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Duct leakage in European buildings: status and perspectives

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Abstract

A large number of modern European buildings are equipped with ducted air distribution systems. To investigate the implications of duct leakage, a field study was performed on 42 duct systems in Belgium and France. The measurement data confirm the findings of the few earlier experimental investigations on these matters in Europe. In our sample, the leakage rate appears to be typically three times greater than the maximum permitted leakage adopted in EUROVENT 2/2 (Class A). The advantages of tight ducts are illustrated with a theoretical case study on a balanced ventilation system with heat recovery. It indicates that the overall effectiveness of the system reduces drastically if the ducts are leaky. The savings potential of an airtight duct policy at the European level is calculated (a) based on estimates of the number of buildings equipped with mechanical ventilation systems, and (b) assuming market penetration scenarios of rehabilitation techniques. At the European level, the cumulative savings potential over a period of 10 years appears to be in the region of 10 TW h (36 pJ). © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Duct leakage; European buildings; Belgium; France

1. Introduction

A large number of modern European buildings are equipped with ducted air distribution systems. Because they represent a key parameter for achieving a good indoor climate, increased attention has been given to their performances during the past 50 years. One aspect that is particularly developed in this paper relates to the airtightness of the ductwork, which has been identified as a major source of inadequate functioning and energy wastage of HVAC systems in previous US studies [1–7]. In Europe however, very little information is available on this subject. In the UK, Babawale et al. (1993) [8] have investigated one forced air-heating system and have come to adverse conclusions in terms of energy use and comfort conditions. They recommend research to ascertain the extent and impact of duct leakage in new and old building stock in the UK, especially when the ducts run through unconditioned spaces. However, such installations are not in general use in other European countries. In Belgium, Ducarme et al. (1995) [9] monitored a demand controlled ventilation (DCV) system recently installed in an office building. It was shown that ductwork airtightness was essential in order to benefit fully from the energy savings potential of the DCV technology. In this specific case, the initial ductwork airtightness was so poor that no savings at all could be achieved: whatever the demand was, the same air flow rate was supplied to the building, either to the occupied offices or to the corridor through the leaks. Afterwards, it proved to be very difficult and time consuming to improve the ductwork air tightness in order to meet EUROVENT [13] Class A. Pittomvils et al. (1996) [10] investigated in detail balanced ventilation systems installed

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in more than 170 very low energy houses built in the Flemish Region of Belgium by field and laboratory testing. They showed that the ductwork was so leaky that about one third of the air supplied by the fan at medium speed escapes through leaks before reaching the ventilated room. In France, Carrié et al. (1996) [11] measured very large leakage rates in nine duct systems in multi-family buildings, eight in schools, two in a day-care centre, and three in office buildings. Their analyses show that potentially large indoor air quality and energy use impacts at a national level.

To our knowledge, these are the only studies conducted in Europe that are relevant to our topic, which means that measurement data is substantially insufficient to evaluate the significance of ducted air distribution system leakage on power demand and energy use in Europe. This paper presents the results of a field study on 42 duct systems in Belgium and France carried out within the SAVE-DUCT project (Carrié et al., 1997 [12]). On this basis, energy analyses are performed to quantify duct leakage implications both at a microscopic and at a macroscopic level.

2. Background

In Europe, national ductwork airtightness standards are in general similar to EUROVENT 2/2 [13] guidelines that propose a one-point measurement of the leakage flow rate at a given pressure differential. The installations are classified according to the value of the leakage factor at a reference test pressure of the system based on the following equation:

$$\frac{Q}{A} = f_{\mathrm{ref}} = K\,\Delta p_{\mathrm{ref}}^{0.65}. \tag{1}$$

The maximum leakage rates for three airtightness classes (A, B, C) are based on maximum values of K (Table 1). Class D is sometimes used based on the same geometric progression, i.e. $K_{\mathrm{D}} = 0.001 \times 10^{-3}\ \mathrm{m}^3\ \mathrm{s}^{-1}\ \mathrm{m}^{-2}\ \mathrm{Pa}^{-0.65}$. According to EUROVENT 2/2 [13], Δp_{ref} is set to the mean operating pressure of the duct system. It is noteworthy that this classification relies on an arbitrary flow exponent of 0.65, which according to DW/143 (HVCA, 1983) [14] is justified by Swedish tests performed on a variety of constructions. However, measurements performed in the SAVE-DUCT project show a broad range of values.

Table 1
Airtightness classes defined in the EUROVENT Guidelines 2/2. For laboratory duct testing, these values are divided by two

Class A	$K_{\mathrm{A}} = 0.027 \times 10^{-3}\ \mathrm{m}^3\ \mathrm{s}^{-1}\ \mathrm{m}^{-2}\ \mathrm{Pa}^{-0.65}$
Class B	$K_{\mathrm{B}} = 0.009 \times 10^{-3}\ \mathrm{m}^3\ \mathrm{s}^{-1}\ \mathrm{m}^{-2}\ \mathrm{Pa}^{-0.65}$
Class C	$K_{\mathrm{C}} = 0.003 \times 10^{-3}\ \mathrm{m}^3\ \mathrm{s}^{-1}\ \mathrm{m}^{-2}\ \mathrm{Pa}^{-0.65}$

3. SAVE-DUCT field measurement results

In the framework of the SAVE-DUCT project the ai tightness of 42 ductwork systems was measured in Franc [20] and Belgium [20]. In Sweden, nearly all installatio are leak-tested at commissioning and, as a consequenc much data are already available. A randomly selecte sample of 69 Swedish control measurements was therefo collected. In Belgium and in France, the multi-point duc work pressurisation method was used, i.e. the ductwo was pressurised at different pressure stations to calcula the leakage characteristics of the systems. The tests we performed at pressures in the range of 50–150% of th operating pressure of the ductwork. In Sweden howeve the control procedures are performed according to a diffe ent protocol. The one-point measurement method (usuall at 400 Pa) with an arbitrary flow exponent of 0.65 is use The results are shown in Figs. 1–3.

Nearly all new Swedish installations have to compl with airtightness requirements detailed in AMA 83 [1 that depend on their type. In Fig. 1, three groups ductwork are represented: one system has to comply wi Class D, 19 systems with Class C and 49 with Class With the Swedish samples, most of the installations see to meet the requirements, only three do not. It is notewo thy that installations that do not fulfil the requiremen have to be tightened until they are; consequently, the thre ''bad'' installations should eventually have at least th desired airtightness. These impressive results are probabl due to the widespread use in Scandinavian countries quality-products with factory-fitted joint sealing device (e.g. gaskets, see Fig. 4). In addition, circular systems th are known to be tighter than rectangular ductwork, have market share in the region of 90%. Further informatio about the advantages of round ducts can be found Andersson (1997) [16].

It is clear that the situation is quite different in Belgiu and in France where conventional in situ sealing tec niques prevail. Leakage rates were found to be typicall three times greater than Class A. In addition, significa deficiencies were observed in some Belgian and Frenc buildings, e.g.:

- inadequate ductwork components selection;
- insufficient sealing work at installation;
- ill-fitted components;
- worn tapes;
- physical damage during inspection or maintenanc work.

In some cases, ducts were found completely disjointe In the Belgian sample, there is a striking difference b tween circular and rectangular systems. The leakage rate typically seven times greater for rectangular ducts, a though in the Swedish sample a difference of (only) 15 was measured.

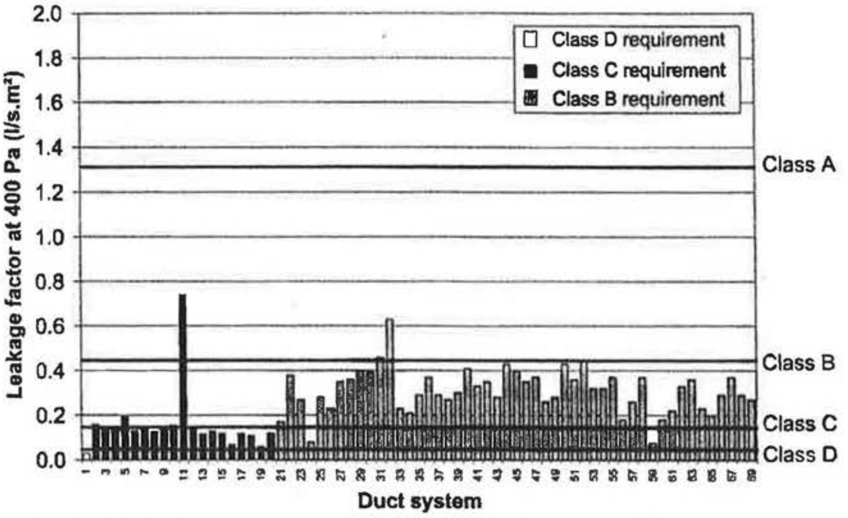


Fig. 1. Leakage factor at 400 Pa for 69 duct systems in Sweden. Leak-tests performed at commissioning.

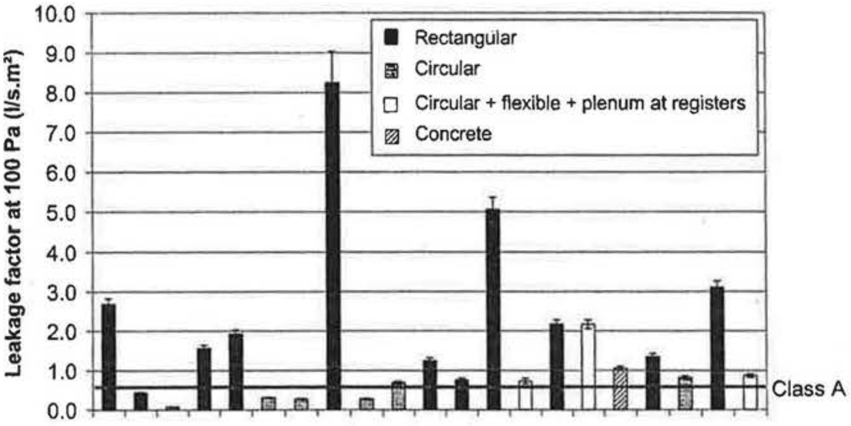


Fig. 2. Leakage factor at 100 Pa for the investigated systems in Belgium.

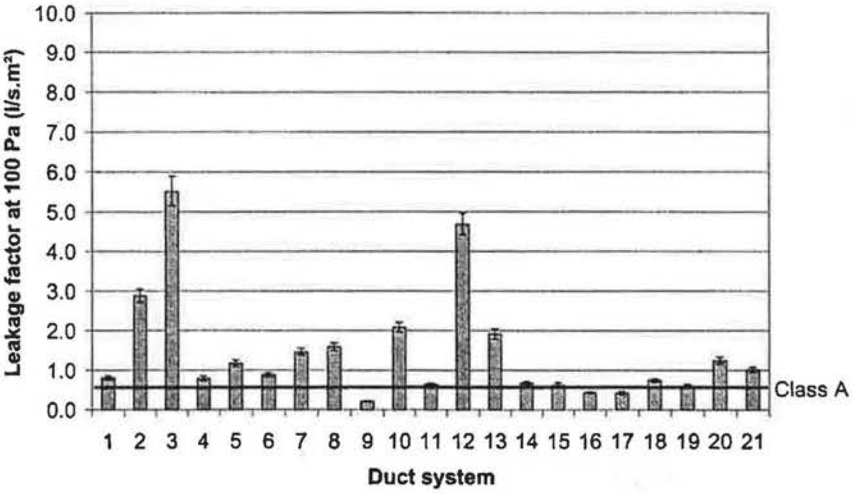


Fig. 3. Leakage factor at 100 Pa for the investigated systems in France.

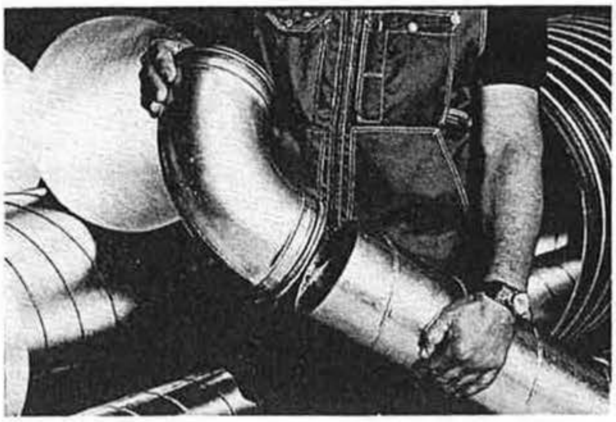


Fig. 4. LindabSafe® sealing system (courtesy Lindab Ventilation). A double sealing gasket of EPDM rubber provides a tight reliable joint.

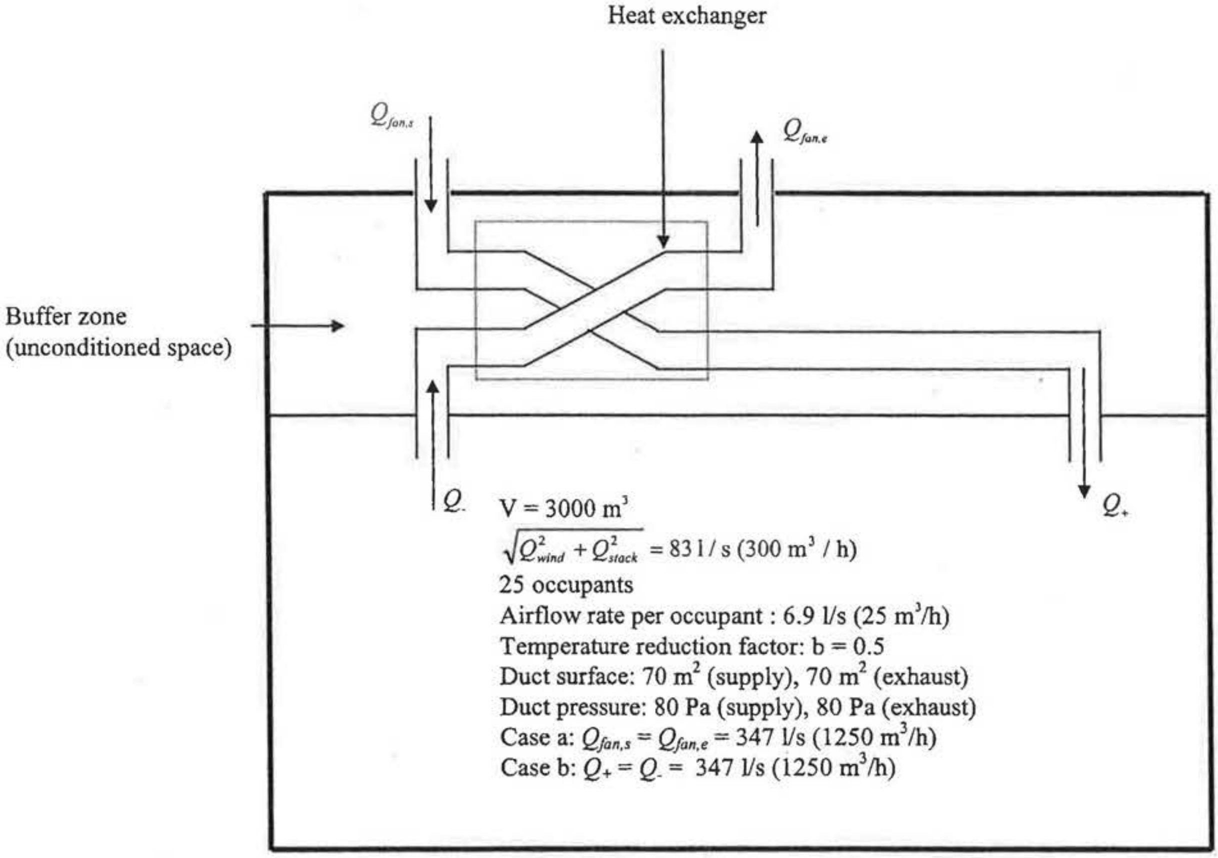
These airtightness deficiencies along with other problems (dirty systems, inadequate design, absence of commissioning, poor or no maintenance, etc.) show the lack of attention paid to those systems in Belgium, France, and probably non-Scandinavian countries. All of this can lead to considerable problems in terms of energy use and indoor air quality.

4. Microscopic analyses

Duct leakage can have a severe impact on the ventilation rates and energy consumption of a building. Two extreme cases may be considered:

(a) The system's sizing does not take into account the presence of the leaks. In this case, the required airflow rates are not met at the registers, which can lead to indoor air quality problems.
(b) The fan is sized so as to obtain the desired airflow rates at the registers. This will lead to increased energy use due to the additional fan power demand. The ventilation load may also be affected due to uncontrolled infiltration through the building envelope and through the ducts.

To illustrate these effects, quantitative analyses were performed on an office building equipped with a balanced ventilation system with heat recovery (Fig. 5). In this case,



$V = 3000\ m^3$
$\sqrt{Q_{wind}^2 + Q_{stack}^2} = 83\ l/s\ (300\ m^3/h)$
25 occupants
Airflow rate per occupant : 6.9 l/s (25 m^3/h)
Temperature reduction factor: b = 0.5
Duct surface: 70 m^2 (supply), 70 m^2 (exhaust)
Duct pressure: 80 Pa (supply), 80 Pa (exhaust)
Case a: $Q_{fan,s} = Q_{fan,e} = 347$ l/s (1250 m^3/h)
Case b: $Q_+ = Q_- = 347$ l/s (1250 m^3/h)

Fig. 5. Schematic diagram of an office building equipped with a heat recovery system.

the infiltration rate can be estimated using the following equation [6]:

$$Q_{\text{vent}} = \sqrt{Q_{\text{wind}}^2 + Q_{\text{stack}}^2 + Q_{\text{unbalanced}}^2} + Q_{\text{balanced}}. \tag{2}$$

The ventilation load is:

$$P_{\text{vent}} = \rho Q_{\text{vent}}(h_{\text{in}} - h_{\text{out}}) + \rho Q_{\text{leak,s}}(h_{\text{s}} - h_{\text{out}}) - \eta_\nu \rho Q_{\text{fan,e}}(h_{\text{e}} - h_{\text{out}}). \tag{3}$$

If we neglect the effect of the water vapour, this equation becomes:

$$P_{\text{vent}} = \rho c_{\text{p}}\left(Q_{\text{vent}} - \frac{Q_+}{Q_{\text{fan,s}}}\eta_\nu(bQ_{\text{leak,e}} + Q_-)\right)\Delta T. \tag{4}$$

The effective heat recovery of the system is:

$$\eta_{\nu,\text{eff}} = 1 - \frac{\left(Q_{\text{vent}} - \dfrac{Q_+}{Q_{\text{fan,s}}}\eta_\nu(bQ_{\text{leak,e}} + Q_-)\right)}{Q_{\text{vent}}}. \tag{5}$$

It can be seen that the system's effectiveness is severely affected by duct leakage (Figs. 6–8). The ventilation rate and load as well as the fan power demand are normalised with respect to the results of Class D. The potential indoor air quality problems appear clearly in Fig. 6 as the ventilation rate is reduced by half for a leakage coefficient of 0.162 l s^{-1} m^{-2} $\text{Pa}^{-0.65}$ (i.e. six times Class A). Going to Class C or D does not significantly change the results as the leakage airflow rate becomes negligible compared to the nominal airflow rate as soon as Class B is achieved. It

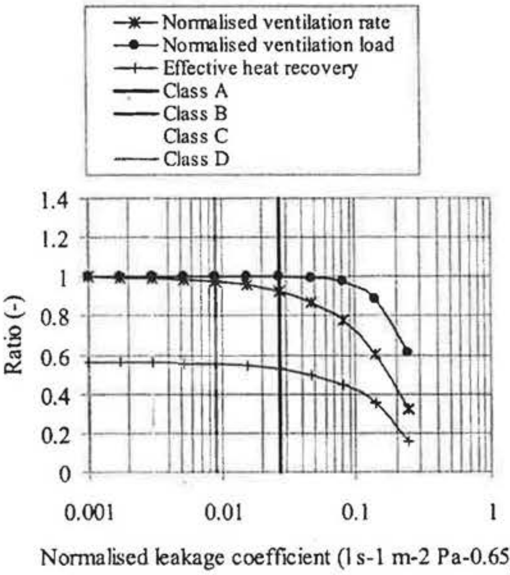


Fig. 6. Ventilation rate and load impacts of duct leakage. The calculations are performed for the system described in Fig. 5 — case a.

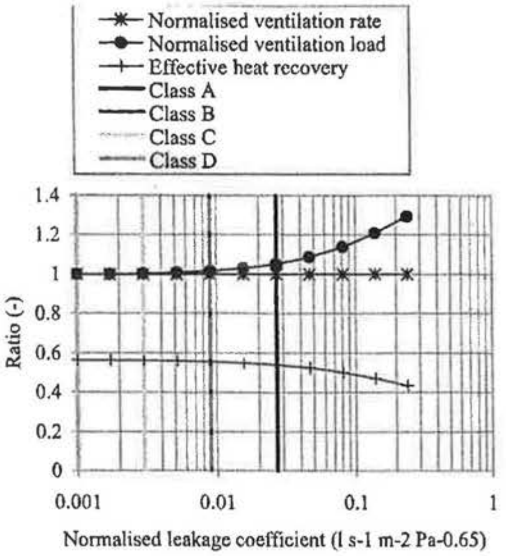


Fig. 7. Ventilation rate and load impacts of duct leakage. The calculations are performed for the system described in Fig. 5 — case b.

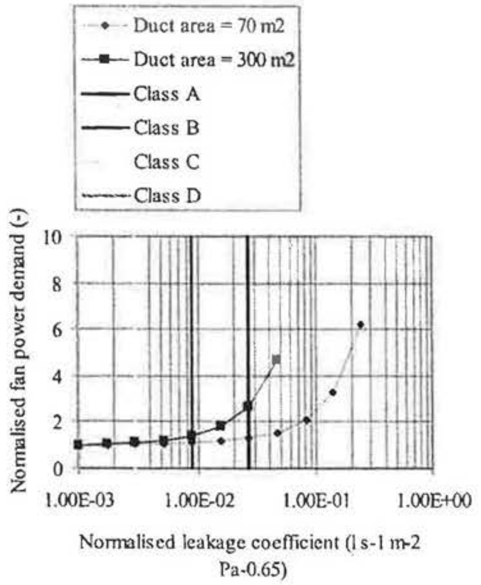


Fig. 8. Fan power demand as a function of duct leakage. The calculations are performed for the system described in Fig. 5 — case b. The specific fan power demand is set to 1.5 kW per m^3/s for Class D and it is assumed to be proportional to the cube of the fan flow rate.

Table 2
Energy impact of duct leakage in Belgium

	Office buildings (assuming 25% are mechanically ventilated)	Dwellings (assuming 5% are equipped with permanently working mechanical ventilation devices)
Heating energy consumption due to leaks	15 GW h/year (0.054 pJ/year)	150 GW h/year (0.54 pJ/year)
Share of leaks in total heating energy	0.30%	0.16%
Required additional fan power demand	0.4 MW	2.7 MW
Additional fan power demand versus available electricity power	0.003%	0.02%

should be noted that if this ratio is made larger (e.g. by increasing the duct area), Class C or even Class D may be considered (Fig. 8).

5. Energy impact at the European level

Very approximate estimates of the order of magnitude of the energy wastage and supplementary peak power demand due to the duct leakage were made for Belgium, based on the assumptions detailed in Appendix A. The energy impact estimates for Belgium are summarised in Table 2. If we extrapolate these results to the rest of Europe (excluding the Former Soviet Union), it appears that the heating energy consumption due to duct leakage is of 0.75 TWh/year (2.7 pJ/year) in offices and 7.5 TWh/year (27 pJ/year) in dwellings.

However, the reader should keep in mind that the Belgian estimates apply to the Belgian climate and building stock. Also, the number of dwellings situated in the Mediterranean area is larger than the number of Scandinavian dwellings. Moreover, the leakage flow rate is probably much smaller in Scandinavian countries. Therefore, caution should be exercised when interpreting the savings estimates quoted before.

In addition, in the previous calculations the energy savings were estimated in the case where all new and existing ductwork systems were airtight. This market transformation can occur only step by step, especially for existing buildings. In order to give an idea of the potential savings in the short term, the energy savings of tight air ducts were calculated for different rehabilitation scenarios (market penetration: 0.0%, 0.1%, 0.5%, 1.0% and 2.0%) based on assumptions detailed in Appendix A. The results are presented in Figs. 9 and 10. The order of magnitude of the energy savings that can be achieved by using airtight ductwork in Europe is probably in the region of 1 to 10 TWh/year (3.6 to 36 pJ/year). This is between 0.007% and 0.07% of the total European energy consumption per year (about 14000 TWh (50400 pJ)-figure from 1992 (EC DGXVII, 1994)).

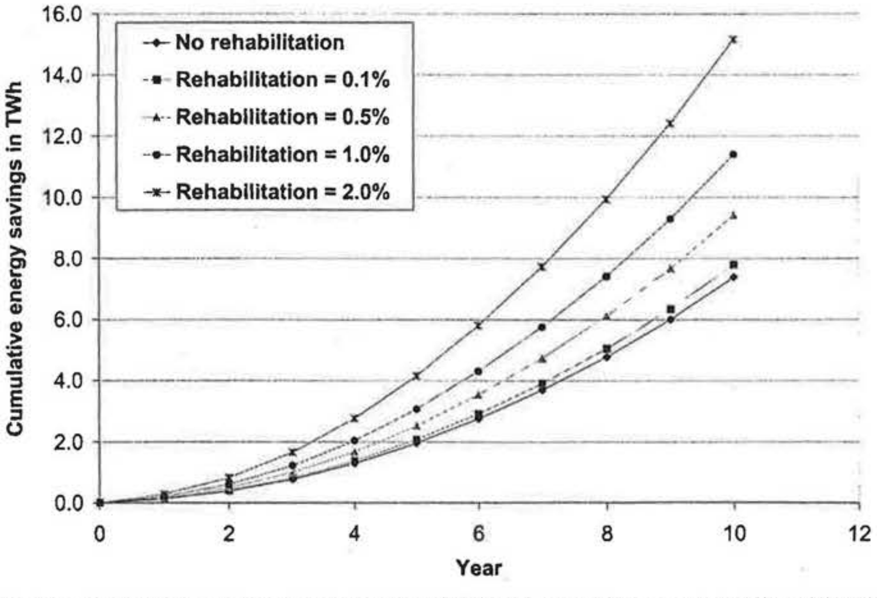


Fig. 9. Energy savings per year due to the installation of airtight ductwork in new and rehabilitated dwellings.

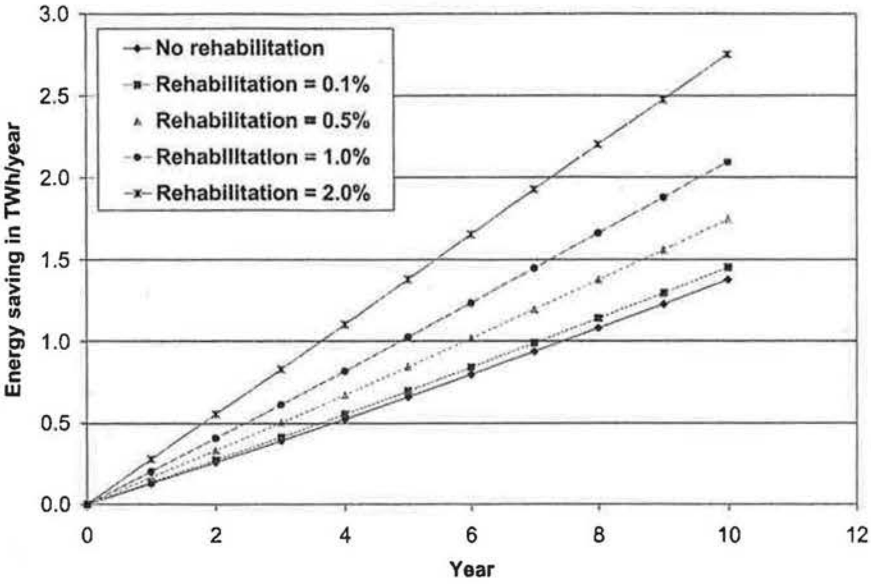


Fig. 10. Cumulative energy savings due to the installation of airtight ductwork in new and rehabilitated dwellings.

In sum, the results presented in this paragraph are approximate estimates, based on simple calculations, but they demonstrate clearly that significant energy savings can be achieved by installing airtight ductwork. The cumulated energy saving over a period of 10 years could well be in the region of 10 TWh.

6. Conclusions

Duct leakage is detrimental to energy efficiency and indoor air quality. In most countries however, designers, installers, building managers and building owners ignore the benefits of airtight duct systems. Furthermore, as there have been no incentives over the years, this has (probably) lead to poor ductwork installations in a large fraction of the building stock.

The duct leakage measurement data on 42 buildings in Belgium and France confirms the findings of the few earlier experimental investigations on these matters in Europe. The tested duct systems are in general very leaky (typically three times leakier than Eurovent [13] Class A). The reason for such poor performances seems to lie in the lack of attention paid to these systems and the technologies adopted. In fact, in these countries, installation is most often done using conventional in situ sealing techniques (e.g. tape or mastic). Therefore, the ductwork airtightness is very much dependent upon the workers' skills.

However, it is possible and easy to install tight duct systems with quality commercially available products. In Sweden, where factory-fitted sealing gaskets are widely used, airtightness Class C is commonly required and fulfilled. This tradition is probably due to the fact that the need for tight ducts was identified in Sweden in the early sixties.

Probably, a major barrier towards tighter systems lies in cost issues. Further work seems necessary in this area. However, the additional investment cost (if any) for quality-products should be looked at along with the potential savings on labour cost. In addition, significant energy savings can be achieved with tight ducts, which will have a positive effect on the Life Cycle Cost of the system.

Because of the wide use of forced-air heating or cooling systems in the US, duct leakage is a very active field of study in this country [1–7]. The analyses presented in this paper show that ventilation and energy use implications of leaky ducts in European buildings are also very large and merit further examination.

List of symbols

A	duct surface area (m^2)
b	reduction factor in the unconditioned buffer zone (−) ($b=\{T_{buf}-T_{out}\}/\{T_{in}-T_{out}\}$)
c_p	specific heat of dry air (J/kg K)
f_{ref}	leakage factor at Δp_{ref} ($m^3\ s^{-1}\ m^{-2}$)
h	specific enthalpy (J/kg)
h_e	specific enthalpy of the extract air (J/kg)
h_{in}	specific enthalpy of the inside air (J/kg)
h_r	specific enthalpy of the air in the return ducts (J/kg)
h_{rz}	specific enthalpy of the air in the zone where the return ducts are located (J/kg)
h_{out}	specific enthalpy of the outside air (J/kg)
h_s	specific enthalpy of the air in the supply ducts (J/kg)
ρ	is the density of air ($kg\ m^{-3}$)

K	leakage coefficient per m^2 of duct surface area ($m^3\ s^{-1}\ m^{-2}\ Pa^{-0.65}$)
n	flow exponent (−)
P_{vent}	ventilation load (W)
Q	(leakage) flow rate ($m^3\ s^{-1}$)
$Q+$	sum of the airflow rates at the supply registers (m^3/s)
$Q_{balanced}$	balanced ventilation rate (m^3/s)
Q_{fan}	fan flow rate (m^3/s)
$Q_{fan,e}$	extract fan airflow rate (m^3/s)
$Q_{leak,r}$	return duct leakage flow rate (m^3/s)
$Q_{leak,s}$	supply duct leakage flow rate (m^3/s)
Q_{stack}	stack-induced ventilation rate (m^3/s)
$Q_{unbalanced}$	unbalanced ventilation rate (m^3/s)
Q_{vent}	total ventilation rate (m^3/s)
Q_{wind}	wind-induced ventilation rate (m^3/s)
$Q-$	sum of the airflow rates at the extract registers (m^3/s)
T_{buf}	temperature of unconditioned (buffer) zone (K)
T_{in}	inside temperature (K)
T_{out}	outside temperature (K)
Δp_{ref}	reference pressure differential across the leaks (Pa)
ΔT	temperature difference between inside and outside (K)
η_v	efficiency of the HRU (−)
$\eta_{v,eff}$	effective heat recovery of the system (−)

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- SCANDIACONSULT, Stockholm, Sweden
- Centre d'Etudes Techniques de l'Equipement, Lyon, France

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Appendix A. Assumptions for macroscopic energy calculations

The following general assumptions were made.

1. The air leaving the ductwork through leaks (in false ceilings, technical rooms, attics, etc.) does not contribute to the indoor air quality. Therefore, air leakage from ductwork results in higher airflow rates through the air handling unit and through outdoor air intakes. This implies a higher fan power and more energy for air treatment.
2. A specific fan energy of 1.5 W per l/s is assumed.
3. The leakage airflow rate is set to 15% of the nominal airflow rate.
4. There is no heat recovery from exhaust air.

A.1. Belgian offices

- 1 million office workers (total population of 10 million).
- required airflow rate: 7 l/s per person.
- total energy consumption for heating for all office buildings together: 5 TW h/year (18 pJ/year), from:
    - 200 kWh/m^2 (BRE, 1991 [17]);
    - Available surface per worker: 25 m^2;
- 1400 degree days during working hours;
- year-round efficiency of heating system: 70%;
- available electrical power (peak-value) in Belgium: 15 GW.

A.2. Belgian dwellings

- nominal airflow rate (supply) per dwelling is about 80 l/s (BBRI, 1998 [18]);
- year-round efficiency of the heating system is about 70%;
- 2000 degree days;
- total energy consumption for heating for all Belgian dwellings together: 90 TWh/year (324 pJ/year), from:
    - typical average heating energy consumption for a Belgian dwelling: 30 000 kWh/year (BBRI, 1998 [18]) (figure typical for new single-family dwelling);
    - about 3 million dwellings.

A.3. Europe

- 50 million office workers;
- 150 million dwellings (University of Oxford, 1998 [19]);
- the loss of cooling energy due to leaky ductwork is not taken into account;
- the total number of existing dwellings at the European level is about 150 million;

- the heating loss due to duct leakage is 1000 kWh/year;
- the number of new constructed dwellings is 1.7% of the existing dwellings (according to the Belgian situation) (BBRI, 1998 [18]);
- 5% of the dwellings are equipped with a permanently operating ventilation system;
- airtight ducts are placed in all new and rehabilitated dwellings.

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