Impact of ventilation non conformities: calculation methodology and on-site examples

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ABSTRACT

Energy efficient buildings are getting more and more airtight to avoid thermal losses through uncontrolled air leakage and rely more and more on mechanical ventilation to ensure a good indoor air quality. In practice ventilation systems are however not always perfectly installed, and several problems are often encountered on-site.
In France the new environmental regulation for new buildings RE2020 now includes a mandatory inspection of ventilation systems for non-residential buildings.
This study is part of an on-going French research project PromevenTertiaire aiming at improving the reliability of inspection of ventilation systems protocols in non-residential buildings. A survey addressed to various professionals of this sector allowed to identify 5 particular non-conformities that are both often encountered in existing ventilation systems and which can rather easily be quantified. This paper presents the calculation methodology to evaluate the impacts, from simple on-site measurements, of 4 of these non-conformities: filter clogging; inadequate fans settings; non-insulated duct sections and inadequate AHU scheduling. Another paper specifically details the calculation methodology for leaky ductwork [1].
On-site inspections of ventilation systems were performed on three non-residential buildings: two secondary schools located in two different French climatic zones and one office building. The data and visual observation collected were used to quantify the extra costs related to each of these non-conformities encountered in one of the buildings. This allows to give practical examples and orders of magnitude in order to raise awareness on these issues and their consequences.
In particular, it is estimated that an AHU of 13 500 m^3/h with a leaky ductwork (2.5 class A) induces yearly thermal losses of 815 kWh (122€) and a fan overconsumption of 2281 kWh (342€); that the fan overconsumption due to filter clogging is higher from the second year of use than the price of a new filter; and that in an office equipped with two 2.5kW AHU a ventilation not switched off at night and not regulated with sensors induces respectively a yearly overconsumption of 22100 kWh (3315€) and 8424 kWh (1263€).

KEYWORDS

Inspection of ventilation systems; impact calculation; overconsumption; IAQ; on-site application

1 INTRODUCTION

Energy efficient buildings are getting more and more airtight to avoid thermal losses through uncontrolled air leakage and rely more and more on mechanical ventilation to ensure a good indoor air quality. In practice ventilation systems are however not always perfectly installed, and several problems are often encountered on-site.
In France the new environmental regulation for new buildings RE2020 now includes a mandatory inspection of ventilation systems for non-residential buildings.
This study is part of an on-going French research project PromevenTertiaire aiming at improving the reliability of inspection of ventilation systems protocols in non-residential buildings. A survey addressed to various professionals of this sector allowed to identify 5 particular non-conformities that are both often encountered in existing ventilation systems and

which can rather easily be quantified: leaky ventilation ductworks; filter clogging; inadequate fans settings; non-insulated duct section; and inadequate air handling unit (AHU) scheduling. This paper presents first the calculation methodology to evaluate the impacts, from simple on-site measurements, of these 5 non-conformities. Data and visual observation from on-site inspection of ventilation systems performed on 3 non-residential buildings is then used to quantify the extra costs related to each of these non-conformities encountered in one of the buildings. This allows to give practical examples and orders of magnitude in order to raise awareness on these issues and their consequences.

2 METHODOLOGY TO EVALUATE THE IMPACT OF VENTILATION NON-CONFORMITIES

This section gives the methodology outlines, further calculation details and explanations are given in the PROMEVENT project report (Hurel and Leprince, 2021). Please refer to the annex for a detailed summary of the required parameters for the impact calculation (including on-site measurements, data from technical documents, etc.)

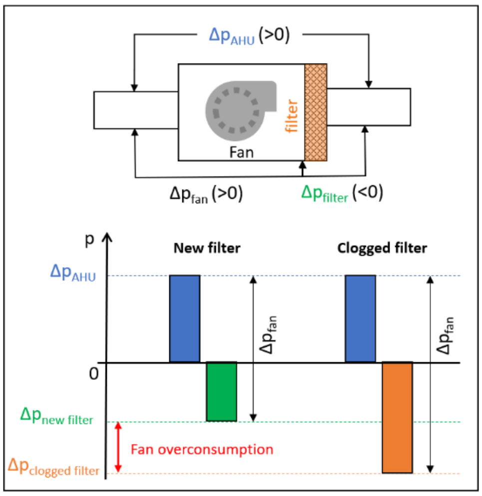
2.1 Ductwork leakage

Ductwork leakage have two main possible impacts:

- An **increased energy use** when the fan compensates the flow and pressure losses induced by leakage
- An **indoor air quality (IAQ) deterioration** when the fan does not compensate these flow and pressure losses: the supply/exhaust air flow rates at the air terminal devices (ATDs) cannot be reached.

The fan often compensates for leakage only partially, inducing both an electrical overconsumption and an IAQ deterioration.
When the air is conditioned by an air handling unit (AHU), leakage from a ventilation duct to a non-conditioned space induces thermal losses and therefore also an electrical overconsumption for air conditioning.
Because of these various impacts, and the complexity of their calculation, the methodology is fully detailed in a separate dedicated paper (Hurel and Leprince, 2022).

2.2 Filter clogging



Air flowing in ventilation ductwork is loaded with dust and other particles which partially accumulate on their way, inducing a clogging issue. The clogging speed depends mostly on the exterior air pollution level and to the ventilation system operating time. All ventilation components are subject to this issue, in particular filters. Clogging induces:

- Electrical overconsumption (quantified here for filters)
- An IAQ deterioration if the fan does not compensate
- A decreased heat exchanger efficiency if it is clogged
- Health risks when clogging induces bacterial growth (with humidity)

The methodology to calculate the impact of filter clogging on the electrical overconsumption is presented Figure 1. It includes two methods for the clogging pressure loss estimation:

- The measurement of the total pressure difference across the clogged filter (preferable when possible since it is the most accurate option)
- An estimation based on two hypotheses: the specified maximal recommended pressure difference for the filter is reached after one year of use; and the clogging pressure loss increases linearly with time (which underestimates the overconsumption as in reality the increase tends to accelerate with time)

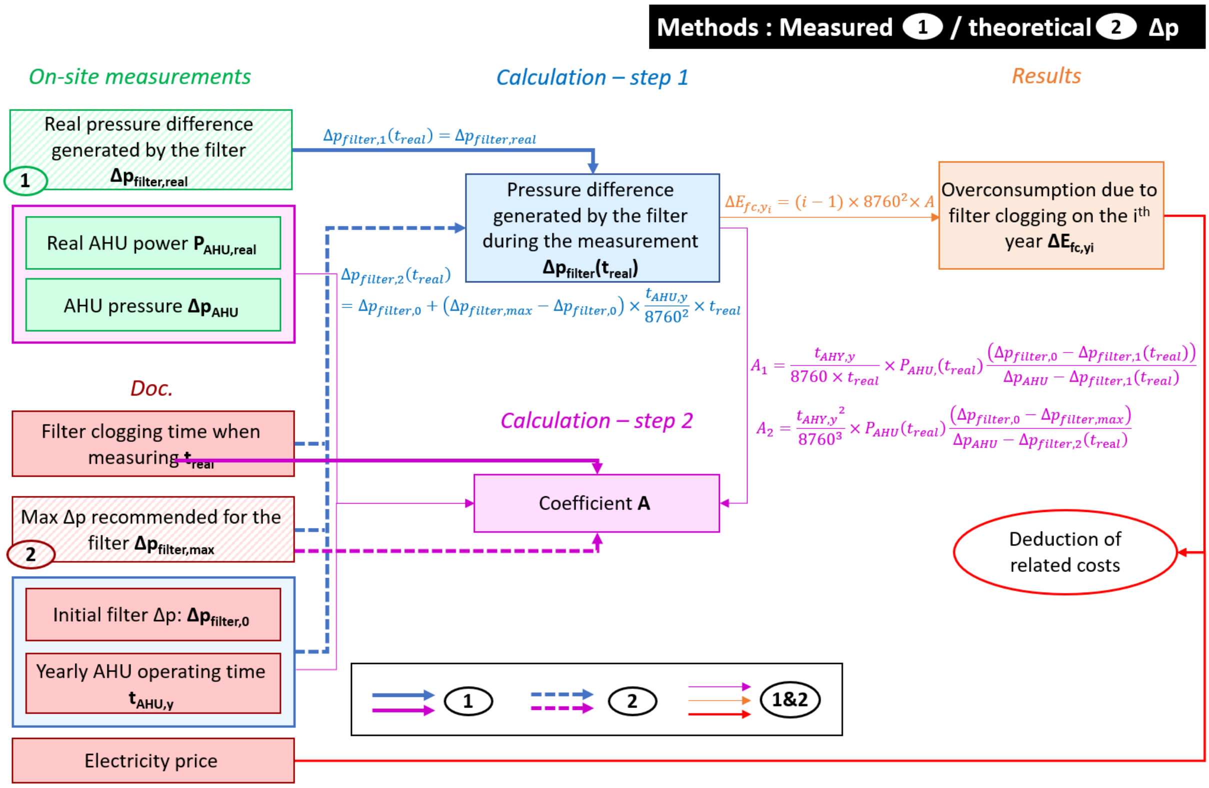


Figure 1 - Methodology for the electrical overconsumption calculation due to filter clogging

2.3 Inadequate fans settings

The AHU energy use is proportional to the pressure and the flow delivered by the fan. The fan pressure is usually controlled by a pressure switch and is kept constant. The pressure set point is theoretically set by the installer according to the design calculation and to pressure measurements performed on-site at the furthest and the closest ATDs from the AHU (in terms of ventilation ductwork path).

If the pressure set point is too low, the furthest ATD will deliver an air flowrate lower than intended. On the other hand, if the pressure set point is too high, it can induce high air flowrates at the closest ATDs and an **electrical overconsumption** (which is estimated here).

The methodology to calculate the impact of inadequate fan setting on the electrical overconsumption is presented Figure 2.

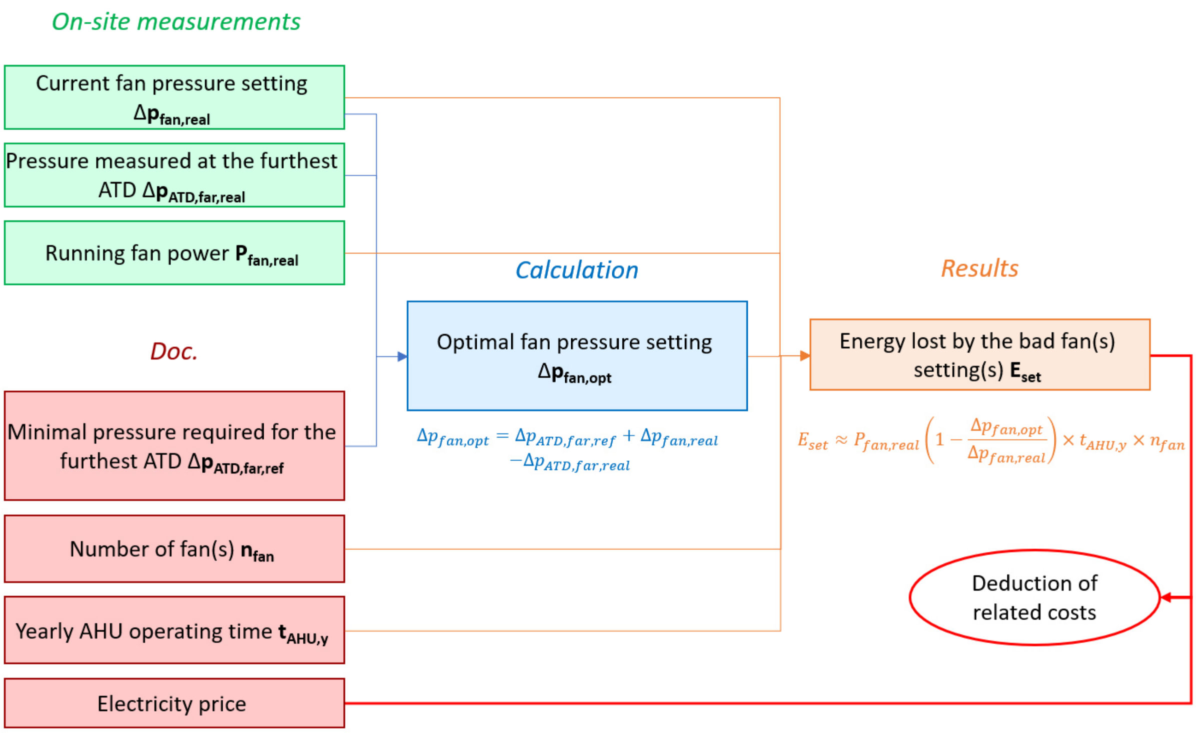


Figure 2 - Methodology for the electrical overconsumption calculation due to inadequate fan setting

2.4 Non-insulated duct section

A ventilation duct in which conditioned air is flowing is subject to heat transfer with the environment. Proper ducts insulation allows to achieve negligible heat transfer and to maintain a temperature almost constant from the AHU to the ATDs.

On the other hand, a badly or non-insulated duct section outside or in non-conditioned spaces induces **thermal losses (heat/cool)** and therefore extra costs.

The methodology to calculate the impact of non-insulated duct sections on the thermal losses is presented Figure 3. It includes approximations for the internal and external surface resistance estimations, which are further detailed in (Hurel and Leprince, 2021).

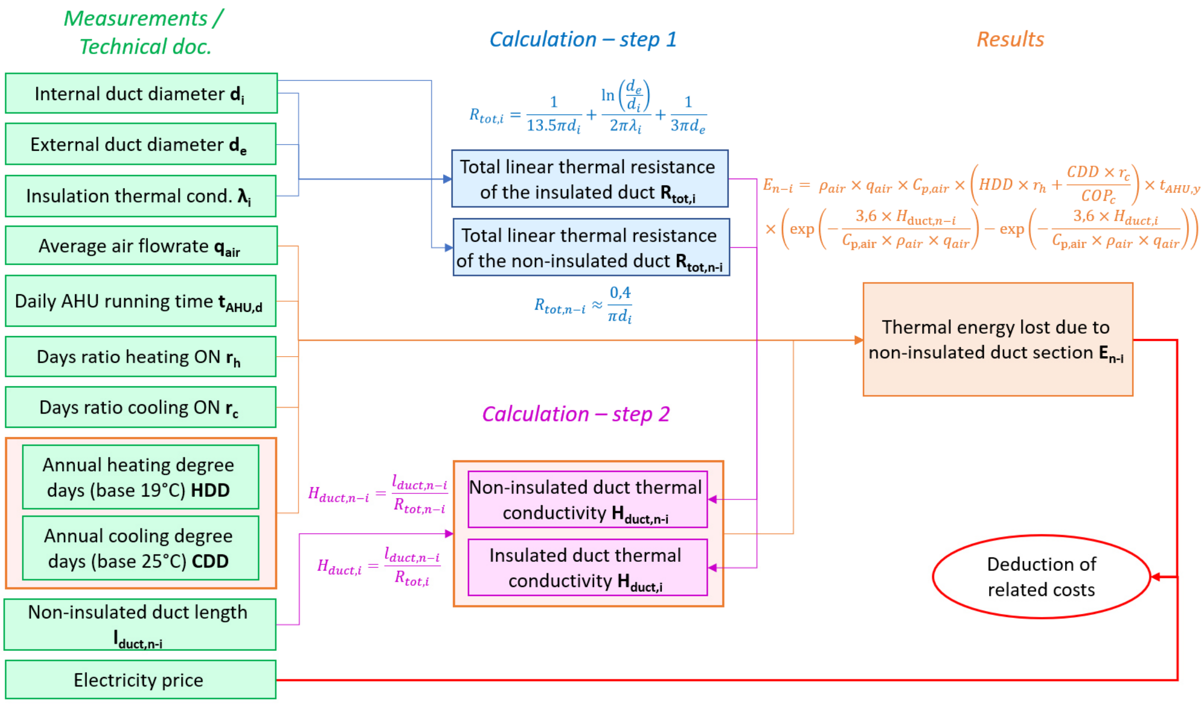
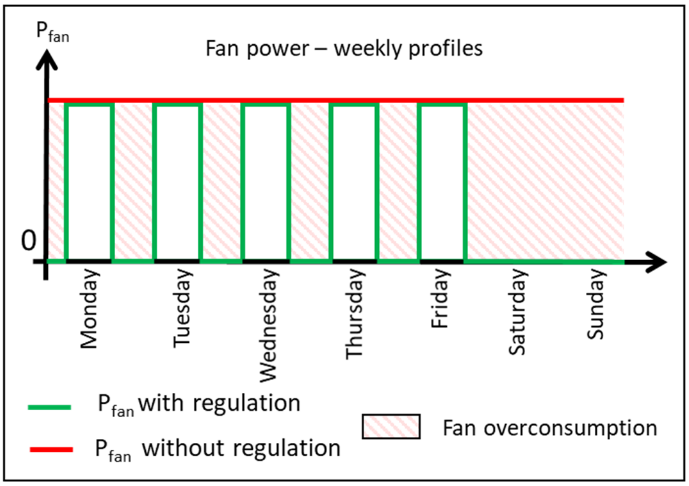


Figure 3 - Methodology for the thermal loss calculation due to non-insulated duct sections

2.5 Inadequate AHU scheduling



For non-residential buildings, ventilation systems usually allow scheduling, that is to say to specify the occupied building periods and to switch off ventilation for the rest of the time. If the occupied building period is shorter than in reality it will induce a risk of poor IAQ. More frequently, the specified occupied building period is rather longer than in reality, which induces electrical overconsumption.

Moreover, inside the building occupied period, air flowrates related to each building zone can be regulated with sensors (ex: CO_2 sensors) to reduce the ventilation in unoccupied spaces. A lack of regulation also induces an electrical overconsumption.

The methodology to calculate the impact of inadequate AHU scheduling on the energy losses is presented Figure 4.

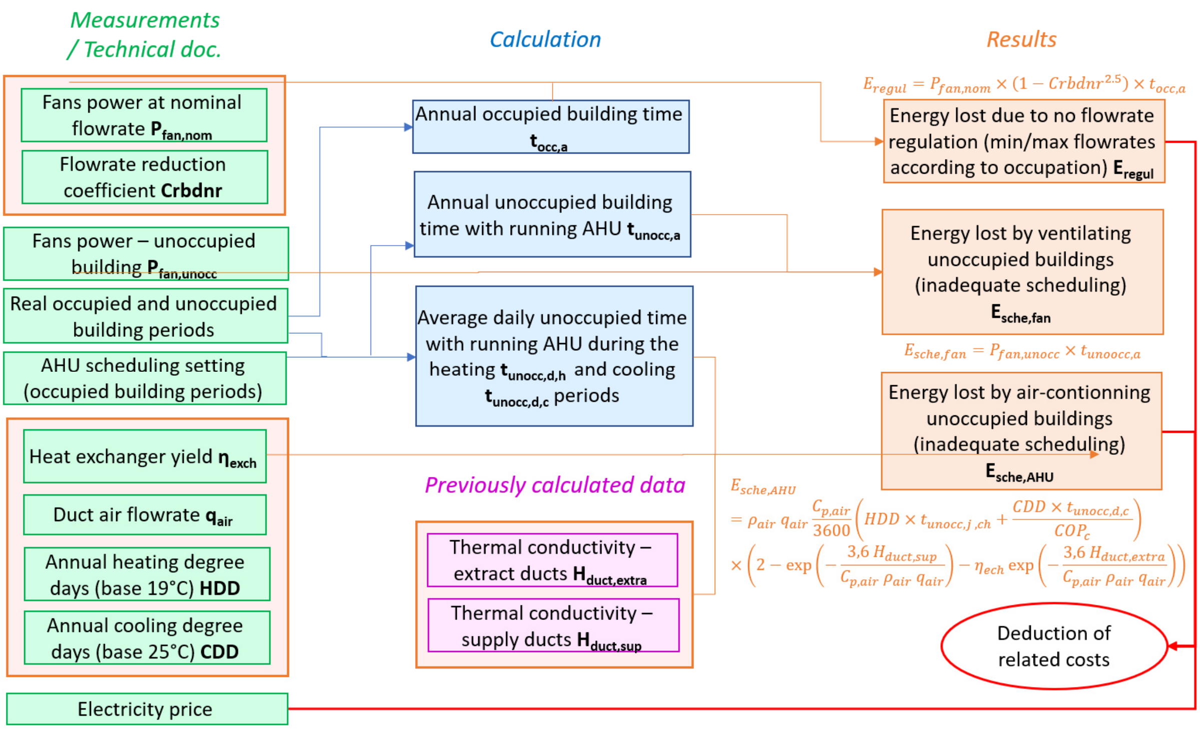


Figure 4 - Methodology for the energy losses calculation due to inadequate AHU scheduling

3 ON-SITE PRACTICAL APPLICATION OF THE METHODOLOGY

As part of the French research project PromevenTertiaire, the ventilation systems of 3 non-residential buildings have been inspected:

- One secondary school located in the French climate zone for heating H1 (North/East: the coldest), built in 2017 and with a surface of about 10 000 m² (capacity of 700 students)
- One secondary school located in the French climate zone for heating H3 (South: the warmest), built in 1973 and retrofitted in 2017-2020, with a surface of about 5 000 m² (capacity of 500 students)
- One office building located in the French climate zone for heating H1 (North/East: the coldest), built in 2021 and with a surface of about 1400 m².

In this section, the methodologies given above are used to evaluate the impact of each studied non-conformity for a given building, using on-site measured/collected data. The results are presented graphically to better visualize the impact regarding:

- Fan overconsumption (in purple)
- Thermal losses (in orange) related both to heated (in red) and cooled (in blue) air.
- IAQ deterioration (in turquoise)

All costs are estimated giving an electricity price of 0.15 €/kWh which corresponds approximately to current prices in France.

3.1 Ductwork leakage

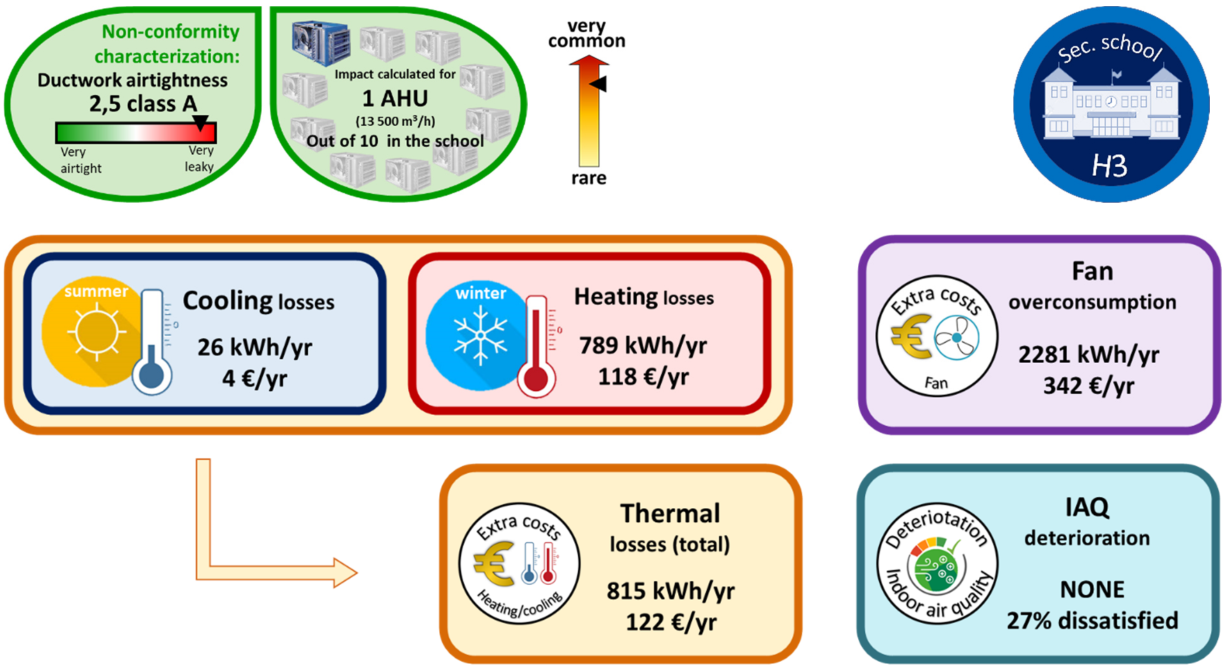
The studied non-conformity is a bad ductwork airtightness (2.5xclass A) in the secondary school located in zone H3. The impact is calculated for only one AHU of the school, with the following characteristics:

- a supply flowrate of 13500 m^3/h; an exhaust flowrate of 11855 m^3/h
- a total supply and exhaust ductwork area of 596 m^2 (resp. 317 m^2 and 279 m^2)
- a generated pressure of 130 Pa
- running 10 hours a day, 5 days a week and 40 weeks a year, that is to say 2100 hours per year
- The COP of the cooling system is considered to be 2.5.

The same calculations should be done for each of the 10 AHU and summed up for the global impact estimation.
Method 1 is used to characterize the ductwork airtightness, that is to say an on-site measurement through a pressurization test on a duct section of 106 m^2.
The total extra costs are induced by this leaky ductwork are:

- 342€/year for this AHU due to the fan compensating for air leakages
- 122€/year to compensate for pre-heated/cooled air leakages in non-conditioned spaces. The fact that the impact is much more significant for the heating period than for the cooling one is mostly due to the rather cold French climate, and also due to a cooling system COP of 2.5 considered for the calculations.

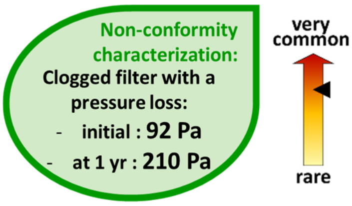
In this case the fan fully compensates for leakage, so there is no IAQ deterioration due to the leaky ductwork. However, regulation on minimum air flowrate for school rooms being relatively low in France (15 m^3/h/student and 25 m^3/h/teacher) the percentage of dissatisfied is quite high anyway; about 27% in the studied room.

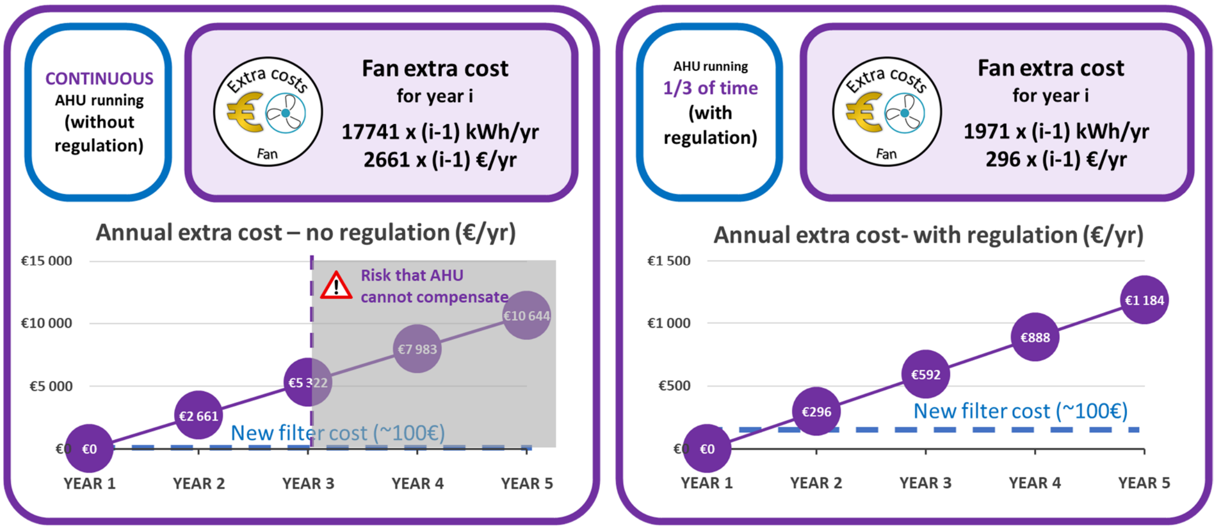


3.2 Filter clogging

The impact of a clogged filter of an AHU in the secondary school in H1 is estimated. The AHU has a power of 3.98 kW and a generated pressure of 130 Pa.

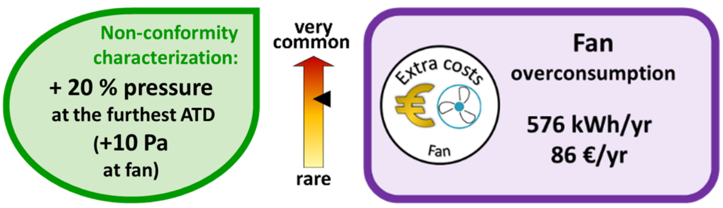
Method 2 is used since the direct pressure difference measurement was not possible: the pressure loss is estimated according to the maximum recommended filter pressure difference, that is to say 210 Pa (for an initial pressure difference for a new filter of 92 Pa).
The extra cost related to the clogged filter for a year i in permanent AHU operating conditions is 2661€*(i-1) € compared to a filter replacement at the beginning of this same year. As a result, in permanent operating conditions, the extra cost for the filter's second year of use is 2661€. For the third year it is 5322€ compared to a filter replacement this same year, to which the 2661€ of the previous year can be added.
One can note that with this calculation method the extra cost is proportional to the square of the AHU operating time. As a result, if the AHU is switched off 2/3 of the time, the extra cost is divided by 9 (296€ for the 2nd year). It could also be possible to not consider the operating time but rather the ration of the effective flowrate to the nominal flowrate.
A better knowledge on the clogging (and therefore pressure losses) evolution with time would improve the accuracy of these estimations.





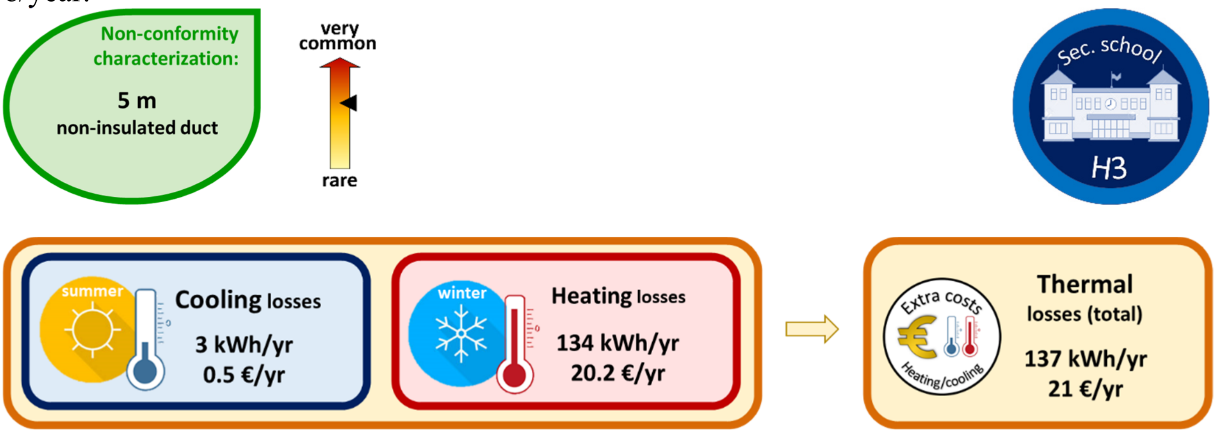
3.3 Inadequate fans settings

This problem of inadequate fans settings has not been observed during the inspection of the three buildings. A fictitious case is therefore studied: an overpressure of 10 Pa at the furthest ATD compared to the required pressure (60 Pa instead of 50 Pa) in the office building, for an optimal fan pressure of 240 Pa, a fan power of 2.5 kW and a yearly operating time of 5760 hours.
The resulting extra cost is estimated to be 86.4 €/year for this office building.



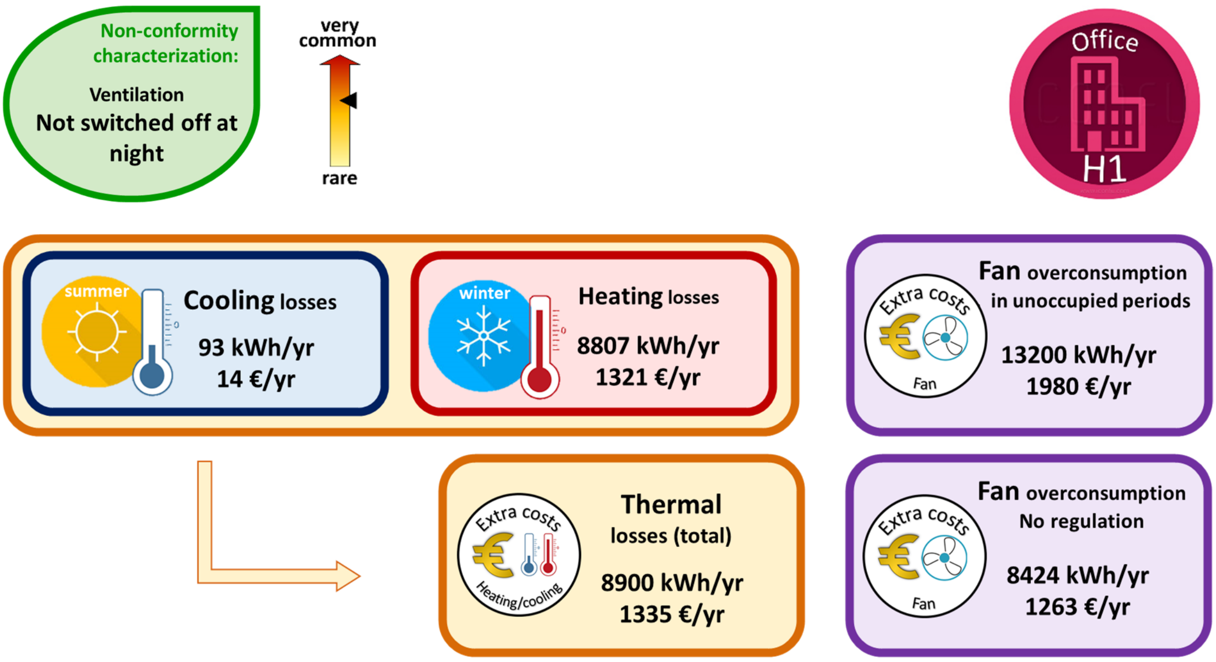
3.4 Non-insulated duct section

A non-insulated 56 cm in diameter duct section of 5 m was observed on the roof of the secondary school located in the H3 climate zone. This duct section, with an air flowrate of 4500 m^3/h should have been insulated with a 40 mm glass wool (λ=0.04 W/m/K), and the AHU is running 10 hours a day, with a COP of the cooling system of 2.5.
The impact estimated is a total thermal loss of 137 kWh/year resulting in an extra cost of 21 €/year.



3.5 Inadequate AHU scheduling

The impact is calculated here for the ventilation that is not switched of at night in the office building. The ventilation system is made of 2 fans with for each a power of 2.5 kW and an air flowrate of 6000 m^3/h. It induces a fan electricity overconsumption of 1980€/year, as well as an extra cost of 1335€/year for the useless conditioning of this air.
Moreover, during the building occupation period, the fact that there is no regulation with sensors to reduce the ventilation flowrate in unoccupied rooms induces an extra cost of 1263 €/year. As a result, the total extra cost of the inadequate AHU scheduling in this building is of 4578€/year.



4 CONLUSION

Calculation methodologies were given in this paper to evaluate the impacts, from simple on-site measurements, of 5 non-conformities.
On-site inspections of ventilation systems were performed on three non-residential buildings: two secondary schools located in two different French climatic zones and one office building. The data and visual observation collected were used to quantify the extra costs related to each of these non-conformities encountered in one of the buildings. This allows to give practical examples and orders of magnitude in order to raise awareness on these issues and their consequences:

- **Leaky ventilation ductworks**: in a secondary school located in the south of France, an AHU of 13 500 m^3/h with an airtightness class of 2.5 class A induces yearly thermal losses of 815 kWh (122€) and fan overconsumption of 2281 kWh (342€), but no IAQ deterioration
- **Filter clogging**: In a secondary school located in the east of France, a clogged filter with a pressure loss of 92 Pa when new and 210 Pa after a year of use, the fan overconsumption the second year if it is not changed is 17741 kWh (2661 €) if the fan is running continuously and 1971 kWh (296€) if it is running 1/3 of the time. As a result, it is more cost-effective to change the filter every year.
- **Inadequate fans settings**: an overpressure of 10 Pa at the furthest ATD compared to the required pressure (60 Pa instead of 50 Pa) in the office building, for a fan power of 2.5 kW induces a yearly fan overconsumption of 576 kWh (86€).
- **Non-insulated duct sections**: a 5 m long and 56 cm in diameter non-insulated duct section, with a flowrate of 4500 m^3/h, leads to yearly thermal losses of 137 kWh (21€)
- **Inadequate AHU scheduling**: in an office building equipped with two fans of 2.5 kW and 6000 m^3/h each, a ventilation not switched off at night induces a fan overconsumption of 13200 kWh (1980€) per year, as well as a thermal loss of 8900 kWh (1335€) per year for the useless conditioning of this air. In addition, the lack of flowrate regulation with sensors during the building occupation period leads to a fan overconsumption of 8424 kWh (1263€) per year.

5 ACKNOWLEDGMENT

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6 REFERENCES

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

- For the electrical overconsumption calculation due to filter clogging

<table>
<tr><th rowspan="2">Symbol</th><th rowspan="2">Description (unit)</th><th rowspan="2">Comments</th><th colspan="2">Methods</th></tr>
<tr><th>1</th><th>2</th></tr>
<tr><td colspan="5">On-site measurements</td></tr>
<tr><td>$P_{AHU,real}$</td><td>AHU power in real running conditions (kW)</td><td></td><td colspan="2">X</td></tr>
<tr><td>Δp_{AHU}</td><td>Pressure difference generated by the running AHU (Pa)</td><td>Measured at time t_{real} but considered as a constant</td><td colspan="2">X</td></tr>
<tr><td>$\Delta p_{filter,real}$</td><td>Real pressure difference generated by the filter at the measurement time (Pa)</td><td>Pressure difference accross the filter (measured on-site or given by the BMS)</td><td>X</td><td></td></tr>
<tr><td colspan="5">To research (technical doc., etc)</td></tr>
<tr><td>$\Delta p_{filter,0}$</td><td>Pressure loss generated by the new filter (Pa)</td><td>Given on the technical documentation of the filter (initial pressure loss)</td><td colspan="2">X</td></tr>
<tr><td>$\Delta p_{filter,max}$</td><td>Maximum recommended pressure loss (Pa)</td><td>Given on the technical documentation of the filter (clogged filter pressure loss)</td><td></td><td>X</td></tr>
<tr><td>t_{real}</td><td>Time since the last filter change (h)</td><td>Corresponds to the filter clogging time (between the installation and the measurement time)</td><td colspan="2">X</td></tr>
<tr><td>$t_{AHU,y}$</td><td>Yearly AHU operating time (h)</td><td rowspan="2">Allows to convert the additional required power to extra running costs</td><td colspan="2">X</td></tr>
<tr><td>$price_{elec}$</td><td>Electricity price (€/kWh)</td><td colspan="2">X</td></tr>
</table>

- For the electrical overconsumption calculation due to inadequate fan setting

<table>
<tr><th>Symbol</th><th>Description (unit)</th><th>Comments</th></tr>
<tr><td colspan="3">On-site measurements</td></tr>
<tr><td>$\Delta p_{fan,real}$</td><td>Pression de réglage du ventilateur en fonctionnement (Pa)</td><td>Measured on-site or given by the BMS</td></tr>
<tr><td>$\Delta p_{ATD,far,real}$</td><td>Pressure measured at the most disadvantaged ATD (Pa)</td><td>The most disadvantaged ATD is the "furthest" from the AHU, that is to say the one that has the highest pressure losses along the airpath from the AHU</td></tr>
<tr><td>$P_{fan,real}$</td><td>Puissance du ventilateur en fonctionnement (kW)</td><td></td></tr>
<tr><td colspan="3">To research (technical doc., etc)</td></tr>
<tr><td>$\Delta p_{ATD,far,ref}$</td><td>Minimal pressure required for the most disadvantaged ATD (Pa)</td><td>The most disadvantaged ATD is the "furthest" from the AHU, that is to say the one that has the highest pressure losses along the airpath from the AHU</td></tr>
<tr><td>n_{fan}</td><td>Number of fan(s) (-)</td><td></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 thermal loss calculation due to non-insulated duct sections

<table>
<tr><th>Symbol</th><th>Description (unit)</th><th>Comments</th></tr>
<tr><td colspan="3">On-site measurements</td></tr>
</table>

$l_{duct,n-i}$	Non-insulated duct length located outside or in a non-conditioned space (m)	
To research (technical doc., etc)		
d_i	Internal duct diameter (m)	L'épaisseur du conduit est ici négligée, si le conduit n'est pas isolé, alors d_i=d_e et s'il est isolé, d_e-d_i correspond à l'épaisseur de l'isolant
d_e	External duct diameter (m)	
λ_i	Insulation thermal conductivity (W/(m.K))	
q_{air}	Average air flowrate inside the duct (m^3/h)	WHen the ventilation air flowrate is regulated according to the occupation (min/max flowrate) thanks to sensors, this air flowrate corresponds to the average over the AHU running time
$t_{AHU,d}$	Average number of daily hours of running AHU for an AHU running day (h)	
r_h	ratio of the number of days for which the building is heated in the heating period (-)	
r_c	ratio of the number of days for which the building is cooled in the cooling period (-)	
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)	
$price_{elec}$	Electricity price (€/kWh)	Allows to convert the energy losses to extra costs

- For the energy losses calculation due to inadequate AHU scheduling

Symbol	**Description (unit)**	**Comments**
On-site measurements/To research		
-	Real occupied and unoccupied building periods	Number of hours per day (counting +1 hour before and after the occupied period), number of days per week and number of weeks per year
-	AHU scheduling setting	Automatic or manual setting, defining hours, days and weeks of operating AHU
q_{air}	Average duct air flowrate (m^3/h)	When ventilation is regulated depending on the occupation (min/max flowrates) thanks to sensors, this flowrate corresponds to the average on the AHU operating time
η_{exch}	Heat exchanger yield (-)	
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)	
$P_{fan,nom}$	Fans power at nominal flowrate (kW)	
$P_{fan,unocc}$	Fans power – unoccupied building (kW)	
Crbdnr	Flowrate reduction coefficient (-)	Given by the systems' technical approval documents
n_{fan}	Number of fan(s) (-)	
$price_{elec}$	Electricity price (€/kWh)	Allows to convert the energy losses to extra costs
Previsousły calculated data		
$H_{cond,extra}$	Thermal conductivity – extract ducts (W/K)	H_{duct}=l_{duct}/R_{tot} Depends on the duct length, its diameter, its thickness, and the insulation thermal conductivity
$H_{cond,souf}$	Thermal conductivity – supply ducts (W/K)	