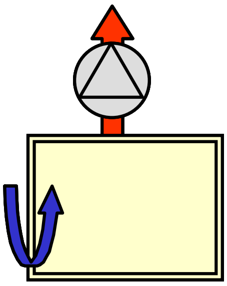


Figure 2. Schematic representation of E system. The air comes naturally into the building through cracks, slots, trickle ventilators, or other devices, and is mechanically driven out through a central exhaust duct system.

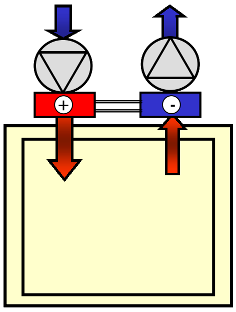


Figure 3. Schematic representation of balanced SE system. The air is mechanically supplied and extracted through two separate ducted systems. The air handling unit includes a heat recovery unit to transfer the energy of the outgoing air stream to the incoming air stream.

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.

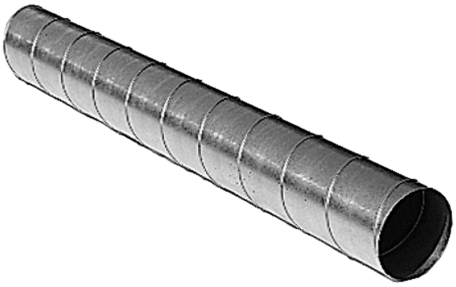


Figure 4. Straight rigid spirally-wound duct.

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.

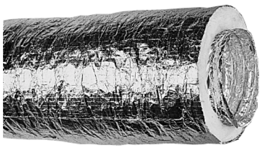


Figure 5. Insulated flexible duct with external vapour barrier.

2.2.3 Bends and branches

These components allow a change in flow direction.

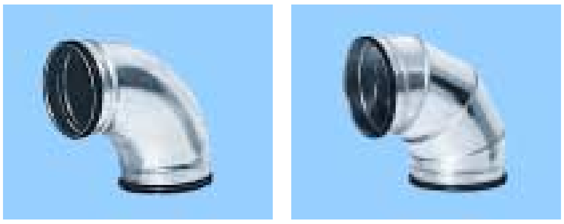


Figure 6: Pressed bend (left). Segmented bend (right).

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.

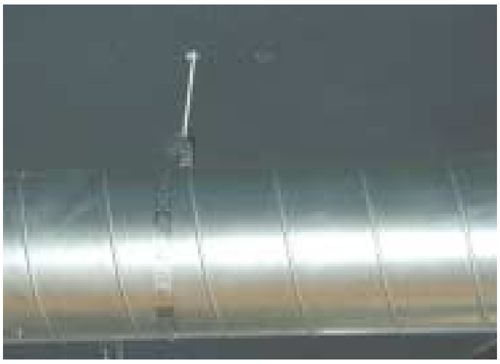


Figure 9 : Hanger.

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.

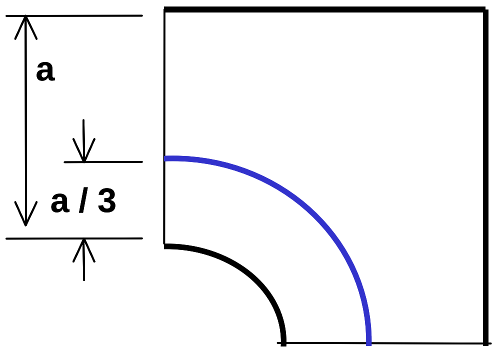


Figure 11 : Schematic representation of turning vane

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.

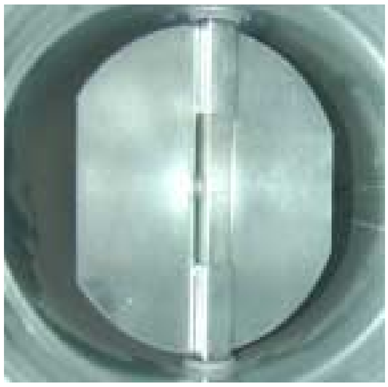


Figure 12 : Single-blade regulating damper. The blade angle can be manually adjusted or controlled with a motor.

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.

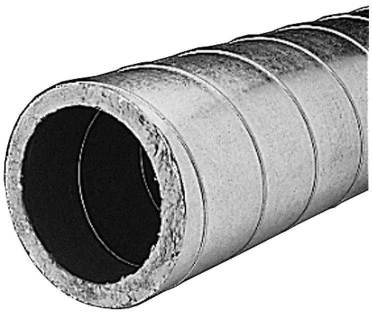


Figure 18. Straight double-cased insulated duct.

[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.

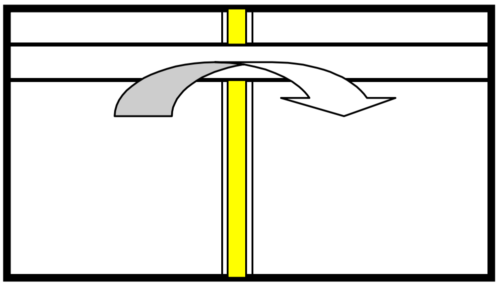


Figure 19 Noise transmitted between two rooms via the ductwork.

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?

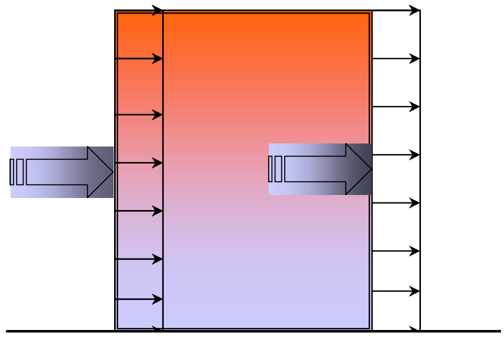


Figure 21 : Wind force on the façades affects the ventilation

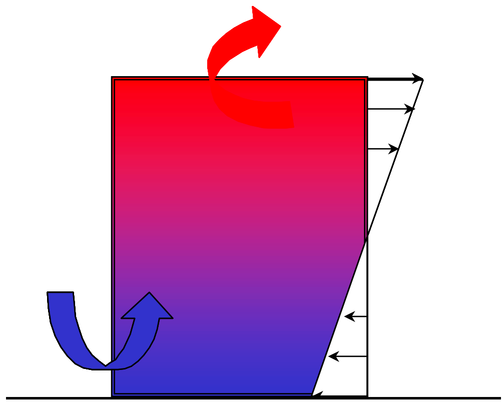


Figure 22 : The airflow differs between winter and summer due to the stack effect

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.

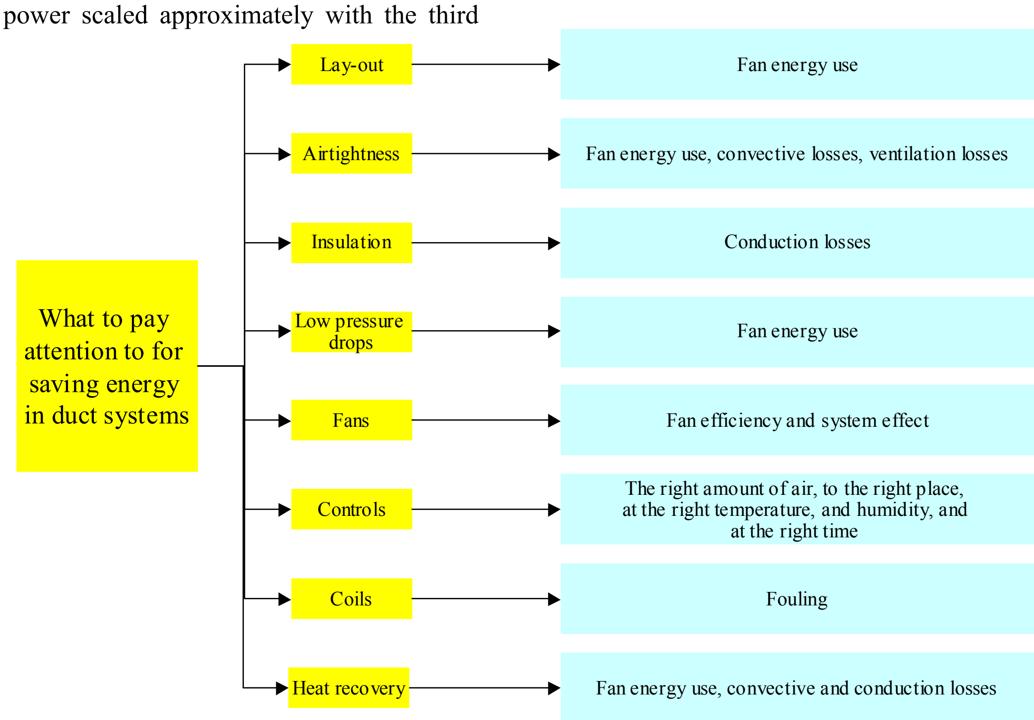


Figure 23 : Energy saving opportunities in duct systems.

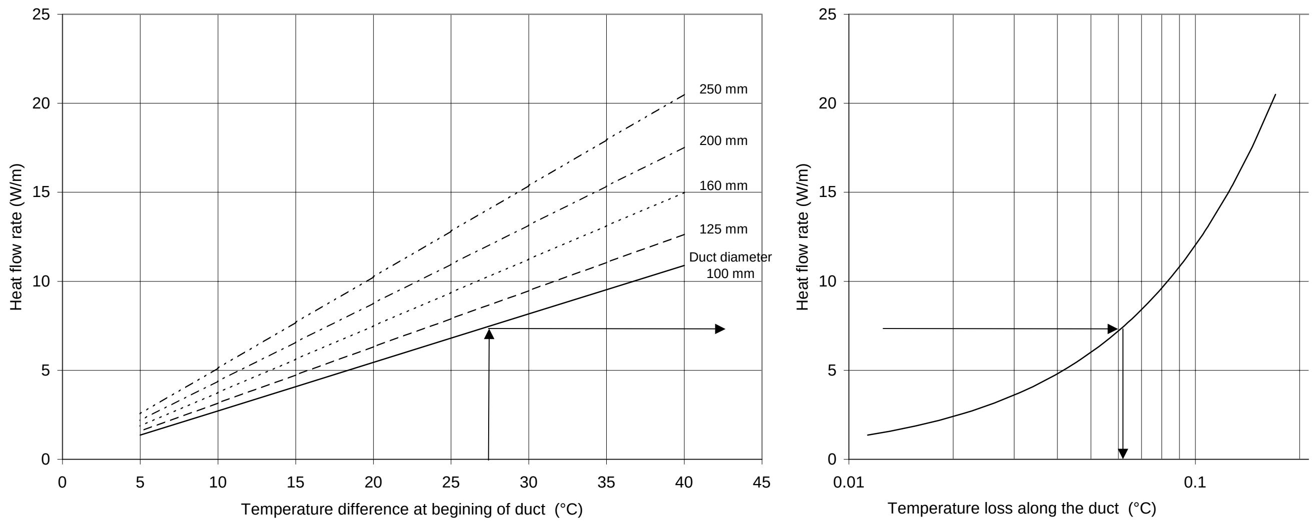


Figure 24 : Heat flow rate and temperature loss per unit length of duct for different duct diameters. Airflow rate = 0.1 m³/s: 60-mm thick insulation

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.

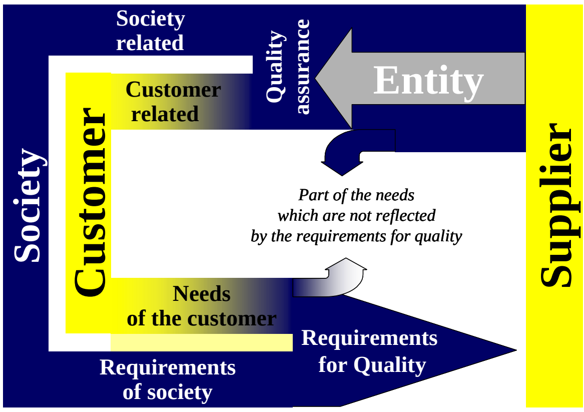


Figure 27: Overall scheme for assessing quality

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.

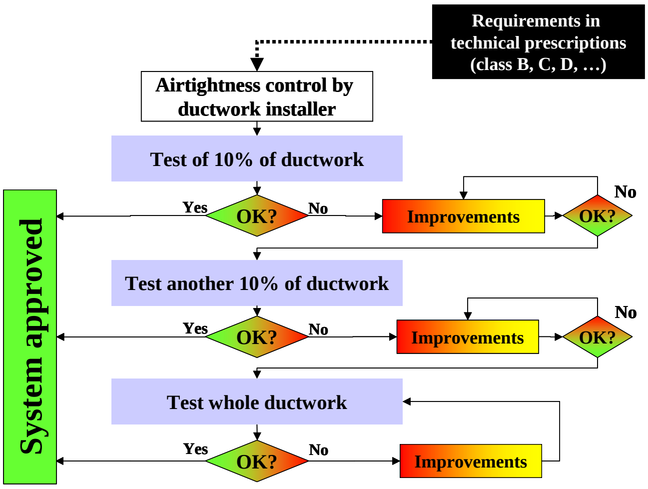


Figure 29 : Swedish approach in framework of AMA procedures

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.

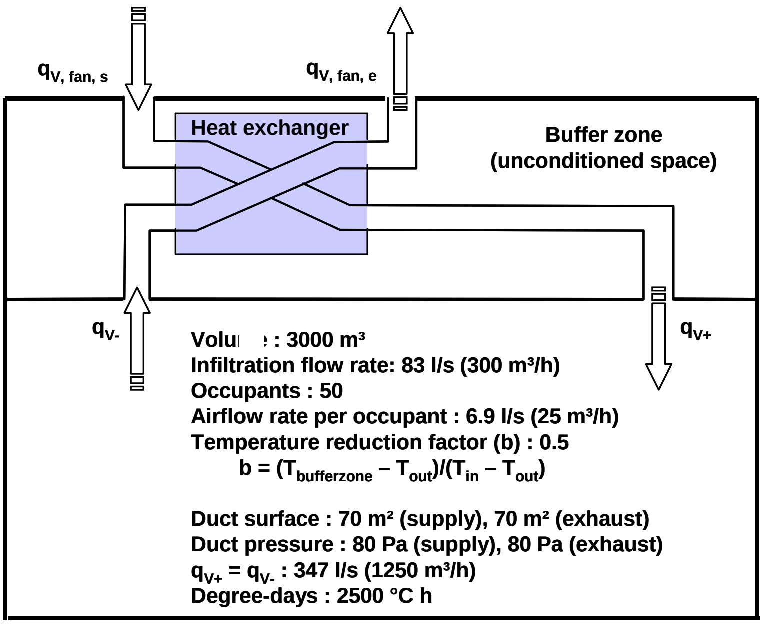


Figure 31. Schematic diagram of the office building used in the LCC calculations . It is equipped with a balanced ventilation system with heat recovery. The fan airflow rate is adjusted to match the required airflows at the air terminal devices.

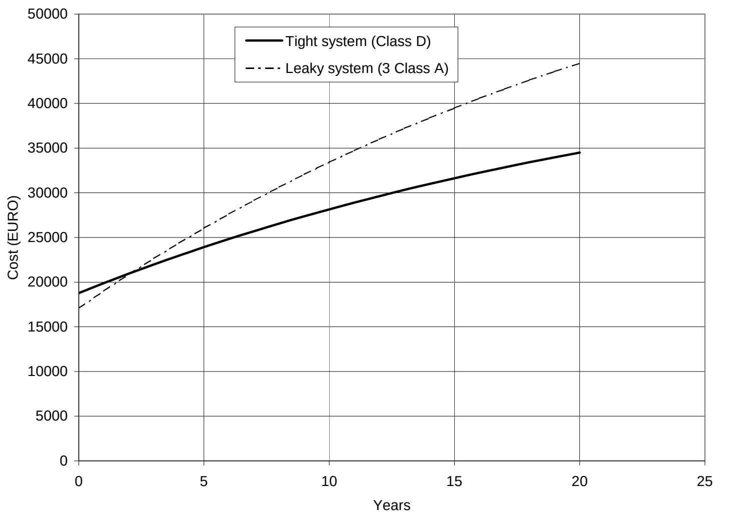


Figure 32: Comparisons of costs (Net Present Values) of a leaky (3 Class A) and an airtight (Class D) duct system. Calculations are based on the system described in Figure 31 and the parameters shown in Table 3. In that case, the pay-back period is about 2 years.

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.

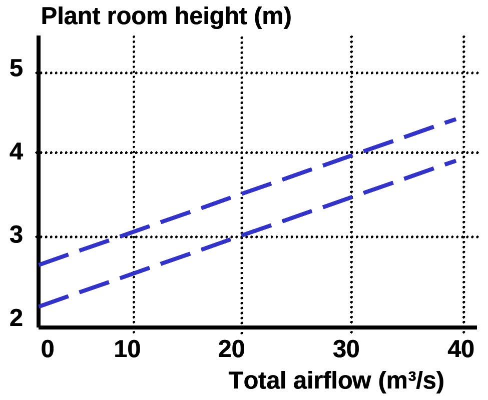


Figure 34 : Estimated room height for air handling installations

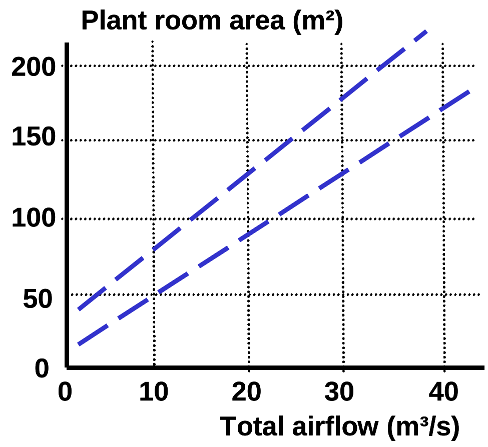


Figure 35 : Estimated plant room area for air handling installations

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.

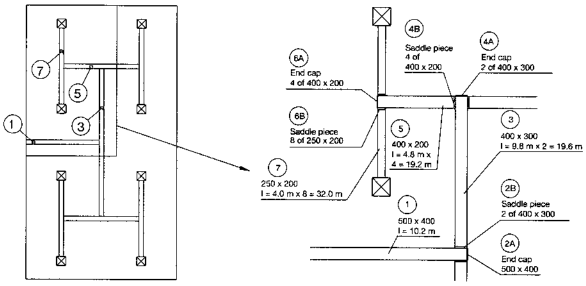


Figure 36 : Symmetrical ductwork where the supply air (entering at 1) passes through identical duct components on its way to the registers. The same principle is shown with round ducts in Figure 38.

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.

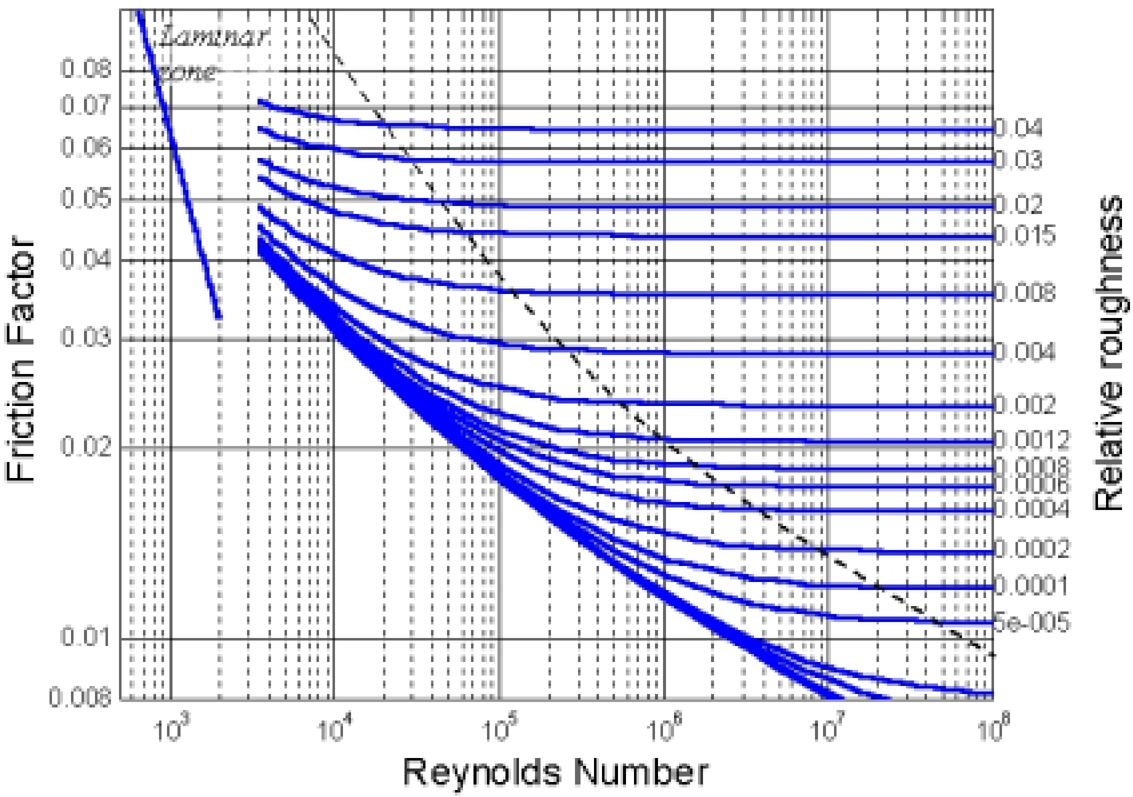


Figure 42 : Moody chart

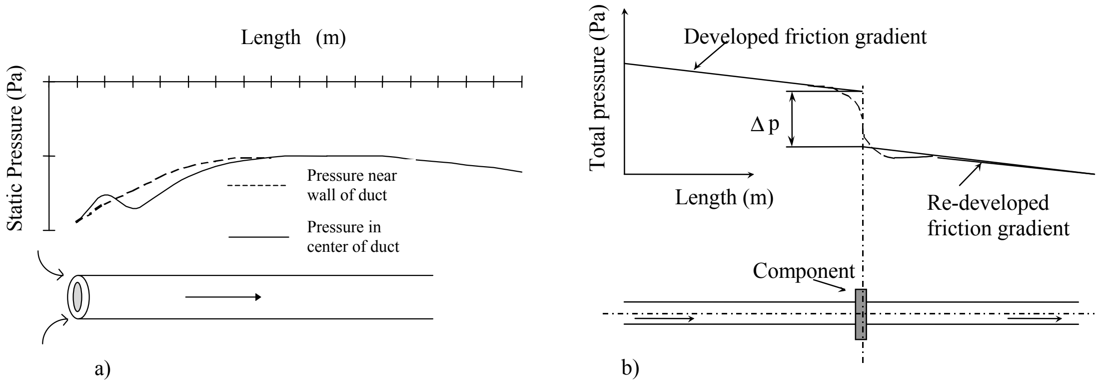


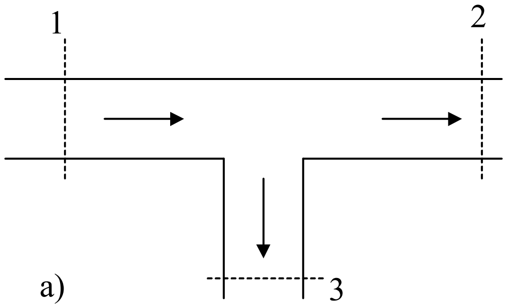
Figure 43: Pressure gradients a) Static pressure measured with a Prandtl static probe in the centre of a duct, downstream of an exhaust terminal device. b) Definition of component pressure drop. After Miller (1978). The graph illustrates the case that airflow rate and duct diameter is constant as the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



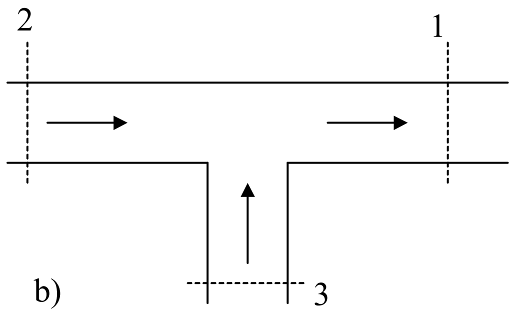


Figure 44 : Flow in dividing and combining T-junctions.

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).

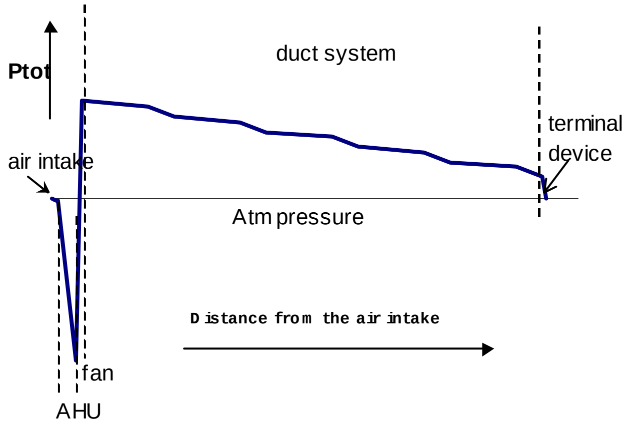


Figure 45 : The pressure distribution in a supply duct system

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.

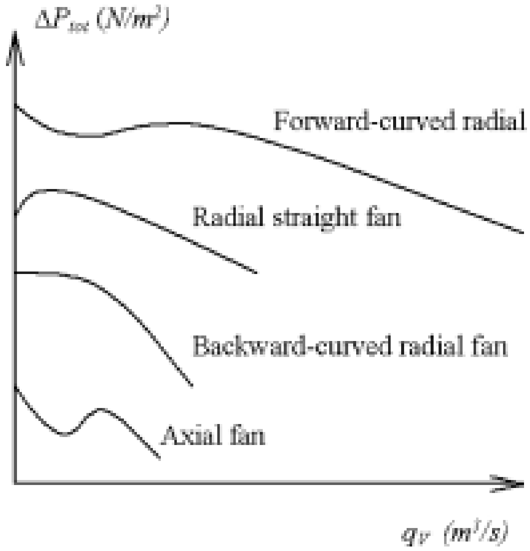


Figure 46: Examples of fan curves for different types of fans

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.

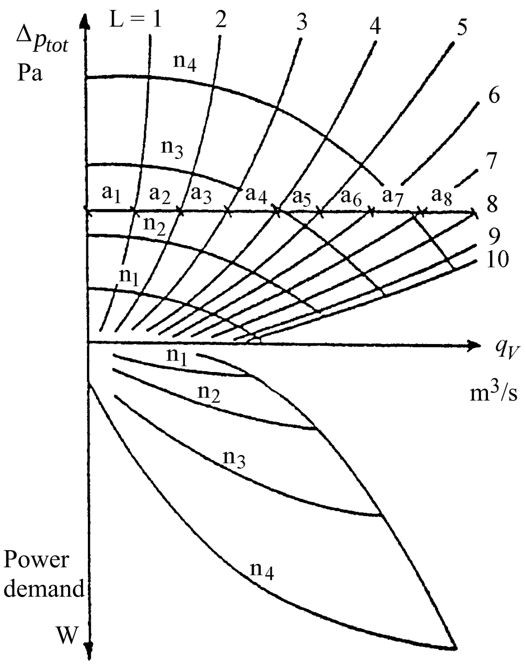


Figure 47: Fan graph with curves for different rotation speeds n, working lines 1-10, and power demand.

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.

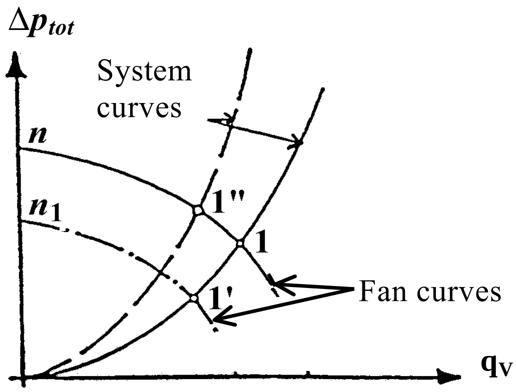


Figure 48: Illustration of the fan working point

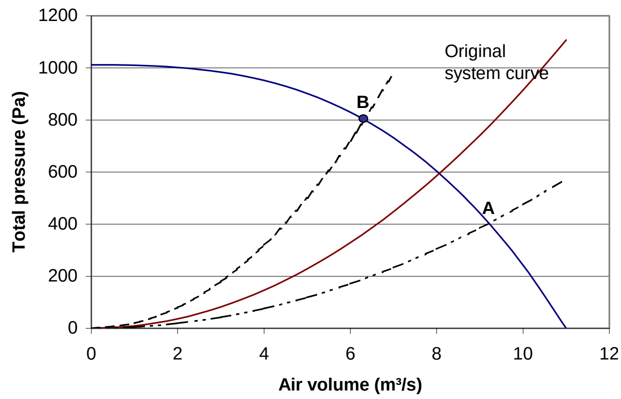


Figure 49 : Illustration of working points for fans

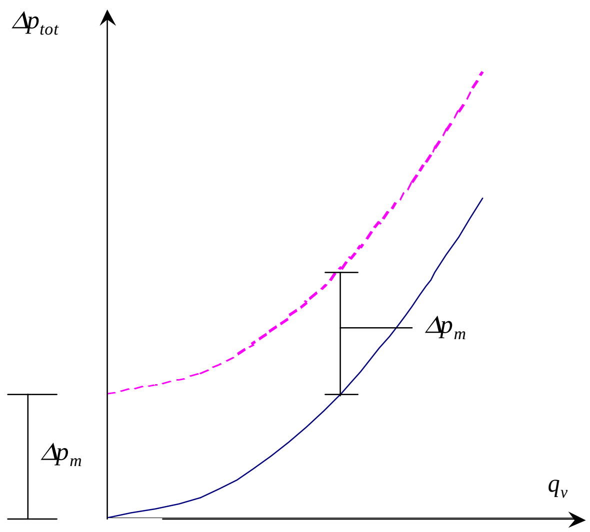


Figure 50: System curve when there is an initial resistance, which has to be created before flow can begin.

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

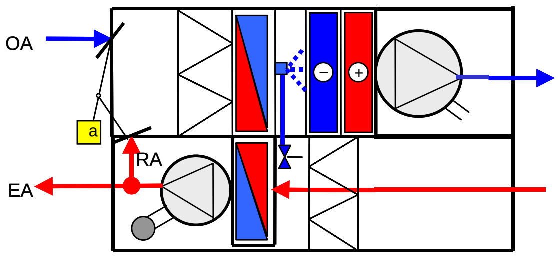


Figure 52 : To reduce the energy used for heating/cooling the AHU should either be equipped with a heat exchanger or – if the extract air has an acceptable quality – use return air. The shown unit has both possibilities!

[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.

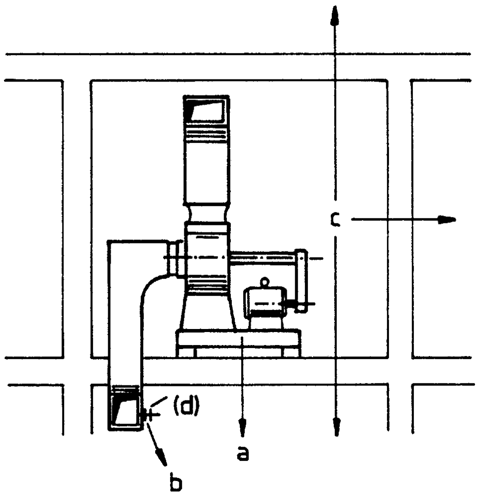


Figure 54 : The noise from the fan can spread in different ways and directions: Vibrations can result in structure borne noise (a) - Air borne noise carried through the ductwork (b) - Airborne noise in the fan room spreading to adjacent rooms (c), and noise emitted from other ductwork components such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

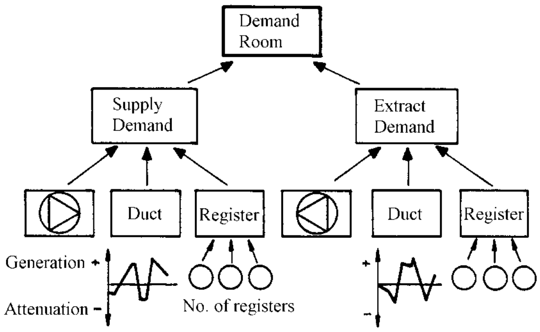


Figure 55 : The ventilation noise calculation has to be split up in several steps as described in the text below

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

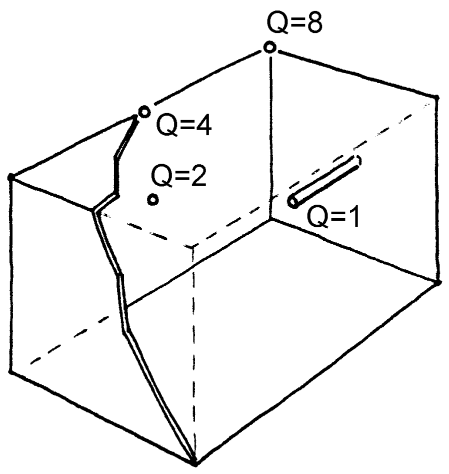
Number of devices	2	3	4	5	6	8	10	20
Add dB	3	5	6	7	8	9	10	13

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.



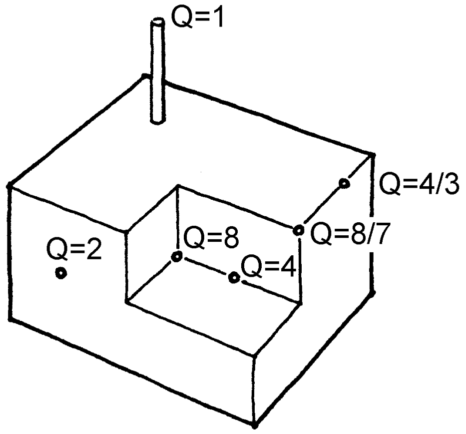


Figure 56 : The noise from a source will be influenced by the surrounding surfaces. The directivity factor Q equals 1 for full sphere and 8 for 1/8 sphere. Near the source each doubling of Q will result in a 3 dB noise level increase: $\Delta L = 10 \cdot \log Q$.

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:

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

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).

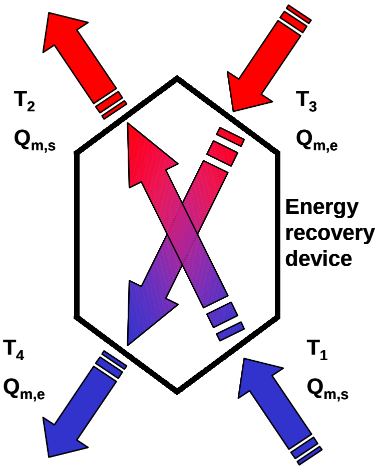


Figure 57. Schematic diagram of energy recovery principle. Subscript s and e denote the supply and extract sides, respectively.

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).

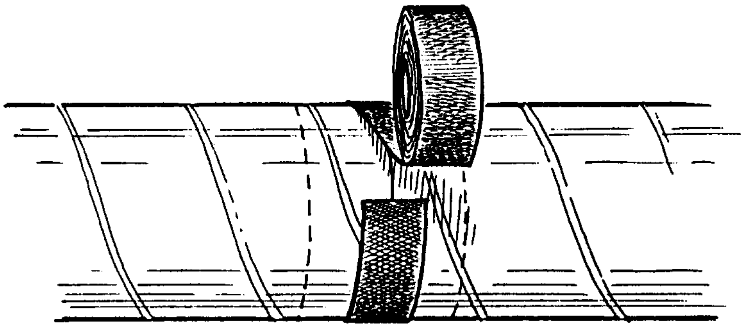


Figure 58. Self-vulcanising sealing tape applied around the duct with overlap.

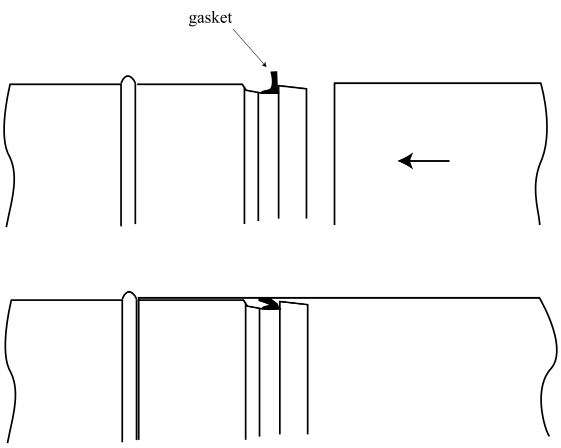


Figure 59. Pre-fitted sealing gaskets for circular ducts. Airtight rivets or plate-screws may be necessary to ensure the mechanical stability of the joint.

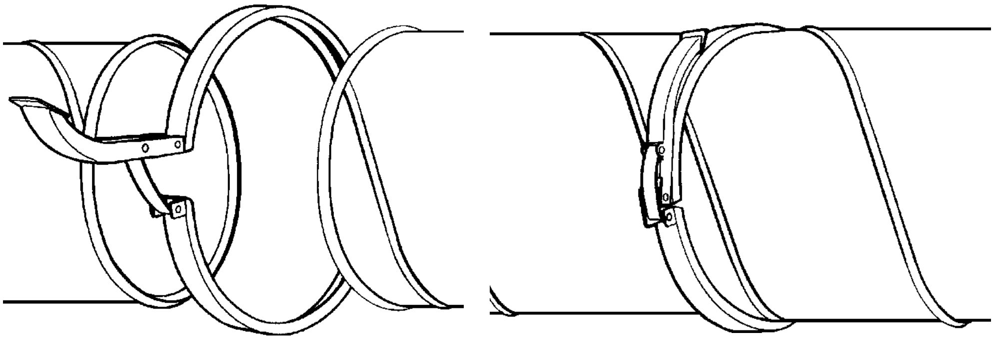


Figure 60. The clips ensure good airtightness and the mechanical stability of the joint. These systems are mainly used for non permanent ductwork or ductwork which has to be cleaned regularly.

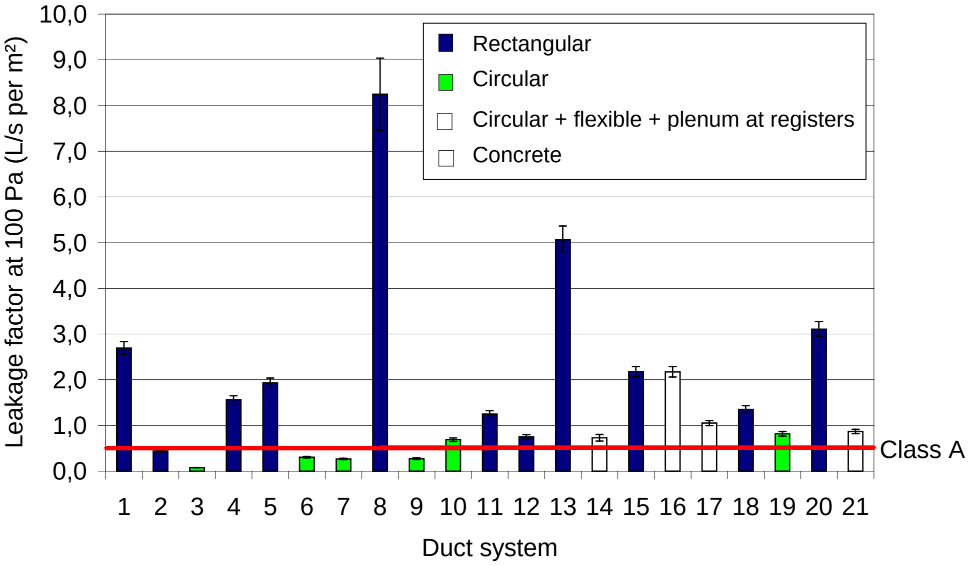


Figure 61. Leakage flow at 100 Pa divided by duct surface area (leakage factor) for systems investigated in Belgium during the SAVE-DUCT project (Carrié et al., 1999).

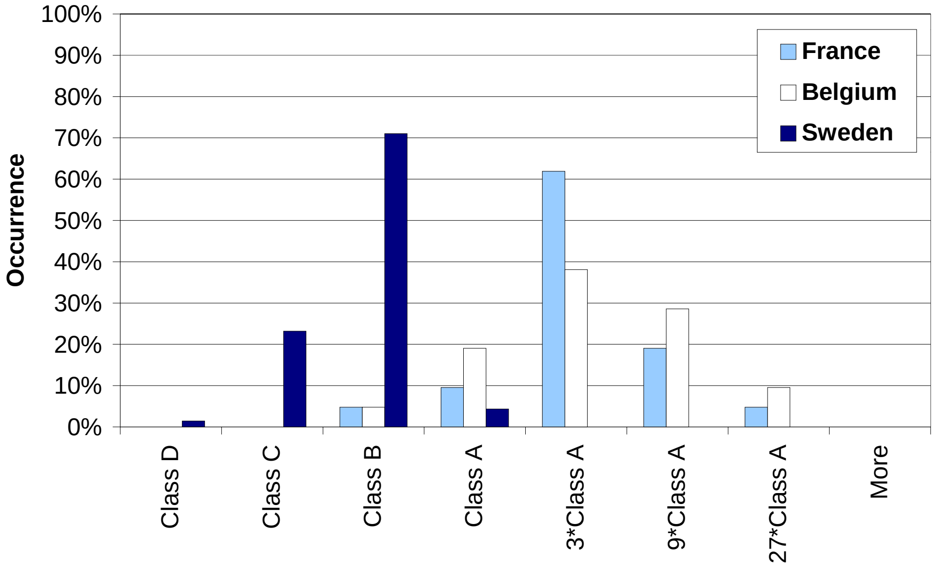


Figure 62. Occurrence of the different tightness classes. Based on 21 systems in Belgium, 21 in France, and 69 in Sweden. Each stack represents the relative number of systems that comply with the specified tightness class.

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.

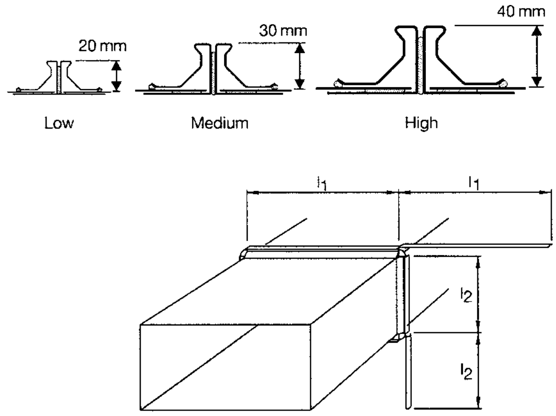


Figure 63 : Slip joints on rectangular ducts add to the space requirement. At installation free space has to be available for the joint connection.

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.

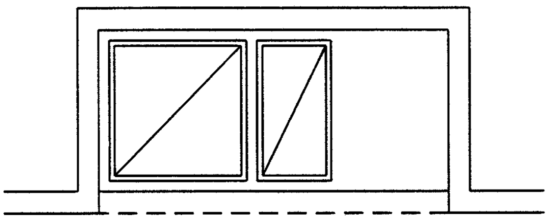


Figure 64 : Slip joints make it difficult to install these ducts in the shaft.

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.

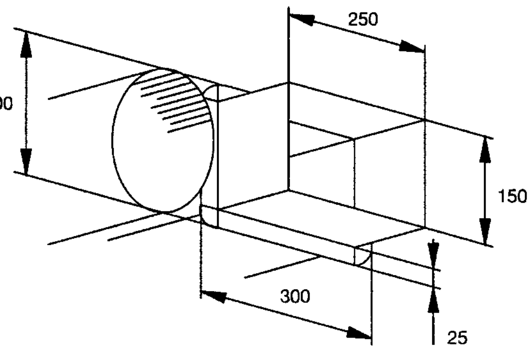


Figure 65 : Same space and same free duct area

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.

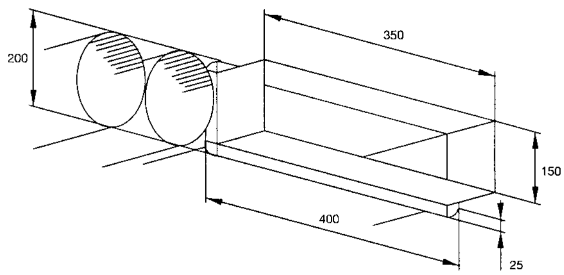


Figure 66 : A flat rectangular duct can often be replaced by several parallel round ducts

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.

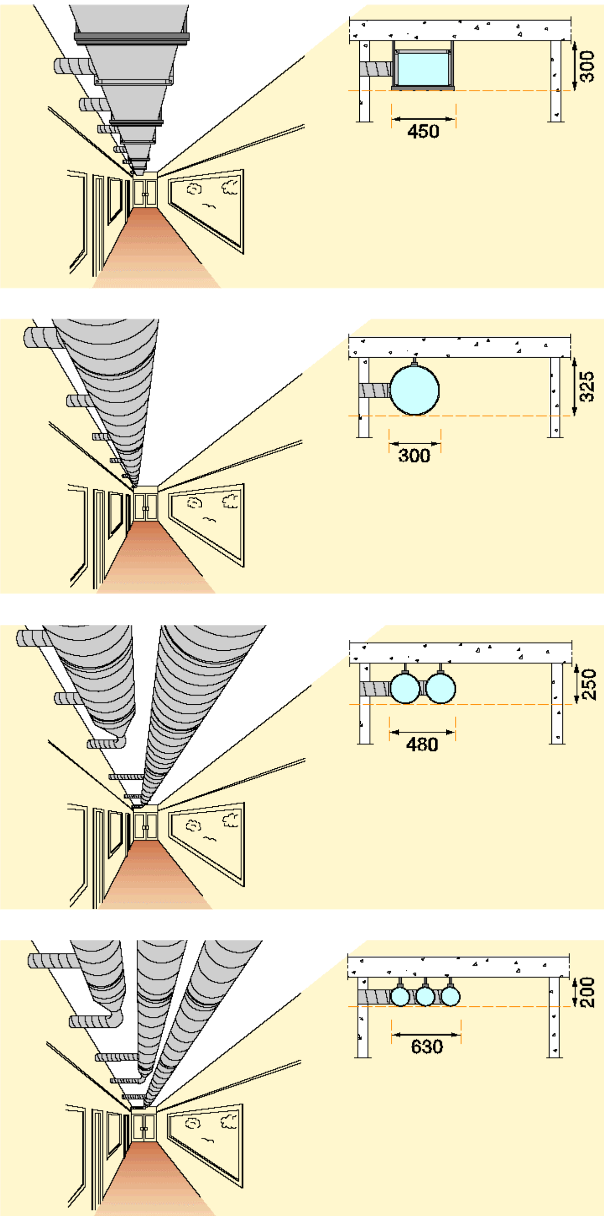


Figure 67 : Space demand for rectangular or circular duct(s)

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.

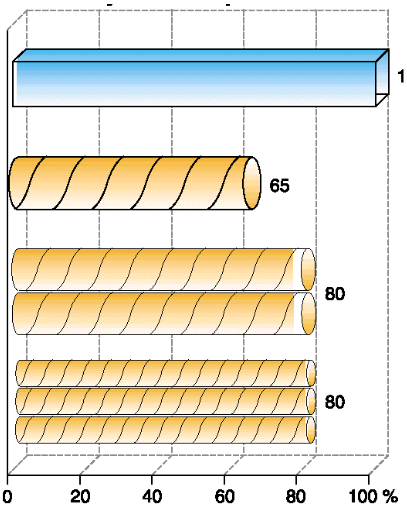


Figure 68 : Weight of ducts comparison

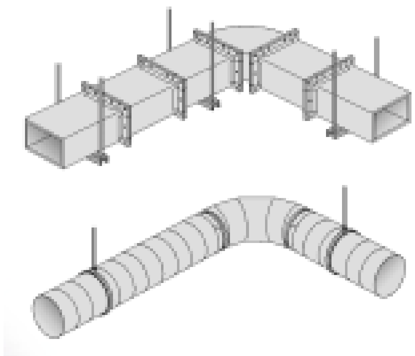


Figure 69: Hangers and joints for rectangular and circular ducts

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.

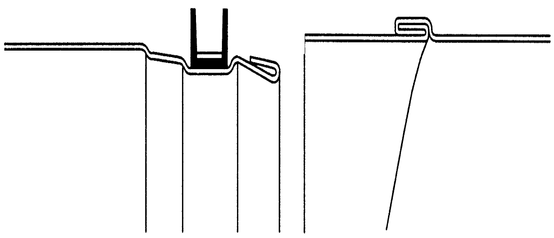


Figure 73 : Double sealing gasket. Due to larger tolerance range between duct and fitting with increasing duct diameters, the gasket size increases in steps with the duct diameter.

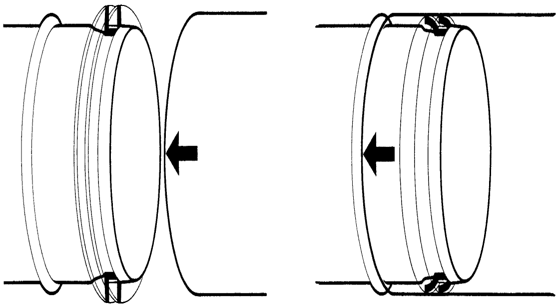


Figure 74 : When the duct is pushed onto the fitting (or vice versa) the gasket is compressed and tightens the space between the two.

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.

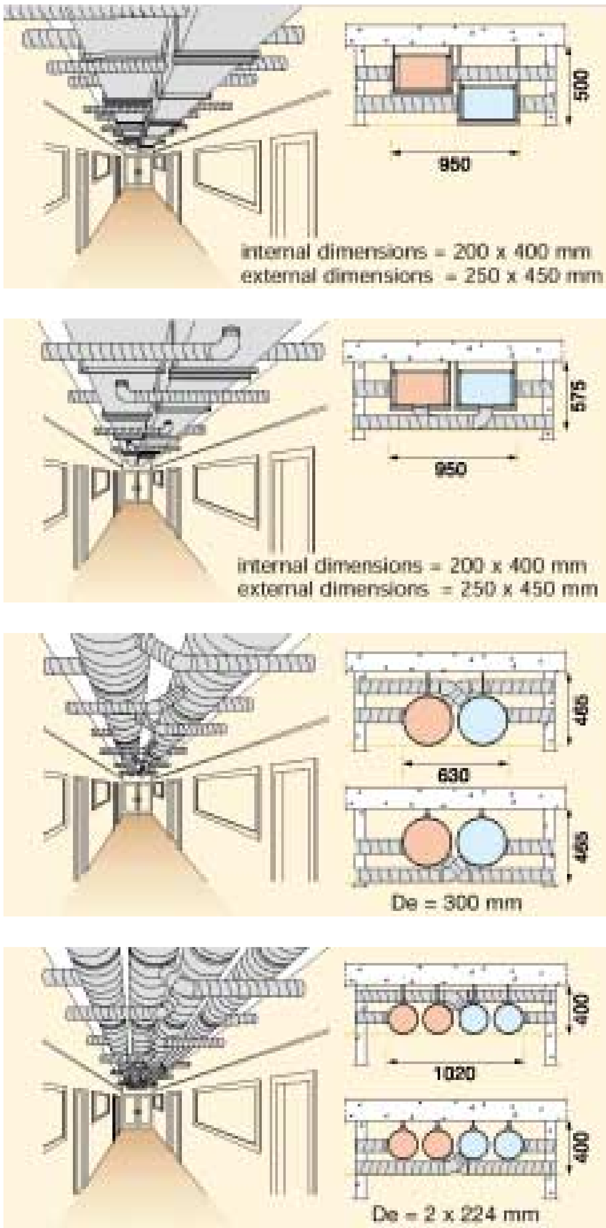
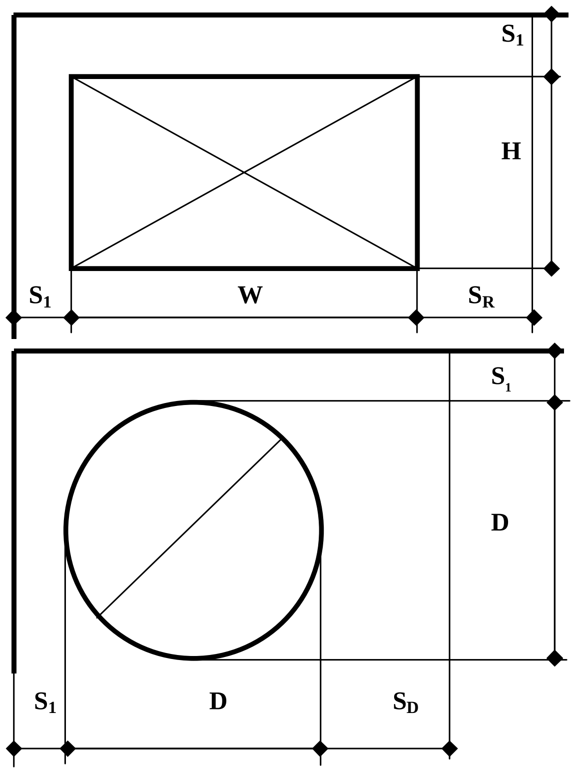


Figure 76 : Four possible alternatives starting with rectangular ducts followed by circular ducts.

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.

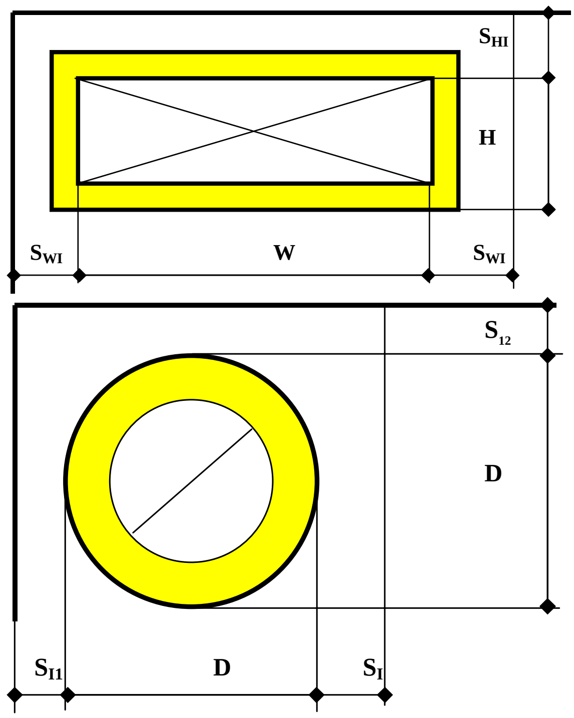


Duct size (mm)				
Circular **D**	Rectangular **W** or **H**		Minimum	Recommended
≤160	≤150	S_1	≥50	≥100
>160	>150	S_1	≥100	
≤800		S_D	≥400	
>800		S_D	≥400	**D**/2
	W≤800	S_R	≥400	
	W>800	S_R	≥400	**W**/2

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.

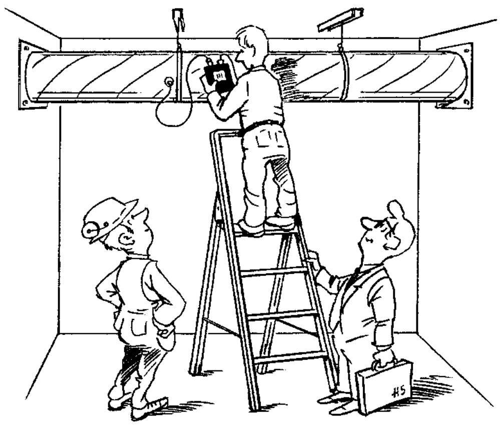


Figure 82 : Airflow measuring in a duct

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.

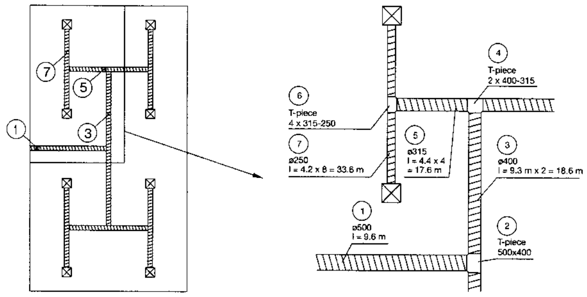
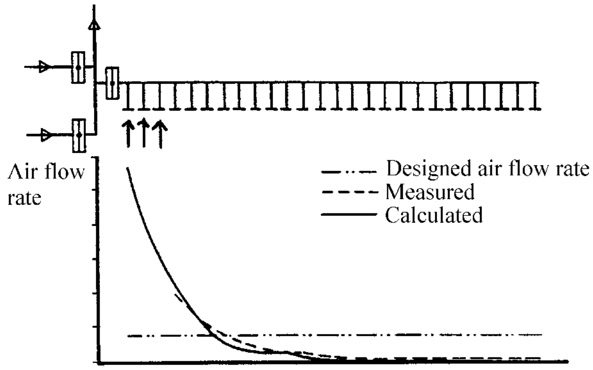


Figure 83 : Symmetrical ductwork where the supply air (entering at 1) passes through identical duct components on its way to the registers.



-.- = 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.

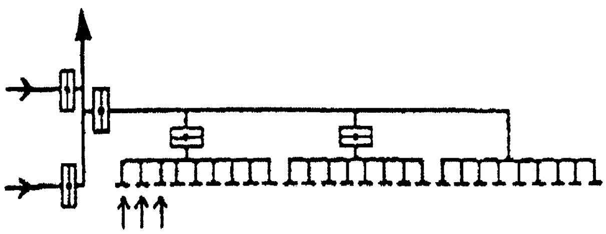


Figure 85 Now it is possible to adjust the airflow. The registers are combined in smaller groups, each with its adjusting damper.

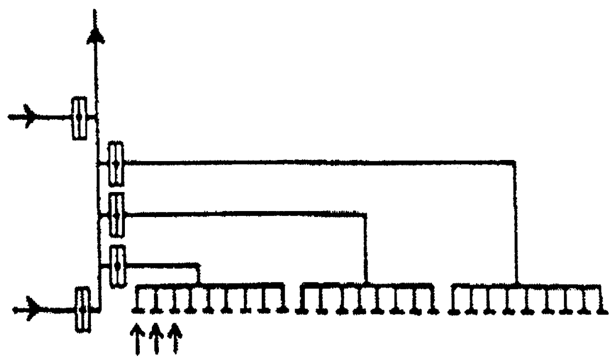


Figure 86 The same system once more solved with an alternative location of the adjusting dampers.

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.

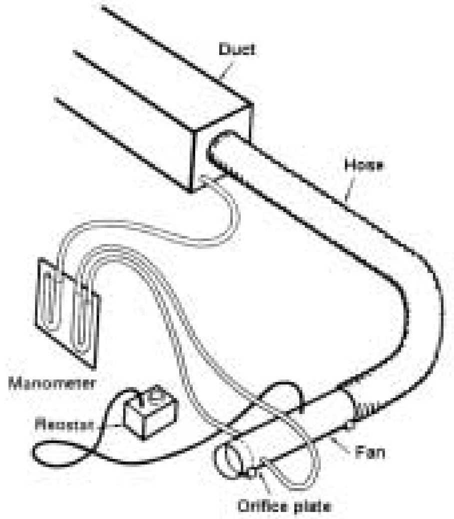


Figure 87 : Typical equipment used for tightness testing of ductwork.

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):

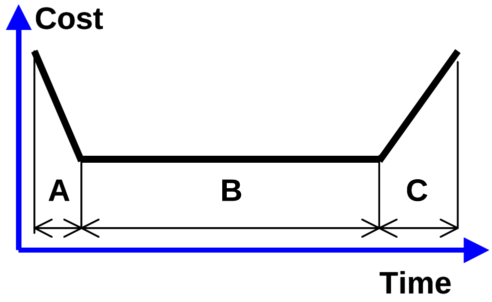


Figure 88 : Life span of a technical installation

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.

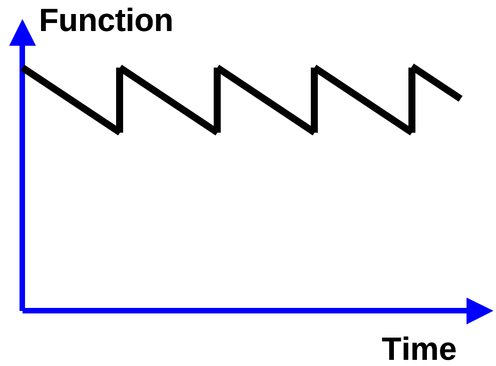


Figure 89 : Function raise up of a technical installation thanks to maintenance

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 Countryside	 1 – 3 0.5 - 2
Industrial areas	2 – 10
Sea water North Sea Baltic Sea	 12 – 46 ca. 10
Fresh water Hard Soft Tap water + 15°C	 2 – 4 <20 <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.

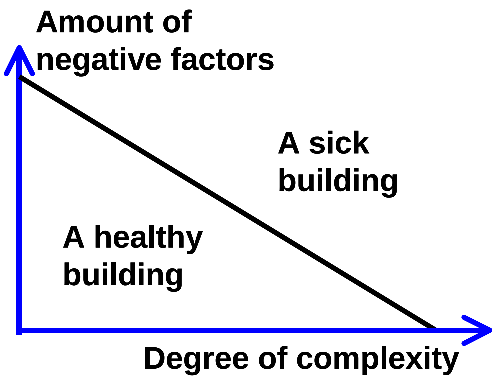


Figure 95 : Relationship between complexity of building installations and the result obtained

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.

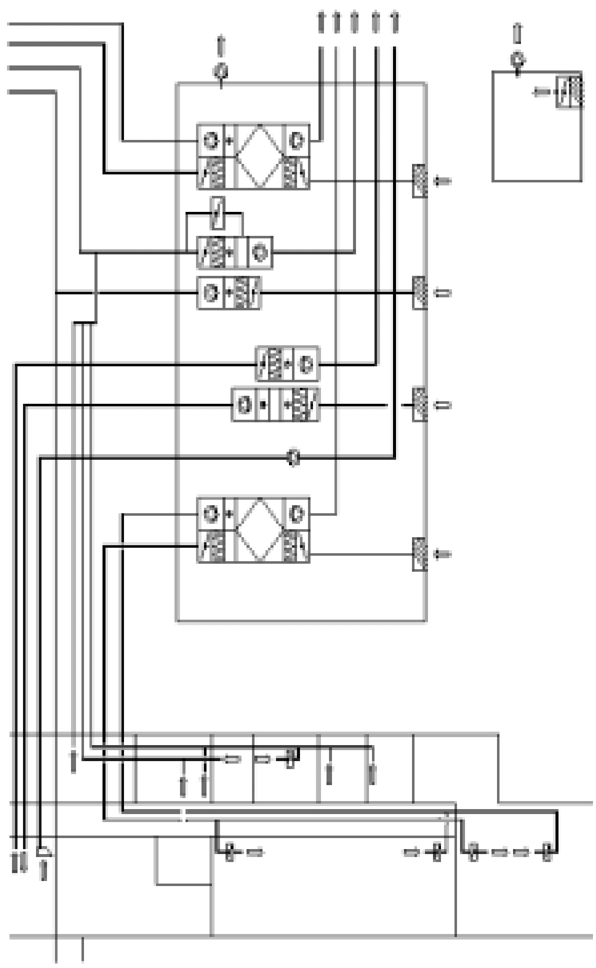


Figure 96 : Typical flow chart for a ventilation system. The designations used are probably self-explanatory.

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^{o}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.

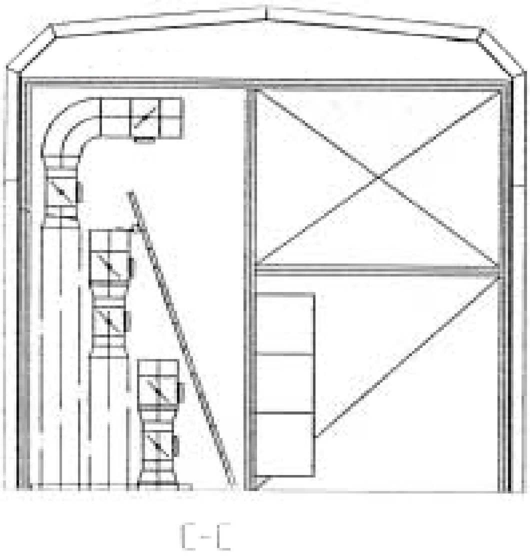


Figure 104 : Cross section "C-C" (see Figure 105) through part of the top floor fan room. The (extract) ducts to the left are the ones shown on the photograph (see Figure 103)

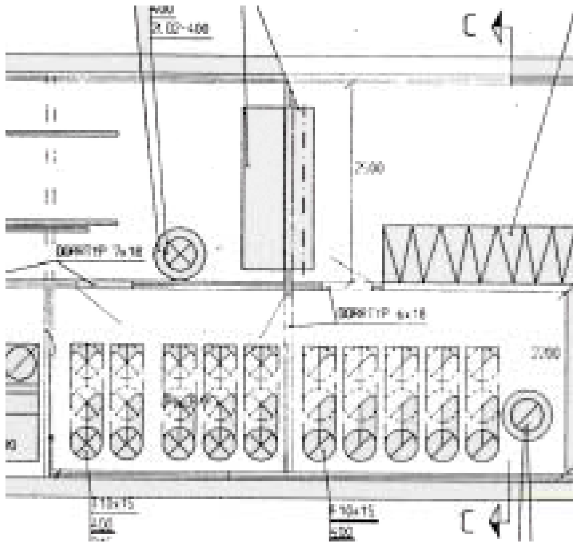


Figure 105 : Part of the fan room drawing with the extract air ducts to the right and the supply air ducts to the left. All these ducts are 400-mm diameter.

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

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 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.

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 (**TAB**):
  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).

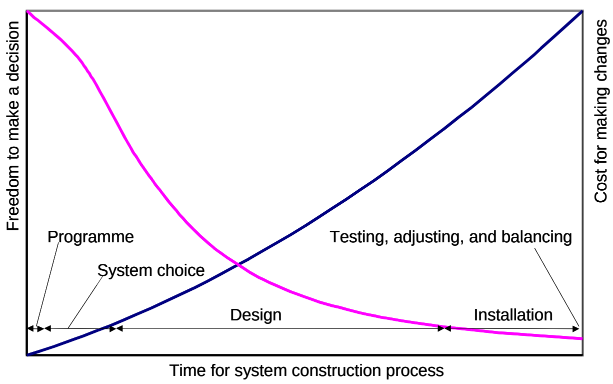


Figure 121 : Freedom to make a decision and cost involved versus time of building construction process.

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.

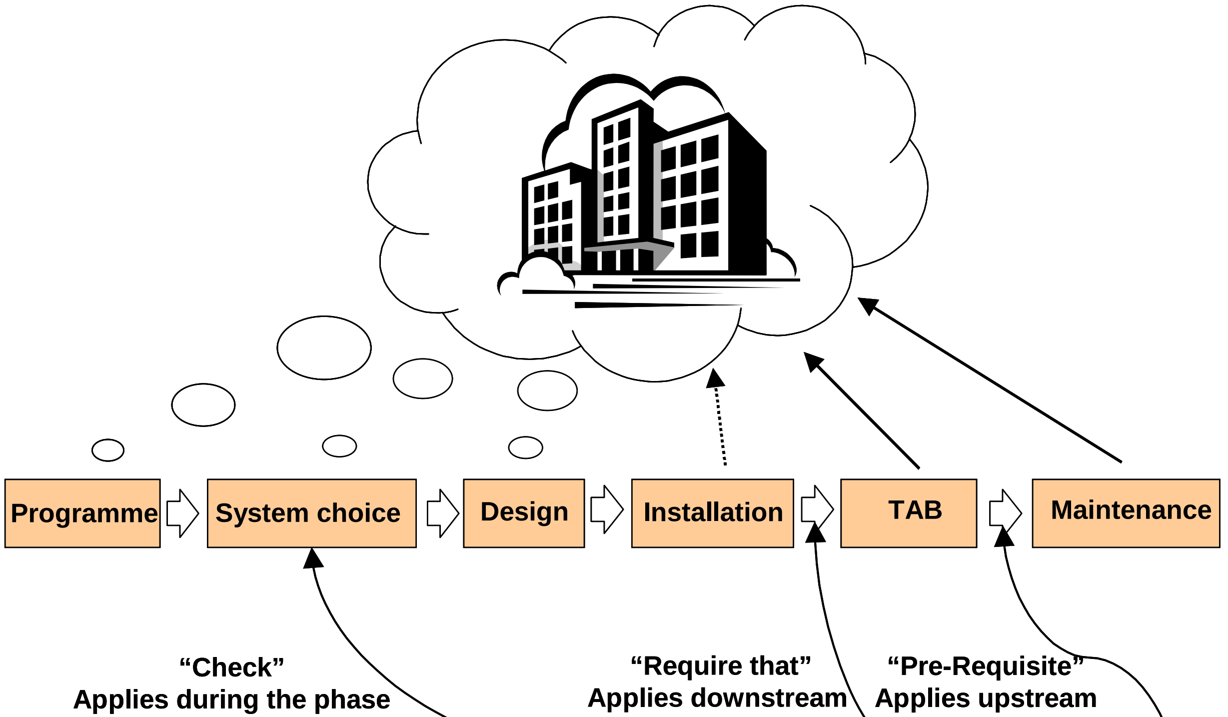
Detailed checklists that address technical issues in more details can be found under "**Specific requirements**". Their generic structure is shown in Figure 123.

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.

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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

Organisations which are participating in the AIRWAYS project

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AIRWAYS