Financial impact of leaky ductwork in buildings – a calculation tool to raise awareness

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ABSTRACT

In the context of energy saving, new buildings are becoming more airtight and purpose-provided, often central mechanical ventilation is required to create and sustain a healthy indoor air quality (IAQ). This policy is summed up by the well-known energy efficiency mantra “Build tight, ventilate right”.

Central mechanical ventilation systems require ductwork systems to distribute air inside the building, but in practice, they are often not airtight. The numerous issues caused by leaky ductwork, including excessive fan energy use, acoustic discomfort and possibly even poor IAQ, if the ventilation system is not commissioned correctly, have been well outlined in literature, but there still appears to be a lack of awareness about the impact of such issues in the construction industry.

A simple tool was developed using a simplified model to estimate the financial impact of leaky ductwork in buildings over their whole life. It assumes that the design or hygienic flow rates in all habitable and wet rooms are achieved, and it is based on two previous publications from the 40th (Leprince et al., 2019) and 42nd (Hurel and Leprince, 2022a) AIVC Conferences. The purpose of this user-friendly tool is to help to raise awareness about this issue and encourage the design and installation of airtight ventilation ductwork systems, which are readily available on the market.

Case studies for 4 houses and one of the 10 AHU of a school building are presented as examples of energy and financial impact of ductwork leakage. It is found that if the fan fully compensates, a very leaky ductwork (class 3A) induces an increase of fan energy use ranging between 58% and 173% for the 4 single-family houses, and of 33% for the school AHU. The financial impact of this poor ductwork airtightness level for 80 years of operation ranges from 4.0 k€ to 33.2 k€ for the 4 single houses and reaches 74 k€ for the school AHU (out of the 10 AHU).

KEYWORDS

Ductwork leakage, calculation tool, energy savings, financial impact, case study

1 INTRODUCTION

In the context of energy saving, new buildings are becoming more airtight and purpose-provided, often central mechanical ventilation is required to create and sustain a healthy indoor air quality (IAQ). This policy is summed up by the well-known energy efficiency mantra “Build tight, ventilate right”.

Central mechanical ventilation systems require ductwork systems to distribute air inside the building, but in practice, they are often not airtight. The numerous issues caused by leaky ductwork, including excessive fan energy use, acoustic discomfort and possibly even poor IAQ, if the ventilation system is not commissioned correctly, have been well outlined in literature and summarised recently in (Leprince et al., 2020), but there still appears to be a lack of awareness about the impact of such issues in the construction industry. Measurements performed in France in the context of the Effinergie + (Moujalled et al., 2018) have shown that almost 50% of the ductwork systems in the tested houses have ductwork airtightness 2.5*class A or worse. This stresses the need to change construction habits because the ductwork in most of the tested buildings was designed to achieve at least class A (required by the Effinergie + label), but missed the target.

A simple tool was developed using a simplified model to estimate the financial impact of leaky ductwork on fan energy use in buildings over their whole life. The impact on other things, for example the heating and cooling energy losses in case the air is pre-conditioned, have not been considered. This tool assumes that the design or hygienic flow rates in all habitable and wet rooms are achieved, and it is based on two previous publications from the 40th (Leprince et al., 2019) and 42nd (Hurel and Leprince, 2022a) AIVC Conferences. It has been designed for central mechanical ventilation systems with energy recovery and central mechanical extract ventilation systems

The purpose of this user-friendly tool is to help to raise awareness about this issue and encourage the design and installation of airtight ventilation ductwork systems, which are readily available on the market.

A case study is presented using the same 4 houses as Leprince et al.(2019), as well as a school building from the PromevenTertiaire project (Hurel and Leprince, 2022b) as examples of energy and financial impacts.

2 MODEL FOR THE LEAKAGE IMPACT CALCULATION

The model used in the calculation tool is detailed below. It is based on two studies by Leprince et al. (2019) and Hurel and Leprince (2022a).

2.1 Fan energy use

The electrical AHU fan power (P_{AHU}) depends on its flowrate (Q_{AHU}) and pressure (Δp_{AHU}):

$$P_{AHU} = \frac{\Delta p_{AHU} \times Q_{AHU}}{\eta \times 3600} \quad (1)$$

P_{AHU}	W	Electrical fan power
Δp_{AHU}	Pa	Pressure induced by the fan
Q_{AHU}	m^3/s	Flowrate delivered by the fan
η	-	Fan efficiency

The higher the pressure loss in the ductwork system, the more the fan needs to produce flowrate and pressure to compensate this resistance and meet the hygienic flowrates to ensure a good IAQ. As illustrated in Figure 1, depending on its settings and characteristics, the fan can be:

- In full compensation of leakage if the ATDs flowrates are the one expected (good IAQ but electrical overconsumption)

- In zero compensation of leakage if no additional flowrate in provided to compensate for leakage (poor IAQ but no electrical overconsumption)
- In partial compensation, with an IAQ more or less deteriorated and a more or less significant electrical overconsumption depending on the compensation rate

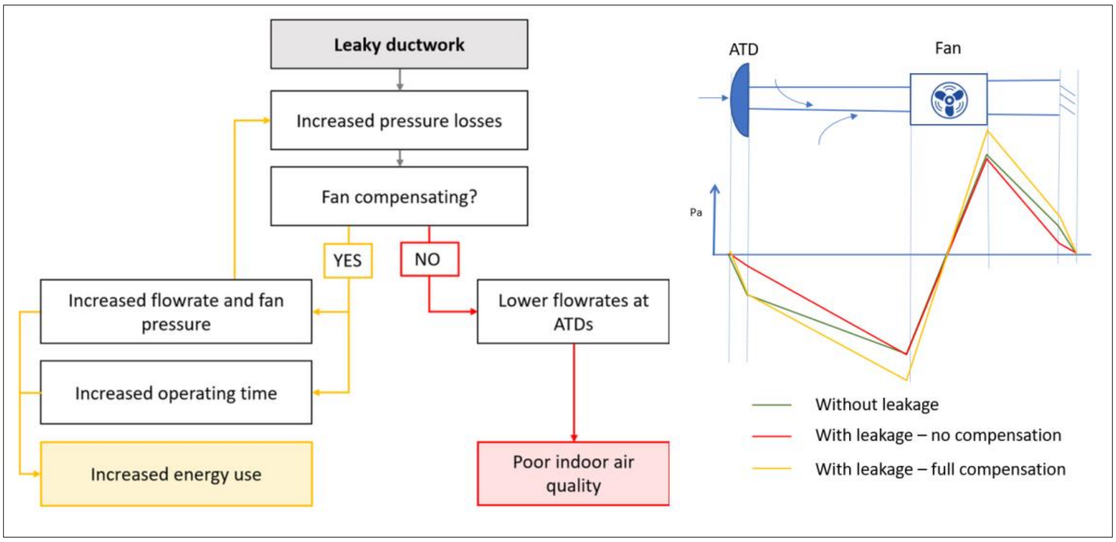

Figure 1- Impact of leaky ductwork

The fan efficiency (η) varies with its flowrate, but for simplification purposes, it is considered constant in this study whatever the airtightness level of the ductwork.

2.2 Pressure losses

Pressure drop in ductwork systems is due to the irreversible transformation of mechanical energy into heat (ASHRAE, 2013). There are two types of losses:

- friction losses (occurring along the ductwork)
- and dynamic losses (occurring at bends and junctions)

Friction losses

Friction losses occur along the entire length of duct. They are due to fluid viscosity. Friction loss can be calculated using the Darcy equation (ASHRAE, 2013):

$$\Delta p_f = \frac{1000 f L}{D_h} * \frac{\rho V^2}{2} \quad (2)$$

Δp_f	Pa	Friction losses in terms of total pressure
f	-	Friction factor
L	m	Duct length
D_h	m	Hydraulic diameter
V	m/s	Velocity
ρ	kg/m^3	Air density

Friction losses are proportional to the flow velocity to the power of 2 so also to the square of the flowrate.

Dynamic losses

Dynamic losses result from flow disturbance caused by duct accessories, which change the direction of the flow (bends) and of the hydraulic diameter (adaptors) and at converging/diverging junctions.

Dynamic loss can be calculated using the following equation (ASHRAE, 2013):

$$\Delta p_t = \frac{C\rho V^2}{2} \quad (3)$$

C	-	Total loss coefficient (from all flow disturbances)
Δp_t	Pa	Total pressure loss due to dynamic losses

Total pressure loss in the ductwork

Total pressure loss in a duct section is calculated by combining friction and dynamic losses.

$$\Delta p_{loss} = \left(\frac{1000f}{D_h} + \sum C\right)\left(\frac{\rho V^2}{2}\right) \quad (4)$$

Therefore, the pressure loss in the ductwork system is proportional to the square of the flowrate and the higher the flowrate to overcome ductwork leakage, the higher resistance in the ductwork.

2.3 Electrical overconsumption calculation in full compensation conditions

The fan electrical overconsumption is estimated assuming a full compensation of ductwork leakage. The fan flowrate increases therefore with the air permeability of the ductwork:

$$Q_{AHU,real} = Q_{AHU,0} + Q_{l,real} \quad (5)$$

$Q_{AHU,real}$	m^3/h	Fan flowrate with the real ductwork airtightness level
$Q_{AHU,0}$	m^3/h	Fan flowrate with no ductwork leakage
$Q_{l,real}$	m^3/h	Leakage flowrate within the ductwork

With:

$$Q_{l,real} = A_{du} \times C_l \times \Delta p_{a,du}^{0.65} \times 3600 \quad (6)$$

A_{du}	m^2	Ductwork area
C_l	$m^3/s/m^2$ at 1Pa	Airtightness factor of the ductwork
Δp_{du}	Pa	Average pressure difference between inside and outside the ductwork

The average pressure difference between inside and outside the ductwork is given by:

$$\Delta p_{a,du} = \frac{\Delta p_{ATD} + \Delta p_{AHU}}{2} \quad (7)$$

$\Delta p_{a,du}$	Pa	Average pressure difference between inside and outside the ductwork
Δp_{ATD}	Pa	Required pressure at air terminal devices to provide required airflow

The pressure induced by the fan Δp_{AHU} depends on the airtightness level of the ductwork as more leakage increase the total flowrate and therefore the pressure losses (see equation (4)).

To simplify the calculation and to avoid cross-reference, the ductwork leakage is calculated using equation (6) assuming a constant average pressure in the ductwork, which is the value without leakage:

$$\Delta p_{a,du} \approx \frac{\Delta p_{ATD} + \Delta p_{AHU,0}}{2} \tag{8}$$

The airtightness factor of the ductwork characterizes the level of airtightness. The limit values for each airtightness classes used in this study can be read in Table 1.

Table 1 - Classification of ductwork airtightness according to EN 16798-3 (CEN, 2017)

Airtightness classes		**Air leakage limit (fmax) according to the test pressure (p_t) [$m^3.s^{-1}.m^{-2}$]**
Prev. name	**New name**	
3A	-	$0{,}0810 \times p_t^{0,65} \times 10^{-3}$
2,5A	ATC 6	$0{,}0675 \times p_t^{0,65} \times 10^{-3}$
1,5A	-	$0{,}0405 \times p_t^{0,65} \times 10^{-3}$
A	ATC 5	$0{,}027 \times p_t^{0,65} \times 10^{-3}$
B	ATC 4	$0{,}009 \times p_t^{0,65} \times 10^{-3}$
C	ATC 3	$0{,}003 \times p_t^{0,65} \times 10^{-3}$
D	ATC 2	$0{,}001 \times p_t^{0,65} \times 10^{-3}$
-	ATC 1	$0{,}00033 \times p_t^{0,65} \times 10^{-3}$

For each airtightness level, the pressure at the fan is calculated as follows:

$$\Delta p_{AHU,real} = \Delta p_{ATD} + \Delta p_{loss,real} \tag{9}$$

Yet, according to equation (4) the pressure losses inside the ductwork increase with the square of the flowrate when leakages are compensated:

$$\frac{\Delta p_{loss,real}}{\Delta p_{loss,0}} = \frac{\left(\frac{1000f}{D_h} + \sum C_t\right)\left(\frac{\rho V_{real}^2}{2}\right)}{\left(\frac{1000f}{D_h} + \sum C_t\right)\left(\frac{\rho V_0^2}{2}\right)} = \frac{V_{real}^2}{V_0^2} = \frac{Q_{AHU,real}^2}{Q_{AHU,0}^2} \tag{10}$$

Combining equations (9) and (10):

$$\Delta p_{AHU,real} = \Delta p_{ATD} + (\Delta p_{AHU,0} - \Delta p_{ATD}) \times \frac{Q_{AHU,real}^2}{Q_{AHU,0}^2} \tag{11}$$

The fan power $P_{AHU,real}$ (W) is calculated for each airtightness level using equations (1), (5) and (11):

$$P_{AHU,real} = \frac{\Delta p_{AHU,real} \times Q_{AHU,real}}{\eta \times 3600} \tag{12}$$

The power difference between the real and no leakage cases is given by:

$$\Delta P_{AHU,real} = P_{AHU,real} - P_{AHU,0} \tag{13}$$

2.4 Related extra costs calculation

The extra costs related ductwork leakage fully compensated are calculated with the fan overconsumption, the yearly operating time ($t_{AHU,y}$) and the electricity price ($price_{elec}$):

$$extra\_cost_l = \frac{\Delta P_{AHU,real}}{1000} \times t_{AHU,y} \times price_{elec} \quad (14)$$

3 RESULTS

3.1 Calculation Tool

A calculation tool was developed using the above model. A screenshot is presented in Figure 2. The objective is to raise awareness about the negative impact of leakage and encourage the design and installation of airtight ventilation ductwork systems, which are readily available on the market. This tool is designed to be user-friendly with few simple inputs:

- **Designed fan characteristics**: flowrate, pressure and power
- **Ductwork area**: with a tool to estimate it from ductwork dimensions if the data is not available
- **Annual operating time:** with a tool to estimate it if the data is not available
- **National cost of a kWh:** to translate the energy losses into costs
- **Years of operation:** to estimate the impact through the whole ductwork lifespan, with a tool to estimate it if the data is not available according to data provided by Andersen and Negendahl (2023).

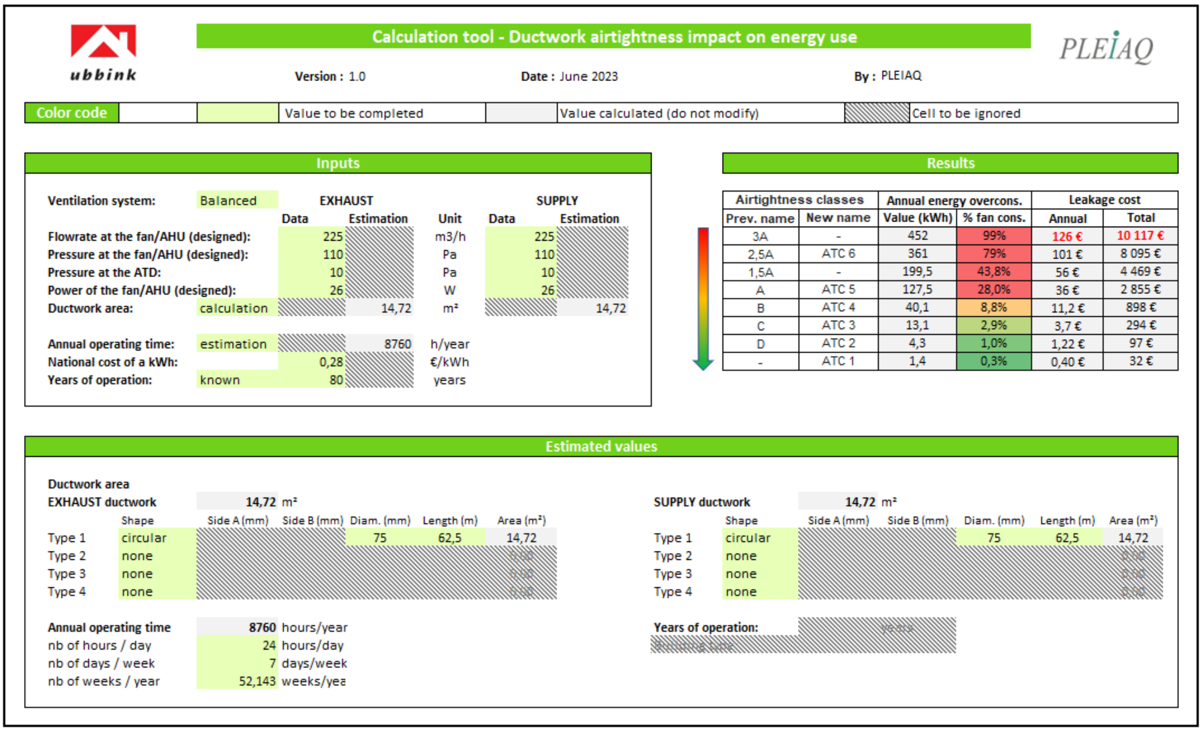

Figure 2 - Calculation tool (for the case study of house 1)

As an output, the impact of the ductwork leakage is calculated using the equations presented in section 2 for the various ductwork airtightness classes (see Table 1), with the following parameters:

- **The annual energy overconsumption** compared to a perfectly airtight ductwork given in kWh and as a percentage of the fan consumption without leakage.
- **The financial cost** of the ductwork leakage compared to a perfectly airtight ductwork, given both annually and as a total for the estimated years of operations.

3.2 Case studies

The following four scenarios have been simulated (data from (Leprince et al., 2019)):

- **House 1** is a medium-sized house with a central mechanical ventilation system with heat recovery. The ductwork system is a radial air distribution system using semi-rigid plastic ductwork. The diameter of the ductwork is 75mm and the total length is 125m. It is assumed that the ductwork is equally split between supply and extract.
- **House 2** is also a medium sized house a central mechanical ventilation system with heat recovery. The ductwork system is a trunk and branch air distribution system using metal or rigid plastic ductwork with 6m of ductwork DN160mm and 40m of ductwork DN125mm. It is assumed that the ductwork is equally split between supply and extract.
- **House 3** is a large house with a central mechanical ventilation system with heat recovery. The ductwork system is a radial air distribution system using semi-rigid plastic ductwork. The diameter of the ductwork is 75 mm and the total length is 200 m. It is assumed that the ductwork is equally split between supply and extract.
- **House 4** is a large house with a humidity-based extract only ventilation system, with self-adjusting ATD. The average flowrate is 100 m³/h. The required pressure at the ATD is 70 PA. The ductwork area is assumed to be 7.4m² (radial air distribution system).

For the houses 1 to 3, the fan power value is read from the performance curves of a ventilation unit with heat recovery with a high efficiency (provided by the manufacturer). The corresponding fan efficiency calculated according to equation (1) is 26% for houses 1 and 2, and 27% for house 3. The fan power value for the house 4 is calculated with equation (1) assuming a similar fan efficiency of 27%.

In addition, one of the 10 AHU of a 4500 m² French school building (for 500 children) has been simulated (data from the PromevenTertiaire project (Hurel and Leprince, 2022b)).

Table 2 – Parameters of the ventilation systems for the 5 case studies (for houses 1 to 3: data apply to both exhaust and supply systems)

	House 1	**House 2**	**House 3**	**House 4**	**School (1 AHU)**	
	Exh./Sup.	Exh./Sup.	Exh./Sup.	Exh.	Exh.	Sup.
Fan flowrate (m³/h)	225	225	300	100	13500	11855
Fan pressure (Pa)	110	110	160	150	130	130
Pressure ATD (Pa)	10	10	10	70	43	35
Fan power (W)	26	26	49	15.4	4701	4143
Ductwork area (m²)	14.72	9.36	23.6	7.4	317	279
Operating time (h/y)	8760				1140*	

* 2000 hours (10 h/d; 5 d/w; 40 w/y) x 57% due to CO_2 regulation (value from the Avis Technique of the ventilation system)

The annual energy overconsumption resulting from ductwork leakage is presented in Table 3 with both the value in kWh and as a percentage of the fan consumption without leakage. If the fans are able to fully compensate for leakage, the annual energy use increase for a very leaky ductwork (3A) compared to an airtight one ranges between 58% and 173% for the 4 single-family houses, and is of 33% for the school AHU.

The corresponding financial losses assuming 80 years of operation and an electricity cost of 0.28 €/kWh (EU average in the second half of 2022 according to Eurostat[1]) are presented in Table 4. For very leaky ductwork (3A), they range from 50€ to 415€ per year (4.0 k€ to 33.2 k€ after 80 years) for the single-family houses, and 922€ per year (74 k€) for one of the school

[1] https://qery.no/consumer-energy-prices-in-europe/

AHU. As there are in total 10 AHU in the school, the total financial impact would probably be in the order of magnitude of 10 k€ each year for this airtightness level.

In addition, the annual fan(s) energy uses for each building are plotted in Figure 3 according to the ductwork airtightness level. One can note that the energy use strongly decreases by improving the ductwork airtightness until ATC 4 (class B) and then tends to decrease more slowly when improving until ATC 1.

Table 3 – Annual energy overconsumption due to ductwork leakage (absolute value and percentage of fan energy use) according to the ductwork airtightness level for the 5 case studies

Airtight. classes		**House 1**		**House 2**		**House 3**		**House 4**		**School (1 AHU)**	
Prev.	New	kWh	%fan	kWh	%fan	kWh	%fan	kWh	%fan	kWh	%fan
3A	-	451,7	99,2%	262,6	57,6%	1482	173%	180,1	133%	3293	33%
2,5A	ATC 6	361,4	79,3%	213,0	46,8%	1164	136%	142,1	105%	2697	27%
1,5A	-	199,5	43,8%	121,1	26,6%	617,6	71,9%	76,1	56,4%	1562	15,5%
A	ATC 5	127,5	28,0%	78,6	17,2%	386,4	45,0%	47,9	35,5%	1023	10,2%
B	ATC 4	40,1	8,8%	25,2	5,5%	118,1	13,8%	14,8	10,9%	333,1	3,3%
C	ATC 3	13,1	2,9%	8,3	1,8%	38,2	4,5%	4,8	3,6%	110,2	1,1%
D	ATC 2	4,3	1,0%	2,8	0,6%	12,6	1,5%	1,6	1,2%	36,6	0,4%
-	ATC 1	1,4	0,3%	0,9	0,2%	4,2	0,5%	0,5	0,4%	12,2	0,1%

Table 4 - Annual and total (for 80 years of operation) cost of ductwork leakage according to the ductwork airtightness level for the 5 case studies

Airtight. classes		**House 1**		**House 2**		**House 3**		**House 4**		**School (1 AHU)**	
Prev.	New	Annual	Total	Annual	Total	Annual	Total	Annual	Total	Annual	Total
3A	-	126 €	10 117 €	73,5 €	5 881 €	415 €	33 199 €	50,4 €	4 035 €	922 €	73 772 €
2,5A	ATC 6	101 €	8 095 €	59,7 €	4 772 €	326 €	26 071 €	39,8 €	3 182 €	755 €	60 415 €
1,5A	-	55,9 €	4 469 €	33,9 €	2 713 €	173 €	13 834 €	21,3 €	1 706 €	437 €	34 999 €
A	ATC 5	35,7 €	2 855 €	22,0 €	1 760 €	108 €	8 655 €	13,4 €	1 073 €	287 €	22 924 €
B	ATC 4	11,2 €	898 €	7,1 €	565 €	33,1 €	2 645 €	4,1 €	331 €	93,3 €	7 463 €
C	ATC 3	3,7 €	294 €	2,3 €	186 €	10,7 €	856 €	1,3 €	107 €	30,8 €	2 468 €
D	ATC 2	1,22 €	97 €	0,77 €	62 €	3,53 €	282 €	0,44 €	36 €	10,26 €	820 €
-	ATC 1	0,40 €	32 €	0,26 €	21 €	1,17 €	94 €	0,15 €	12 €	3,41 €	273 €

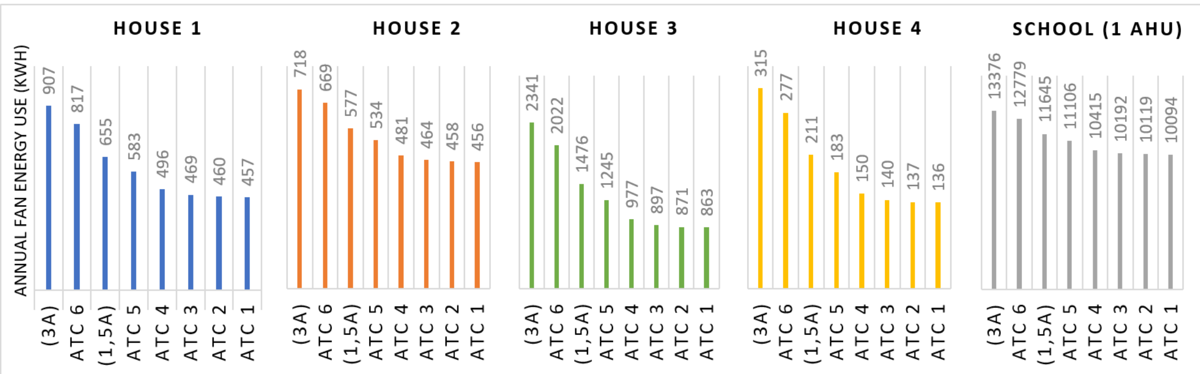

Figure 3 - Annual fan energy use for each case study according to the ductwork airtightness level

4 CONCLUSIONS

A simple tool was developed using a simplified model to estimate the financial impact of leaky ductwork in buildings over their whole life. It assumes that the design or hygienic flow rates in all habitable and wet rooms are achieved, that is to say that the fan fully compensates for ductwork leakage. The purpose of this user-friendly tool is to help to raise awareness about this issue and encourage the design and installation of airtight ventilation ductwork systems, which are readily available on the market.

It has been designed for central mechanical ventilation systems with energy recovery and central mechanical extract ventilation systems
Case studies for 4 houses and one of the 10 AHU of a school building show the significant impact of ductwork leakage on energy use and electricity bills. It is found that a very leaky ductwork (class 3A) induces:

- an increase of fan energy use ranging between 58% and 173% for the 4 single-family houses (180 to 1482 kWh) and of 33% for the school AHU (3293 kWh).
- a financial impact for 80 years of operation ranging between 4.0 k€ to 33.2 k€ for the 4 single-family houses and reaching 74 k€ for the school AHU (out of the 10 AHU).

To conclude, this tool shows the significant financial benefits of installing airtight ventilation ductwork systems in all buildings, including single-family houses with rather small ductwork areas. For larger buildings with more powerful fans and larger ductwork areas, the energy use and financial impact are vastly increased. A good level of ductwork airtightness also reduces the risks of noise and/or odour hindrance, and in case the air is preconditioned the energy and financial savings are even more substantial.

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