Ductwork leakage: practical estimation of the impact on the energy overconsumption and IAQ

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ABSTRACT

In a context of energy savings, new buildings are becoming more and more airtight. The good indoor air quality (IAQ) relies therefore more and more on mechanical ventilation systems with specific air flowrates to be met. However, in practice, ventilation ductworks are not always very airtight. The numerous issues induced by leaky ductwork have been well outlined in the literature and summed up in (Leprince et al., 2020). Yet the awareness is not forthcoming, and on-site workers do not always realize the consequences of ductwork leakages.

In particular, the electrical overconsumption induced to compensate for ductwork leakage is usually not really taken into account. This paper provides a practical methodology to estimate from simple on-site measurements the impact of ductwork leakage on:

- the fan electrical overconsumption to compensate for leakage
- the thermal losses due to pre-conditioned air leakage in non-conditioned spaces
- the IAQ quantified by the predicted percentage of dissatisfied.

These calculations can help to raise awareness on the duct leakage issue, to perform cost-benefit analyses, and encourage for example ductwork sealing interventions on existing leaky ductworks.

Practical application of this methodology is presented in another paper together with the impact of other non-conformities of ventilation systems (Hurel and Leprince, 2022).

KEYWORDS

ductwork leakage, IAQ, overconsumption, practical estimations

1 INTRODUCTION

In a context of energy savings, new buildings are becoming more and more airtight. The good indoor air quality (IAQ) relies therefore more and more on mechanical ventilation systems with hygienic air flowrates to be met. However, in practice, ventilation ductworks are not always very airtight. The numerous issues induced by leaky ductwork have been well outlined in the literature and summed up in (Leprince et al., 2020). Yet the awareness is a long time in coming, and on-site workers do not always realize the consequences of ductwork leakages.

In particular, the electrical overconsumption induced to compensate for ductwork leakage is usually not really considered. The goal of this paper is to provide a practical methodology to estimate, from simple on-site measurements, the impact of leaky ductworks on the energy overconsumption and/or on the IAQ and to raise awareness on this issue. These calculations can also allow cost-benefit analyses, and encourage for example a ductwork sealing through aerosols as detailed in (Hurel et al., 2022)

This paper is part of the on-going French research project PROMEVENT Tertiaire which aims at improving the reliability of inspection of ventilation systems protocols in non-residential buildings, and which includes the inspection of three buildings. This data was used for practical application of this methodology and is presented in another paper together with the impact of other non-conformities of ventilation systems (Hurel and Leprince, 2022).

2 ELECTRICAL OVERCONSUMPTION FOR VENTILATION

This chapter gives the methodology outlines, further calculation details and explanations are given in the PROMEVENT project report (Hurel and Leprince, 2021). The main calculation steps are illustrated in section 2.6. Please refer to this section and to the annex for the nomenclature.

2.1 Leakage caracterization: leakage coefficient $K_{l,real}$ and flowrate $Q_{l,real}$

Method 1: ductwork permeability test

This method should be chosen first when a ductwork airtightness test is possible. It consists in pressurizing the whole ductwork (Δp_{test}) and measuring the required flowrate to compensate leakage ($Q_{l,test}$) . For a better accuracy, the test should ideally be performed on the entire ductwork ($A_{test}=A_t$). However, for very leaky or very large ductwork, air leakage flow rates may be too high to maintain a given pressurization/depressurization in the whole ductwork. It is then necessary to isolate and test only a ductwork section (of area A_{test}) which should be consistent with the sampling rules detailed in standard EN 12599. The total leakage rate is given by:

$$Q_{l,real,1} = \frac{Q_{l,test} \times \Delta p_{a,real}^{0.65} \times A_t}{\Delta p_{test}^{0.65} \times \mathrm{A_{test}}} = K_{l,réel,1} \times \Delta p_{a,real}^{0.65} \times A_t \qquad (1)$$

The average ductwork pressure in real operating conditions ($\Delta p_{a,real}$) can be estimated averaging the maximal pressure (p_{AHU} at the fan outlet) and the minimum pressure ($p_{ATD,far}$ measured at the furthest air terminal device (ATD) from the air handling unit (AHU)). If the ductwork airtightness cannot be measured by a pressurization test, as an alternative it is possible to estimate the global (method 2a) or local (method 2b) leakage flowrate when the AHU is running.

Method 2a: global leakage flowrate estimation

The global ductwork leakage flowrate in the real AHU running conditions is given by the flowrate difference between the flowrate at the AHU outlet ($Q_{AHU,real}$) and the sum of flowrates at all the ATDs ($Q_{ATD,t,real}$). One should note that the ATD flowrate measurement has a significant uncertainty, so for buildings with a large number of ATDs the total error related to this estimation is higher than with method 1.

Method 2B: Local leakage flowrate estimation

If both the airtightness test and the flowrate measurements at every ATD are not possible, the last option is to estimate the leakage rate locally, on a given duct supplying one or several ATD(s). The leakage coefficient K_l of this method 2b is then calculated locally and allows to estimate the total leakage rate in the whole ductwork for real AHU running conditions. This method has the highest risk of error.

2.2 Calculation method to estimate the electrical overconsumption

Fan leakage compensation rate

Fan consumption:

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

$$P_{AHU} = \frac{\Delta p_{AHU} * Q_{AHU}}{\eta * 3600} \quad (2)$$

The higher the pressure losses in the ductwork, the more the fan needs to produce flowrate and pressure to compensate this resistance and meet the hygienic flowrates to ensure a good IAQ. 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 (see Figure 2).

Yet, the fan efficiency (η) varies with its flowrate. According to the support Excel sheet of standard EN 16798-5-1, one can use the following approximation (with the subscript 0 standing for the no leakage case):

$$\eta_{real} \approx \sqrt{\frac{Q_{AHU,real}}{Q_{AHU,0}}}\eta_0 \quad (3)$$

Electrical overconsumption calculation in real compensation conditions

Equations (2) and (3) allow to calculate the electrical overconsumption ($\Delta P_{AHU,real}$) in real compensation conditions:

$$\Delta P_{AHU,real} \approx P_{AHU,real}\left(1 - \left(\frac{Q_{AHU,0}}{Q_{AHU,real}}\right)^{2.5}\right) \quad (4)$$

Electrical overconsumption calculation in full compensation conditions

If in real conditions the fan does not fully compensate ductwork leakage, it is interesting to calculate the maximal overconsumption that can me induced by this level of air permeability. This maximal overconsumption corresponds to a full leakage compensation case. The ductwork pressure is then higher, and the leakage flowrate increases therefore also.

The average ductwork pressure for full compensation conditions is approximated as follows[1]:

$$\Delta p_{a,max} \approx \left(\frac{Q_{AHU,0} + Q_{l,real}}{Q_{AHU,0}}\right)^2 \times \Delta p_{a,real} \quad (5)$$

[1] Note: This allows a first correction of the ductwork pressure to estimate the leakage flowrate, but this pressure depends itself on the leakage flowrate. An iterative resolution would be required for an exact calculation, but for this study, this approximation is considered sufficient.

With $Q_{l,real}$ the total ductwork leakage flowrate in real running conditions calculated with method 1, 2a or 2b.

The overconsumption ($\Delta P_{AHU,max}$) in full compensation conditions is estimated as follow:

$$\Delta P_{AHU,max} \approx P_{AHU,real}\left(\left(1+\frac{K_{l,real}\times A_t\times \Delta p_{a,max}{}^{0.65}}{Q_{AHU,real}}\right)^{2.5}-\left(\frac{Q_{AHU,0}}{Q_{AHU,real}}\right)^{2.5}\right) \quad (6)$$

2.3 Related extra costs calculation

The extra costs related to a real of full fan compensation of ductwork leakage are calculated with the fan overconsumption, the yearly operating time ($t_{AHU,y}$) and the electricity price ($price_{elec}$):

$$extra\_cost_l = \frac{\Delta P_{AHU}}{1000}\times t_{AHU,y}\times price_{elec} \quad (7)$$

2.4 Compensation rate

The fan leakage compensation rate is given by (0: no compensation; 1: full compensation):

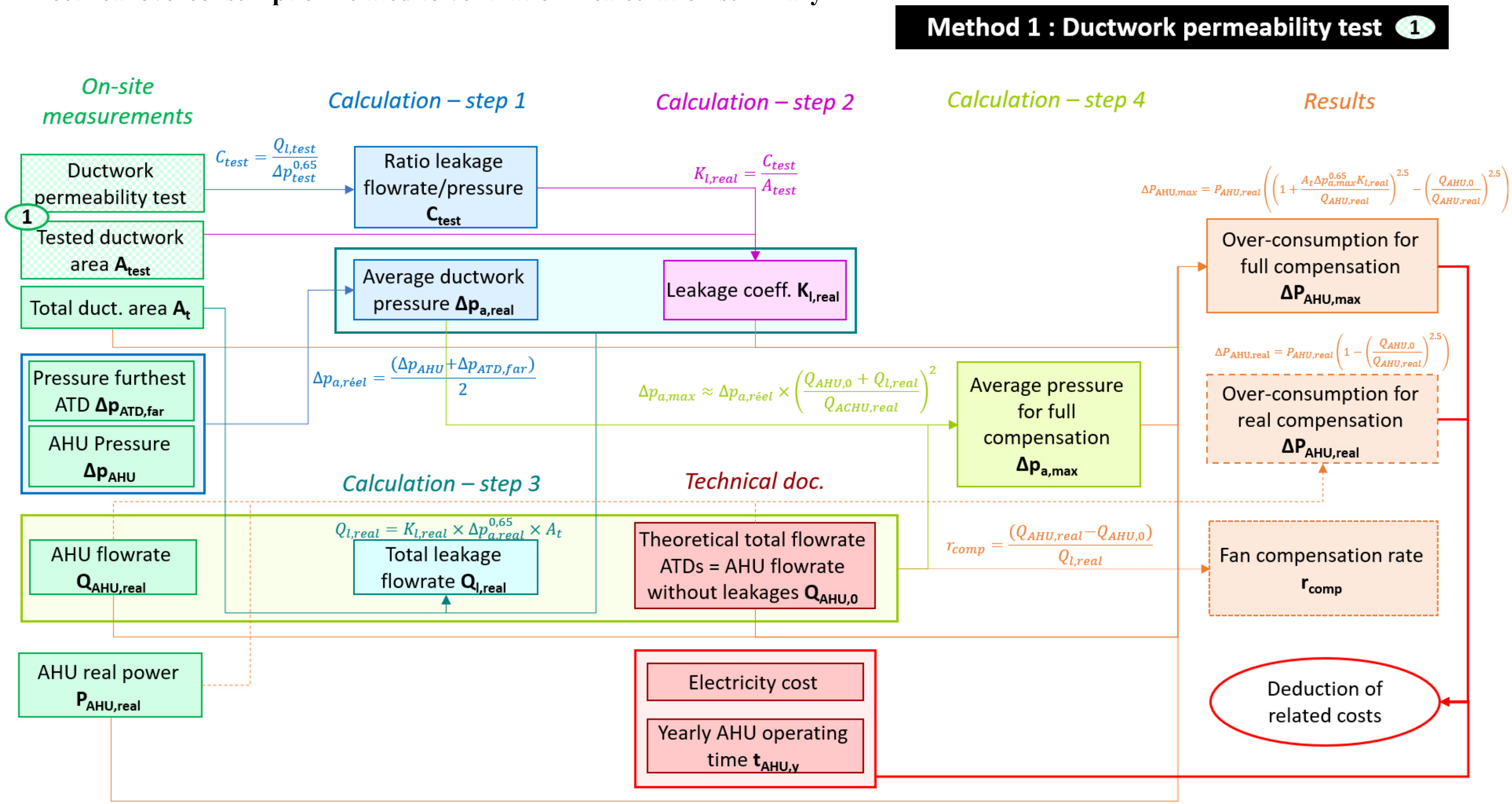
$$r_{comp} = \frac{(Q_{AHU,real} - Q_{AHU,0})}{Q_{l,real}} \quad (8)$$

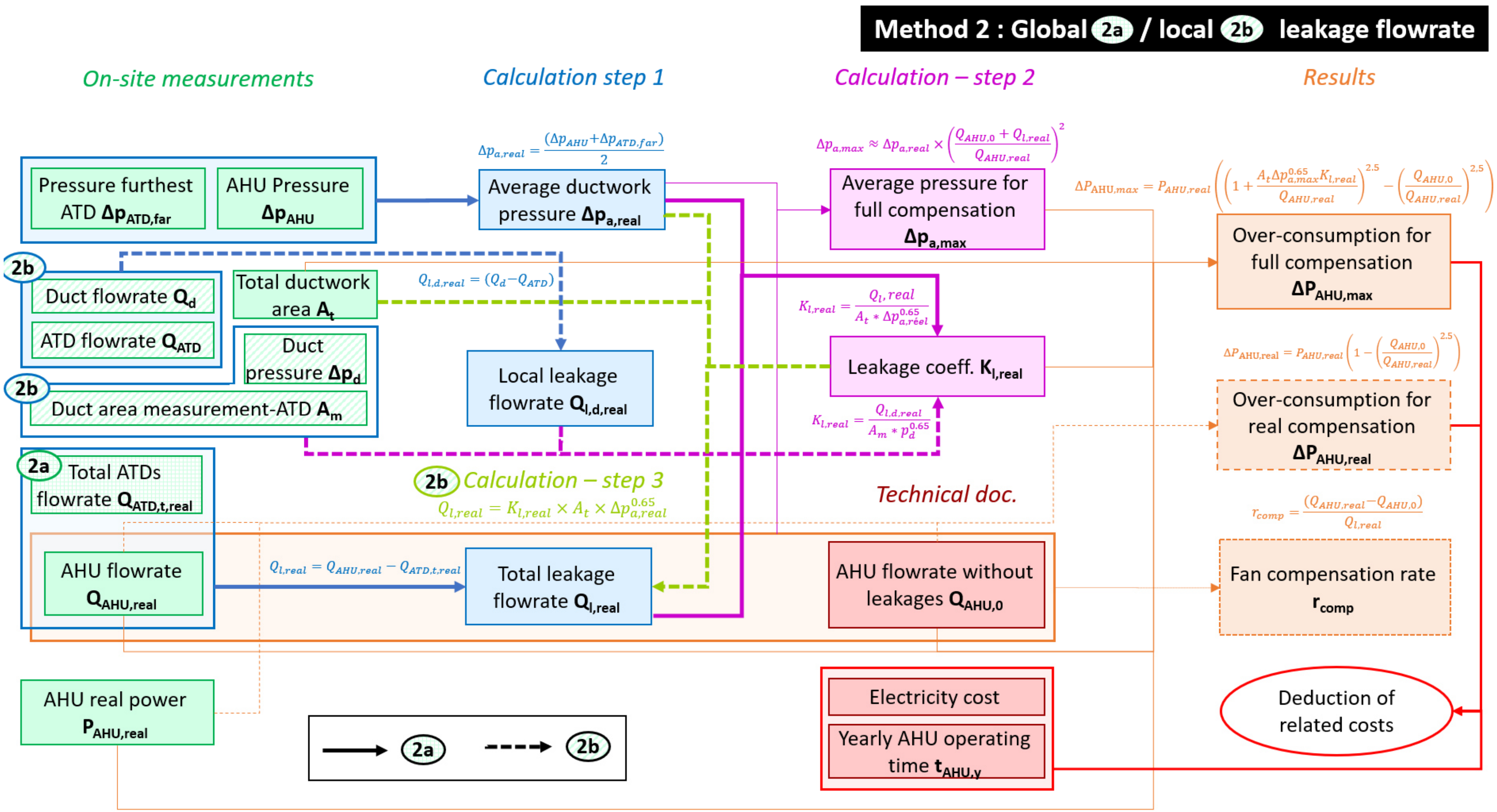
2.5 Case of reduced flowrates in inoccupation

Buildings usually have AHU operation periods, for example running from 8am to 8pm and completely off at night.

One should note that some buildings have two distinct AHU operation modes: a maximum flowrate for occupied building spaces, and a minimum flowrate for vacant building spaces. It is then necessary to do these calculations for both modes and then weight the results according to their occurrence rates (average flowrates can be evaluated with the systems' technical approval documents).

2.6 Electrical overconsumption related to ventilation – calculation summary





Method 2 : Global 2a / local 2b leakage flowrate
On-site measurements
Calculation step 1
Calculation – step 2
Results
Pressure furthest ATD Δp_ATD,far
AHU Pressure Δp_AHU
Δp_a,real = (Δp_AHU + Δp_ATD,far) / 2
Average ductwork pressure Δp_a,real
Δp_a,max ≈ Δp_a,real × ((Q_AHU,0 + Q_l,real) / Q_AHU,real)^2
Average pressure for full compensation Δp_a,max
ΔP_AHU,max = P_AHU,real ((1 + A_t Δp_a,max^0.65 K_l,real / Q_AHU,real)^2.5 − (Q_AHU,0 / Q_AHU,real)^2.5)
Over-consumption for full compensation ΔP_AHU,max
2b
Duct flowrate Q_d
ATD flowrate Q_ATD
Total ductwork area A_t
Duct pressure Δp_d
2b
Duct area measurement-ATD A_m
Q_l,d,real = (Q_d − Q_ATD)
Local leakage flowrate Q_l,d,real
K_l,real = Q_l,real / (A_t * Δp_a,réel^0.65)
Leakage coeff. K_l,real
K_l,real = Q_l,d,real / (A_m * p_d^0.65)
ΔP_AHU,real = P_AHU,real (1 − (Q_AHU,0 / Q_AHU,real)^2.5)
Over-consumption for real compensation ΔP_AHU,real
2a
Total ATDs flowrate Q_ATD,t,real
2b Calculation – step 3
Q_l,real = K_l,real × A_t × Δp_a,real^0.65
Technical doc.
r_comp = (Q_AHU,real − Q_AHU,0) / Q_l,real
AHU flowrate Q_AHU,real
Q_l,real = Q_AHU,real − Q_ATD,t,real
Total leakage flowrate Q_l,real
AHU flowrate without leakages Q_AHU,0
Fan compensation rate r_comp
AHU real power P_AHU,real
2a
2b
Electricity cost
Yearly AHU operating time t_AHU,y
Deduction of related costs

3 ELECTRICAL OVERCONSUMPTION FOR AIR CONDITIONNING

3.1 Impact of leakage on heating and cooling demands

For supply ductworks, leakage in non-heated/cooled spaces of the conditioned air induce a thermal loss increasing the building's heating/cooling demand. Srinavasan estimated that in average these losses are of 10 to 30% in the USA (Srinivasan, 2005), and Dyer that they represent 1 Million $ over the lifetime of a large pharmaceutical plant (Dyer, 2011).

3.2 Heat/cold recovery rate

Thermal losses related to air conditioning occur when conditioned air leaks from a ventilation duct to a non-conditioned space.
The task 1 report of the PROMEVENT project (Leprince et al., 2019) showed that the most common supply temperatures for non-residential buildings are approximately:

- 19°C in winter: leakage flowrate vainly preheated for lower outside temperatures
- 25°C in summer: leakage flowrate vainly precooled for higher outside temperatures

Modera (Modera, 2005) has however estimated that in certain cases, part of the heat/cold dissipated with ductwork leakage is recovered. 4 duct location configurations lead to different recovery rates as illustrated in Figure 1. In case the duct location and/or insulation type changes along the ductwork route in the non-conditioned space, the areas of the various sections should be identified and a mean recovery rate calculated.

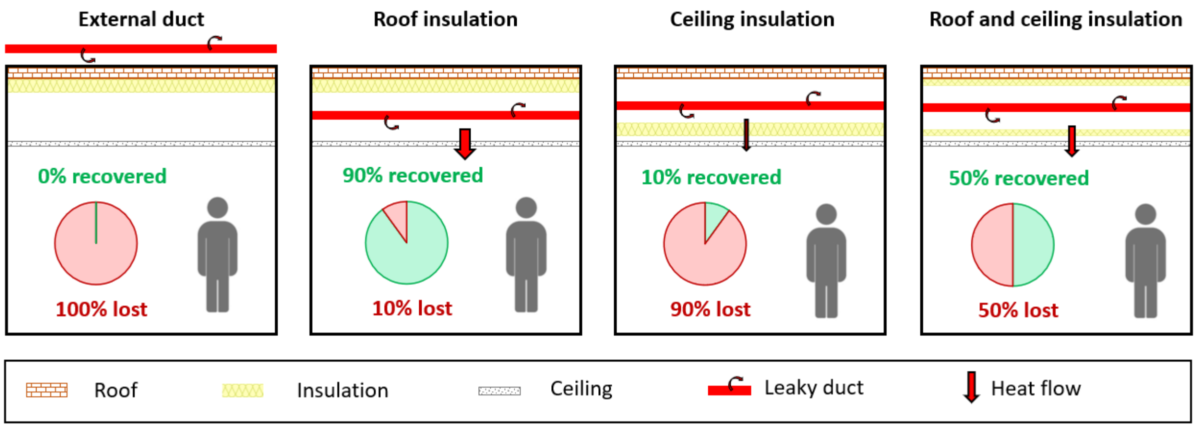


Figure 1 – Recovery rates and thermal losses due to leakage in non-conditioned spaces for the 4 configurations

3.3 Degree days

The heating/cooling degree days (HDD/CDD) allow to quantify the difference between the external median temperature on a given day and the internal setpoint temperature. They are used to estimate respectively the heating and cooling demand on a specific location and are defined as follows (COSTIC calculation method (Observatoire économique de l'achat public, 2007)):

$$HDD = \sum_{Days\ of\ heating\ period} max\left(0; (S_h - T_n) \times \left(0.08 + 0.42 \times \frac{S_h - T_n}{T_x - T_n}\right)\right) \quad (9)$$

$$CDD = \sum_{Days\ of\ cooling\ period} max\left(0; (T_x - S_c) \times \left(0.08 + 0.42 \times \frac{T_x - S_c}{T_x - T_n}\right)\right) \quad (10)$$

3.4 Thermal losses due to air conditioning

Heat losses in heating period

The heat losses related the ventilation ductwork leakage in non-conditioned spaces (E_h) can be calculated over a year as follows:

$$E_h = Q_{l,nc} \times (1 - r_{recov}) \times \rho_{air} \times C_{p,air} \times HDD \times t_{AHU,d} \times r_h \quad (11)$$

Cold losses in cooling period

Cold losses (E_c) can be calculated similarly to heat losses, using CDD over the year, and taking into account the cold production system's COP:

$$E_c = \frac{Q_{l,nc} \times (1 - r_{recov}) \times \rho_{air} \times C_{p,air} \times CDD \times t_{AHU,d} \times r_c}{COP_c} \quad (12)$$

Annual thermal losses in real compensation conditions

So, over a year the thermal losses can be estimated as follows in real AHU running conditions:

$$E_{th,real} = Q_{l,nc,real} \times (1 - r_{recov}) \times \rho_{air} \times C_{p,air} \times \left(HDD \times r_h + \frac{CDD \times r_c}{COP_c}\right) \times t_{AHU,d} \quad (13)$$

With the leakage flowrate in non-conditioned spaces in real AHU running conditions defined as:

$$Q_{l,nc,real} = Q_{l,real} \times \frac{A_{nc}}{A_t} \quad (14)$$

Annual thermal losses in full compensation conditions

Similarly, annual thermal losses can be calculated in case of a full leakage compensation by the fan, which corresponds to the maximal losses for this ductwork airtightness level:

$$E_{th,max} = Q_{l,nc,max} \times (1 - r_{recov}) \times \rho_{air} \times C_{p,air} \times \left(HDD \times r_h + \frac{CDD \times r_c}{COP_c}\right) \times t_{AHU,d} \quad (15)$$

With the leakage flowrate in non-conditioned spaces in full compensation conditions defined as:

$$Q_{l,nc,max} = Q_{l,max} \times \frac{A_{nc}}{A_t} \quad (16)$$

3.5 Related extra costs calculation

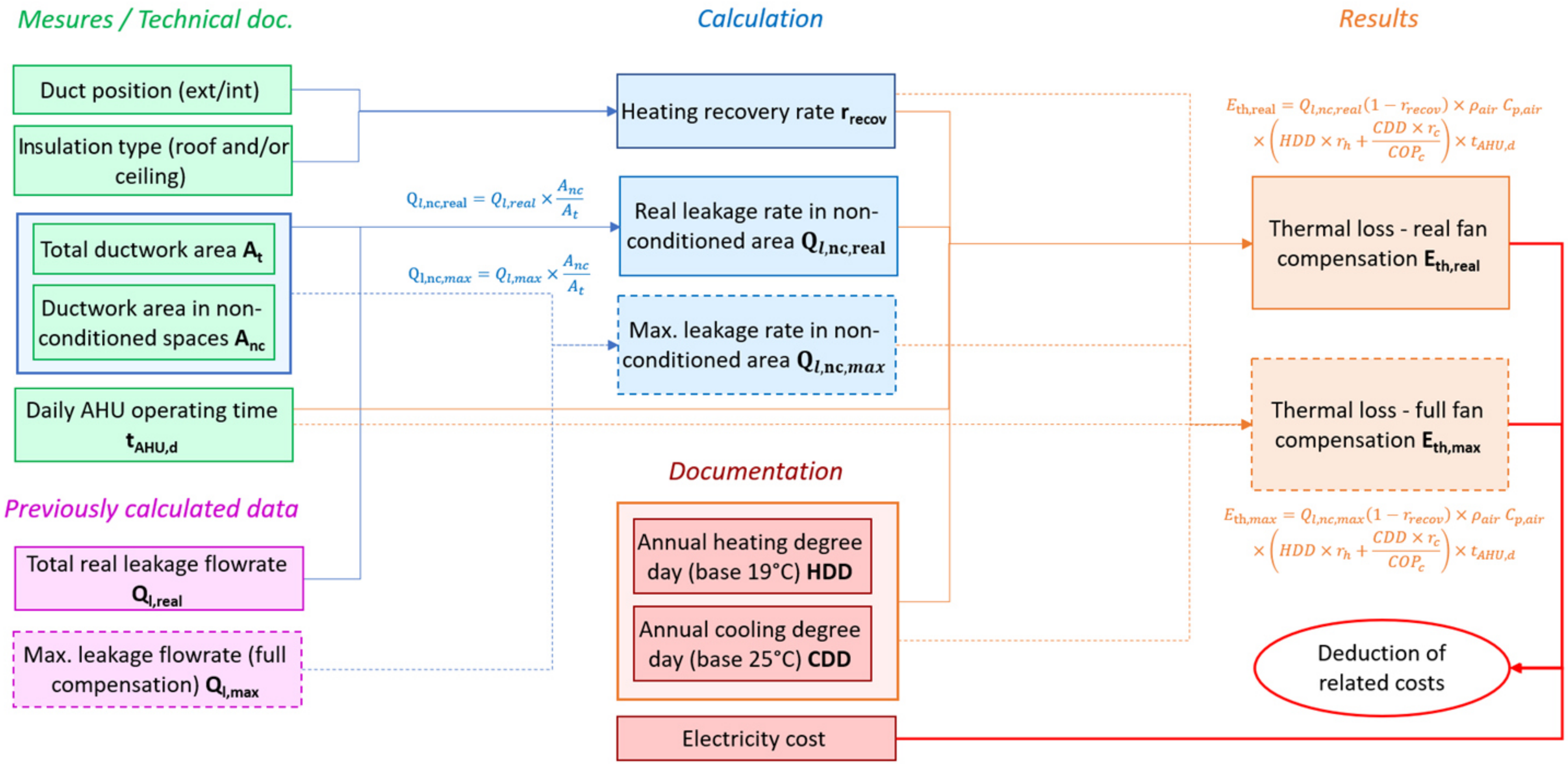
The extra costs related to the conditioned air leakage in non-conditioned spaces is given in real or maximal compensation conditions by:

$$over\_cost_{AC} = \frac{\mathrm{E_{th}}}{3600} \times price_{elec} \quad (17)$$

3.6 Case of reduced flowrates in inoccupation

As explained in section 2.5, some buildings have two AHU modes allowing a maximal flowrate for occupied spaces and a minimal one for vacant spaces. As for the overconsumption calculation related to ventilation, thermal losses calculation should be performed for both modes and the results should be weighted according to the occurrence rates.

3.7 Thermal losses related to air conditionning – calculation summary



4 INDOOR AIR QUALITY DETERIORATION

4.1 Estimation of the IAQ deterioration through the dissatisfied percentage

One of the main consequences of ventilation ductwork leakage is the deterioration of the IAQ. If the fan does not fully compensate the ductwork leakage with increased pressure and flowrates, some ATDs will not deliver the required hygienic flowrate.
In a given building, the room for which the IAQ deterioration issue is the most critical is the furthest one from the AHU, that is to say the one supplied by the longest ventilation ductwork length. Indeed, the further the air goes in the duct, the more the leakages induce pressure losses and reduced flowrates. As a result, this study on IAQ deterioration focuses on the furthest room, but other building parts can also be impacted.
There are various indicators to characterize IAQ, as pollutant concentrations (CO_2, humidity, etc.). The consequence of a poor IAQ is generally a discomfort felt more or less strongly by occupants, so standard EN 16798-1 associates ventilation flowrates in a room to a category defined by a predicted percentage of dissatisfied (see table in section **Error! Reference source not found.**). Two flowrates are given: per person (Q_{pers}) and per surface (Q_{surf}) (considering a low polluting building). They must be used to calculate the limit values of each category (i):

$$Q_{min,i} = Q_{pers,i} \times n_{occ,far} + Q_{surf,i} \times A_{far} \tag{18}$$

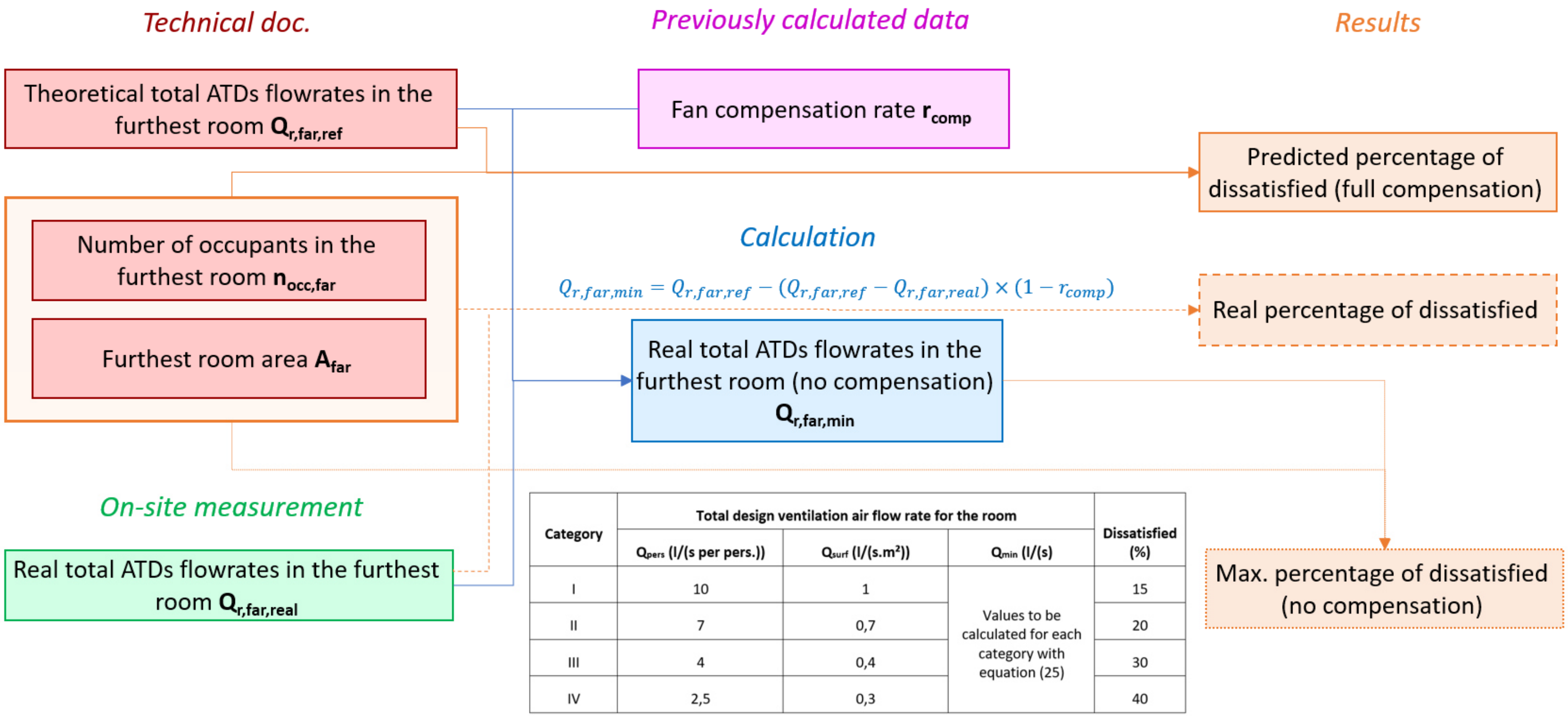
Dissatisfied percentage in full fan compensation conditions
In case the fan fully compensates the ventilation ductwork leakage, on electrical overconsumption is induced as detailed in sections 2.2 and 3.4 but no IAQ deterioration. However, it does not mean that the dissatisfied percentage is the minimum according to EN 16798-1 (15%), it can be calculated using the table in section **Error! Reference source not found.**.

Dissatisfied percentage in real fan compensation conditions
The impact of ductwork leakage on the IAQ for the real fan compensation in the furthest room can be evaluated as well as the potential increase of the dissatisfied percentage compared to a full compensation (again with the table in section **Error! Reference source not found.**).

Dissatisfied percentage without fan compensation
In the IAQ point of view, the most critical case is when the fan is not compensating at all for ductwork leakage. This maximal IAQ deterioration, expected in the furthest room, can also be quantified with a predicted percentage of dissatisfied. For this, the flowrate in the furthest room with no fan compensation ($Q_{r,far,min}$) is estimated with the theoretical and real flowrates as well as the fan compensation rate (equation (8)):

$$Q_{r,far,min} = Q_{r,far,ref} - (Q_{r,far,ref} - Q_{r,far,real}) \times (1 - r_{comp}) \tag{19}$$

4.2 Summary of the IAQ deterioration estimation



Category	Total design ventilation air flow rate for the room			Dissatisfied (%)
	Q_{pers} (l/(s per pers.))	Q_{surf} (l/(s.m²))	Q_{min} (l/(s)	
I	10	1	Values to be calculated for each category with equation (25)	15
II	7	0,7		20
III	4	0,4		30
IV	2,5	0,3		40

Source: EN 16798-1

5 GRAPHICAL SUMMARY OF THE LEAKY DUCTWORK IMPACTS

To conclude, the main impacts of leaky ductwork can be graphically summarized as in Figure 2. One can note, that when ductwork leakage occure, there are always consequences, either on the electricity bill or on the IAQ.

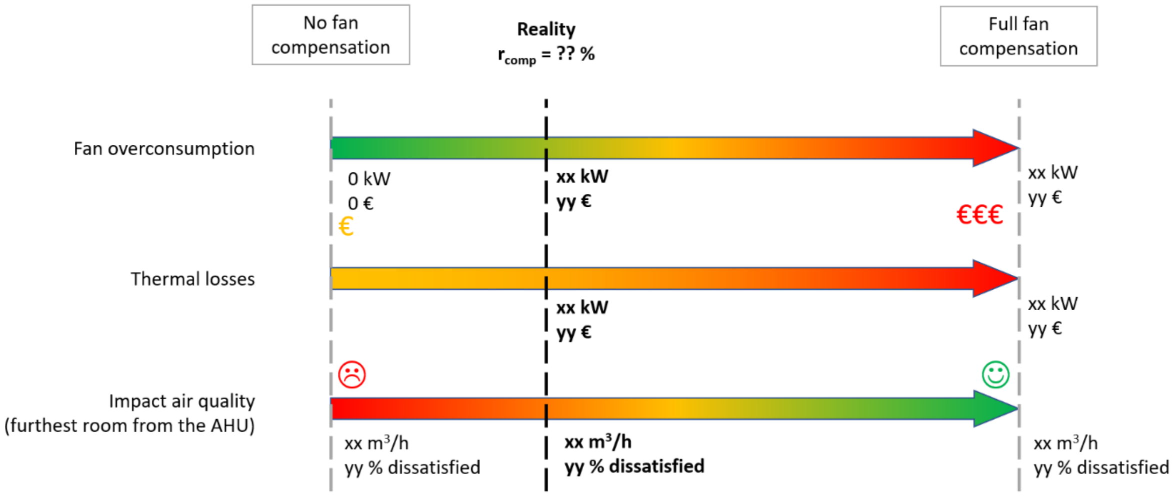


Figure 2 - Graphical summary of leaky ductwork impacts

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9 ANNEX 1: PARAMETERS TO MEASURE ON-SITE OR TO RESEARCH

- For the electrical overconsumption calculation related to ventilation:

<table>
<tr><th rowspan="2">Symbol</th><th rowspan="2">Description (unit)</th><th rowspan="2">Comments</th><th colspan="3">Methods</th></tr>
<tr><th>1</th><th>2a</th><th>2b</th></tr>
<tr><th colspan="6">On-site measurements</th></tr>
<tr><td>A_t</td><td>Total ventilation ductwork area (m²)</td><td>From on-site measurement or technical documents (or default values such as the one provided in the RT 2012 in France)</td><td rowspan="5" colspan="3">X</td></tr>
<tr><td>$\Delta p_{ATD,far}$</td><td>Pressure at the furthest ATD from the AHU (Pa)</td><td rowspan="2">To evaluate the average ductwork pressure : measurement of the maximal (AHU) and minimal (furthest ATD) pressures</td></tr>
<tr><td>Δp_{AHU}</td><td>Pressure at the AHU outlet (Pa)</td></tr>
<tr><td>$Q_{AHU,real}$</td><td>Volumic air flowrate at the AHU outlet (m^3/h)</td><td rowspan="2">Characterization of the real AHU running conditions</td></tr>
<tr><td>$P_{AHU,real}$</td><td>AHU power for real running conditions (W)</td></tr>
<tr><td>$Q_{l,test}$</td><td>Leakage flowrate measured by airtightness test (m^3/h)</td><td rowspan="3">Results of an airtightness test (pressurization/depressurization) on the whole ventilation ductwork, or if not possible, part of it</td><td rowspan="3">X</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Δp_{test}</td><td>Average ductwork pressure during the test (Pa)</td></tr>
<tr><td>A_{test}</td><td>Tested ductwork section area (m²)</td></tr>
<tr><td>$Q_{ATD,t,real}$</td><td>Total flowrate at the ATDs supplied by the AHU (m^3/h)</td><td>To evaluate the ductwork airtightness by comparing the flowrate at the AHU outlet and the total ATDs flowrates</td><td></td><td>X</td><td></td></tr>
<tr><td>Q_d</td><td>Flowrate in the duct supplying the studied ATD(s) (m^3/h)</td><td rowspan="4">To evaluation the ductwork airtightness by studying the air supply in a particular room: measure of the flowrate in the duct and at the connected ATD(s)</td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4">X</td></tr>
<tr><td>Q_{ATD}</td><td>Flowrate (or sum of flowrates) at the studied ATD(s) (m^3/h)</td></tr>
<tr><td>Δp_d</td><td>Pressure in the duct supplying the studied ATD(s) (Pa)</td></tr>
<tr><td>A_m</td><td>Duct area between the duct (Q_d) and ATD (Q_{ATD}) measurement points (m²)</td></tr>
<tr><th colspan="6">Technical doc.</th></tr>
<tr><td>$Q_{AHU,0}$</td><td>Theoretical total flowrate at ATDs (m^3/h)</td><td>Sum of the foreseen flowrates at the ATDs, also corresponding to the flowrate at the AHU unit in case of a zero-leakage ductwork.</td><td rowspan="3" colspan="3">X</td></tr>
<tr><td>$price_{elec}$</td><td>Electricity price (€/kWh)</td><td rowspan="2">Allows to convert the additional required power to extra running costs</td></tr>
<tr><td>$t_{AHU,y}$</td><td>Yearly AHU operating time (h)</td></tr>
</table>

- For the electrical overconsumption calculation related to air conditioning (for supply ductworks only):

Symbol	Description (unit)	Comments
-	Location of ventilation ductwork in non-conditioned spaces (outside/ceiling)	Of the duct location and/or the insulation type changes along the duct section located in non-conditioned spaces, it is required to evaluate the areas of these sections which will weight the recovery rates
-	Insulation type (roof and/or ceiling)	
A_{nc}	Ductwork area in non-conditioned (non-heated / non-cooled) spaces (m²)	
A_t	Total ventilation ductwork area (m²)	
HDD	Annual heating degree day (base 19°C)	Can be obtained in France thanks to the online tool: *https://cegibat.grdf.fr/simulateur/calcul-dju*
CDD	Annual cooling degree day (base 25°C)	
$t_{AHU,d}$	Average number of daily hours of running AHU for an AHU running day (h)	
$price_{elec}$	Electricity price (€/Wh)	

- For the IAQ deterioration estimation:

Symbol	Description (unit)	Comments
$Q_{r,far,ref}$	Theoretical total flowrate of ATDs in the furthest room from the AHU (m^3/h)	The study focuses on the furthest room from the AHU (longest ventilation ductwork) since it is the one with the highest pressure losses due to ductwork leakage, so the one with the highest risks of poor IAQ
$Q_{r,far,réel}$	Real total flowrate of ATDs in the furthest room from the AHU (m^3/h)	
$n_{occ,far}$	Occupant number in the furthest room from the AHU (-)	
A_{far}	Area of the furthest room from the AHU (m²)	

- Additional symbols used in this paper without description:

Symbol	Description (unit)
ρ_{air}	Air density at 20°C (≈ duct temperature) (1.204 kg/m^3)
$C_{p,air}$	Air heat capacity (1.004 kJ/K/kg)
r_c	ratio of the number of days for which the building is heated in the heating period (-)
r_h	ratio of the number of days for which the building is cooled in the cooling period (-)
S_c	Internal temperature setpoint in cooling period (25°C for this study)
S_h	Internal temperature setpoint in heating period (19°C for this study)
T_n	Minimum external temperature of the day (°C)
T_x	Maximum external temperature of the day (°C)