# IMPACT OF A POOR QUALITY OF VENTILATION SYSTEMS ON THE ENERGY EFFICIENCY FOR ENERGY-EFFICIENT HOUSES

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## ABSTRACT

The "VIA-Qualité" project (2013-2016) focuses on low energy, single-family dwellings. It proposes the development of quality management approaches (ISO 9001) which aim to increase both on-site ventilation and indoor air quality. One of the main benefits of those approaches is the improvement of ventilation system performance, especially thanks to a rigorous follow-up from design to installation. Efficient ventilation system performance is rewarded in the French EP-calculation, through a primary energy consumption estimation. In order to evaluate the energy impact of the proposed quality approaches, some sensitivity studies have been carried out for single humidity-controlled ventilation system. The primary energy consumption of typical single-family dwellings has been estimated along various parameters, such as:

- Ductwork airleakage
- Exhaust and incoming airflow
- Electrical fan power
- System localization (to take into account leakages in and out of heated volume).

This paper presents variations of the estimated dwellings energy consumptions as an indicator of the impact of several typical dysfunctions of ventilation systems which have been observed during different campaigns and controls.

## KEYWORDS

Ventilations systems – Dysfunctions – Energy impact – Single-family house

## 1 INTRODUCTION

In France, the energy performance regulation (RT2012) generalizes requirements of the BBC-Effinergie label, in particular regarding the envelope airtightness. For a single family dwelling, the requirement is $Q_{4Pa\text{-}Surf}$ [1]$\leq 0.6\ m^3.h^{-1}.m^{-2}$ (around $n_{50} \leq 2.3\ h^{-1}$). In those airtight dwellings, the air change rates have to be adequate to insure a good indoor air quality, and at the same time they have to induce low thermal losses in order to comply with requirements of the regulation. Nevertheless, the RT2012 does not include any new requirement on ventilation rates, which are provided by another 30-years-old regulation (JO, 1983). Therefore, without compulsory check of the proper functioning of ventilation systems, how inhabitants can be sure that the air renewal of their houses is adequate to ensure a good indoor air quality? In addition, in the current energy

[1] Air permeability at 4 PA divided by the loss surfaces area excluding basement floor

context, mechanical ventilation systems are spreading, including high technical systems such as single humidity-controlled ventilation systems and balanced ventilation systems. These systems require knowledge and skills from each of the three main actors: designers, installers and inhabitants, who in most cases are not even aware of the ventilation principles. Indeed, various campaigns (Paul Van Den Bossche, 2013) in different countries have brought forward the poor quality of ventilation systems, mainly related to a poor design or installation and a lack of maintenance. In France, a study (Romuald Jobert, 2013) has been carried out from regulatory compliance control reports of almost 1300 dwellings. This survey confirms that ventilation system dysfunctions are very frequently observed in dwellings, and it gives clear information about their localization and qualification.

Therefore, we need solutions to prevent those dysfunctions and ensure a good indoor air quality. Various countries (Paul Van Den Bossche, 2013) are developing different schemes to secure the quality of ventilation systems through actions during all steps of the process of a building construction. Such a system is already in place since 5 years in France regarding the envelope airtightness. The good experience of this quality approach (Sandrine Charrier, 2013) and the current ventilation systems quality assessment have motivated the "VIA-Qualité" project. Started in 2013, this 3-years French project proposes to develop quality management (QM) approaches (ISO 9001) with the goal of increasing both on-site ventilation and indoor air quality (IAQ). It focuses on low energy, single-family dwellings, which mainly concerns in France the individual homebuilders sector. The benefits would be to: 1- Improve ventilation system performance, especially thanks to rigorous monitoring from design to installation; 2- Limit indoor internal pollution sources, monitoring materials selection (Wargocki P, 2012); 3- Increase final users' awareness and understanding. An assess of the effectiveness of these QM approaches will be carried out, through ventilation measurements and IAQ measurements in 8 test houses. Moreover, in order to ensure the reproducibility of this kind of operation, the economic and energetic interests of these QM approaches have to be evaluated. This analysis will be carried out in two steps: 1- evaluation of the impact of ventilation system performance on energy consumptions; 2- crossed analysis between the energy-savings and the additional costs due to materials, studies, controls... This paper presents an analysis of impacts of ventilation system dysfunctions on the regulatory energy performance calculations (RT2012) for the three first single-family houses of the VIA-Qualité project.

## 2 VENTILATION PARAMETERS IN THE FRENCH EP-CALCULATION

The in-force French EP-regulation (RT2012) is mainly based on 3 kind of performance requirements: 1- energy efficiency (independent of systems); 2- primary energy consumption [Cpe[2]] and 3- summer comfort (for buildings without air-conditioning). In this study, the variations of the energy consumptions have been calculated as an indicator of the energy cost of several ventilation systems dysfunctions.

The EP-calculation is run with XML data which define the values of various input parameters. The following part briefly explains how ventilation is taken into account in the EP-calculation for a classic single-family house, with a single humidity-controlled ventilation system. Concerning ventilation system, the input parameters used in this study are listed in table 1.

[2] In France, it is noted Cep

Table 1: Income parameters concerning ventilation systems in the French EP-calculation

| **Income parameter** | **Definition** | **Possible values** |
|---|---|---|
| Air inlet module ($m^3.h^{-1}$) | Coefficient which is used to estimate the total airflow incoming through all air inlets | From 0 to ∞ |
| $Q_{ext}$ ($m^3.h^{-1}$) | Total extraction airflow | From 0 to ∞ |
| Type_air_intake (-) | Two types of air intake are identified in the EP-calculation: humidity & pressure controlled air intake or pressure controlled air intake | 0: humidity & pressure controlled air intake<br>1: pressure controlled air intake |
| Engine_Power (W) | Engine power of the fan | From 0 to ∞ |
| $C_{dep}$ (-) | Coefficient of design quality | From 1 to ∞ |
| Ratfuitevc (-) | Ratio of leaks to heated volume | From 0 to 1 |
| Cletres | Airtightness class of the ductwork (A,B,C,D): defined the value of the ductwork leakage coefficient $K_{res}$ | C: $K_{res}$ = 0,003.$10^{-3}$ $m^3.s^{-1}.m^{-2}$<br>B: $K_{res}$ = 0,009.$10^{-3}$ $m^3.s^{-1}.m^{-2}$<br>A: $K_{res}$ = 0,027.$10^{-3}$ $m^3.s^{-1}.m^{-2}$<br>Default (2.5A): $K_{res}$ = 0,0675.$10^{-3}$ $m^3.s^{-1}.m^{-2}$ |

## 2.1 Some equations of the EP-calculation concerning ventilation systems

The following equations and fixed values of some coefficients are defined in the EP-calculation method.

<u>Exhaust airflow model</u>

For a single-family house, the regulated exhaust airflow is defined with two indicators: $Q_{ext,\ min}$ which represents the base flow, and $Q_{ext,\ max}$ which represents the flow at full load. The values of these two airflows have to be consistent with the French ventilation regulation (JO, 1983). The average flow $Q_{ext,\ regul}$ is calculated according to equation 1:

$$Q_{ext,regul} = \frac{Q_{ext,max} * Dugd + Q_{ext,min} * (168 - Dugd)}{168} \tag{1}$$

*Dugd [hour/week] is the duration of use at full load expressed in h/week. For a single-family house, Dugd = 7 hours per week.*

Then, the EP-calculation introduces the coefficient $C_{dep}$ in order to take into account some dysfunctions of the system due to design. Therefore, the extraction flow becomes $Q_{ext,\ dep}$:

$$Q_{ext,dep} = C_{dep} * \ Q_{ext,regul} \tag{2}$$

*The default value of $C_{dep}$ is 1.25, and in most cases $C_{dep}$=1.1 (justification with a certified document).*

The following equation defines the leakage rate through all duct leaks $Q_{ext,\ leaks}$ for a pressure difference ΔP:

$$Q_{ext,leaks} = 3600 * \ K_{res} * \ \Delta P^{0,667} * A_{duct,ext} \tag{3}$$

*$K_{res}$ [$m^3.s^{-1}.m^2$] depends on the leaktightness class of the network*
*$A_{duct, ext}$ [$m^2$] is the surface of the air duct, which can be estimated as a percentage of the floor area (the uncertainty of this parameter value is not analysed in this study).*

The final extraction flow is calculated according to equation 4:

$$Q_{ext} = Q_{ext,dep} + Ratfuitevc * Q_{ext,leaks} \tag{4}$$

*$K_{hv}$ [-] describes the part of the exhaust duct in the heated volume (from 0 to 1).*

<u>Intake airflow model</u>
In a single humidity-controlled ventilation system, the characteristic curve which represents the air inlets performance has a straight line format. The following equation corresponds with the principal part, which is used when the pressure difference at the air inlet is under 20 Pa.

$$Q_{AI}\,(\Delta P) = C_d * \left(\frac{2}{\rho_{ref}}\right)^{0.5} * 10^{-4} * M * \left(\frac{10}{|\Delta P_{ref}|}\right)^{0.5} \tag{5}$$

*$Q_{AI}$ [$m^3.h^{-1}$] is the airflow which enters through the air inlets.*
*$C_d$ [-] is the coefficient of discharge. Its value is 0.68.*
*$\rho_{ref}$ [$kg.m^{-3}$] is the air density at 19°C. Its value is 1.2 $kg.m^{-3}$.*
*M is the sum of the air inlet modules.*
*$\Delta P_{ref}$ [Pa] is the pressure difference for which the module is defined. Its value is 20 Pa.*

The two airflows $Q_{ext}$ and $Q_{AI}$ are then used to estimate the indoor temperature for each time step. The difference between the indoor temperature and the setpoint temperature is an input for evaluating the heating needs. With those needs and the performance of the house systems, the EP-calculation establishes the regulatory primary energy consumptions for 1 year and for 1 square meter of a specific floor area named $SHON_{RT}$ (without some parts like non-heated places, balcony...): $C_{pe}$ [$kWhpe.m^{-2}.year^{-1}$]. In order to respect the EP-regulation (R2012), the $C_{pe}$ of a house have to be lower a limit value $C_{pe\ max}$, which depends on various parameters including climate zone and altitude. The average limit value is 50 $kWhpe.m^{-2}.year^{-1}$.

## 2.2 Definition of dysfunction scenarios

A list of dysfunctions of ventilation systems has been established based on the analysis of Jobert, 2013, and supplemented with results of a 20 houses campaign realised during the first step of the VIA-Qualité project. In this list, dysfunctions which could have an impact on energy consumption of the house have been identified. For each of them, related parameters of the EP-calculation and the appropriate variation range have been identified. Those criteria have been introduced into six scenarios which correspond to different common situations in low-energy houses. Table 2 presents those scenarios.

Table 2: Various scenarios representing common ventilation system dysfunctions

| Scenario | Characteristic | Concerned parameters |
|---|---|---|
| 1: Lack of humidity-control | In this scenario, the installer has put in place the wrong air inlets: they are not humidity-controlled, but just pressure-controlled | • Type_air_intake<br>• Air inlet module [74.9 $m^3.h^{-1}$ ;<br>• 186 $m^3.h^{-1}$] |
| 2: Excessive number of air inlets | This scenario corresponds with a common situation where 1 additional air inlet has been installed in a room | • Air inlet module [74.9 $m^3.h^{-1}$ ;<br>• 115 $m^3.h^{-1}$] |
| 3: Low battery in toilets air outlets | Most of the air outlets which are installed in the toilet fitted out with a presence sensor. In most cases, the sensor runs with batteries. This scenario represents the impact of low batteries, which impact on the exhaust airflow. | • $Q_{ext}$ [59 $m^3.h^{-1}$ ; 110.1 $m^3.h^{-1}$] |
| 4: Duct leakage | In this scenario, various configurations are texted, which correspond with different airtightness classes of the ductwork and different duct positions in the heated volume | • Airtightness class of the ductwork [2.5A ; C]<br>• $K_{hv}$ [0.25 ; 1] |
| 5: Over ventilation | In some cases, fans are wrongly adjusted, which induces an over ventilation of the house. In this scenario, various level of over ventilation are simulated. | • $Q_{ext}$ [59 $m^3.h^{-1}$ ; 100 $m^3.h^{-1}$] |
| 2: Fan performance | In this scenario, various fan with different performance are tested. | • Engine_Power [8W ; 45 W] |

## 2.3 Houses presentation

Those scenarios have been modelled with the EP-calculation for three low-energy houses. Each of them are equipped with a single humidity-controlled ventilation system, which equips most of new single-family houses. Table 3 describes some characteristics of those houses. A first simulation in normal situation (no modification of the project input data) has been performed for each house. The calculated value of the $C_{pe}$ [Consumption calculated in primary energy[3]] is then used as the reference value for the six previously described scenarios.

Table 3: Houses presentation

| House | Type | Heating system | **$C_{pe}$ (total)** / $C_{pe\ max}$ [$kWhpe.m^{-2}.year^{-1}$] | **$C_{pe}$ (heating consumption)** [$kWhpe.m^{-2}.year^{-1}$] |
|---|---|---|---|---|
| House 1 | Two-storey house<br>Floor area: 97 m² | Heat pomp | **51.3** / 60 | 24.4 |
| House 2 | Single-storey house<br>Floor area: 84 m² | Heat pomp | **55.2** / 64.6 | 26.9 |
| House 3 | Single-storey house<br>Floor area: 90 m² | Condensing boiler | **57.2** / 73.2 | 39.9 |

[3] Consumptions are presented in energy primary: for electrical source, a multiplier factor equal to 2.58 is applied.

# 3 RESULTS

Each of the 6 scenarios has been simulated for the three test houses with the EP-calculation. In this study, every consumption is expressed in primary energy: electrical source is penalised (1 kWh of final energy = 2.58 kWh en primary energy[4]). Houses 1 and 2 use only electrical source for all energy consumers (heating, cooling, lighting, domestic hot water, ventilation fans and distribution systems). House 3 uses gas source for heating and a part of the domestic hot water.
Except for scenario 6, the analysed dysfunctions only impact on the heating consumptions. The following part presents those impacts and gives some explanations of those results. Results of scenario 6 are presented in a second time, as the impact of the studied dysfunctions does not concern the heating consumption.

## 3.1 Impact of several ventilation dysfunctions on regulatory heating consumption

As the relative impacts on the heating consumption of each dysfunctions are almost the same for the three houses, figure 1 introduces the average impact for each scenario (except scenario 6). Table 4 gives results for each house.

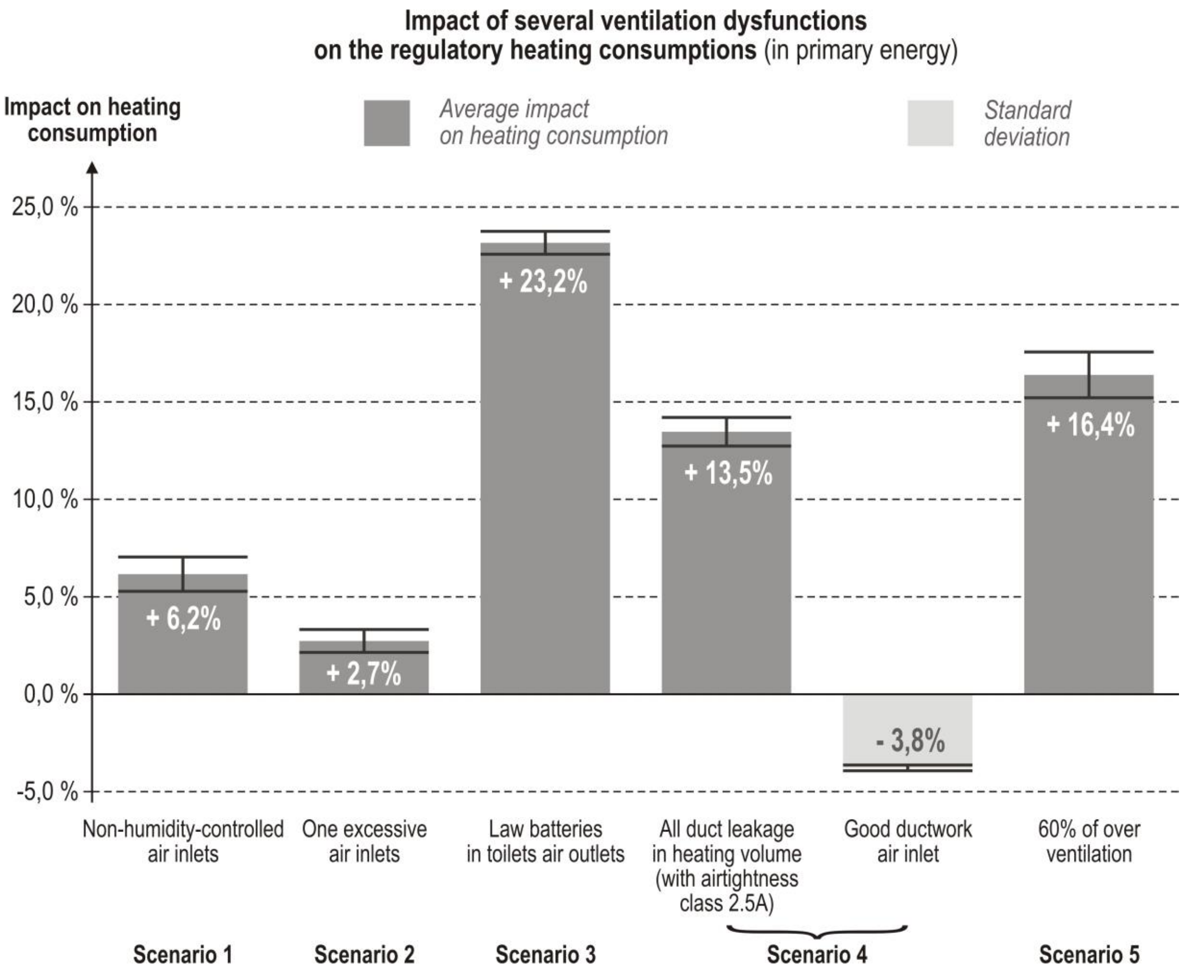


Figure 1: Impact of several ventilation dysfunctions on the regulatory heating consumptions *[in primary energy]*

[4] This coefficient is defined in the French regulation

Whereas different kinds of heating systems with a 2.58-coefficient for electrical source, the standard deviations of the impacts of these dysfunctions are small. Indeed, house 3 (which uses gas-source) has been built in a colder climate, so even with a 1-coefficient for primary energy consumption, the part of heating consumption is almost the same than for the two other houses. It will be interesting to perform the same study with a gas-source house built in a "hot" climate, for which the part of heating consumption should be significantly lower.

Table 4: Impact of several ventilation dysfunctions on the regulatory heating consumption depending on the test house (in primary energy)

| | **Relative impact on the regulatory heating consumption (primary energy)** | | | | | |
|---|---|---|---|---|---|---|
| | Scenario 1: Non-humidity-controlled air inlets | Scenario 2: One excessive air inlet | Scenario 3: Low batteries in toilets air outlets | Scenario4: All duct leakage in heating volume | Good ductwork airtightness | Scenario 6 : 60% of over ventilation |
| **House 1** | +7.4% | +2.9% | +22.5% | +13.9% | -3.7% | +16% |
| **House 2** | +5.6% | +3.3% | +23.4% | +12.6% | -3.7% | +16% |
| **House 3** | +5.5% | +2.0% | +23.6% | +14.0% | -4.0% | +18% |
| **Average** | **+6.2%** | **+2.7%** | **+23.2%** | **+13.5%** | **-3.8%** | **+16%** |
| **Standard deviation** | *0.9%* | *0.6%* | *0.5%* | *0.6%* | *0.1%* | *1.2%* |

According to (Jobert, 2013), among the key elements of a ventilation system, air inlet is one of the worse installed. Within those dysfunctions, 18% concern the non-compliance with prescribed rules and regulations and 18% concern the presence of an additional air inlet.

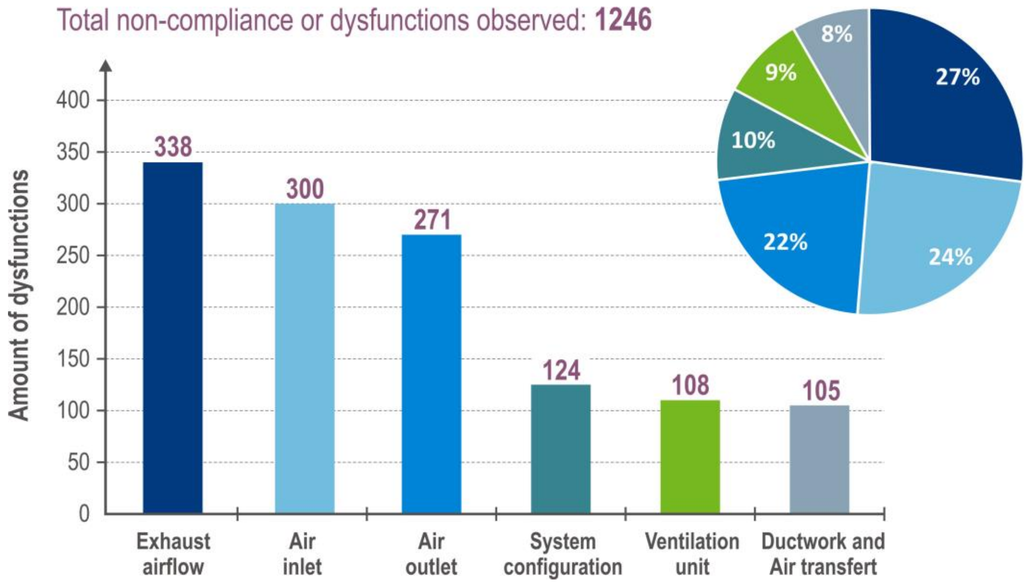


Figure 2: Number of non-compliance or dysfunctions items per category (Jobert, 2013)

Scenario 1 corresponds with an installation of wrong air inlets. Indeed, in France, there are two types of single-flow humidity-controlled ventilation systems called A and B. For the A system, air outlets are humidity and pressure controlled, but air inlets are pressure-controlled only. On the contrary, for the B system, outlets and inlets are humidity and pressure controlled. In most houses, the B system is installed, which induces a lower total incoming airflow than the A systems. Figure 1 shows that this error could increase the heating consumption of about 6%.

Scenario 2 also corresponds with an air inlet dysfunction: it models the implementation of one excess air inlet somewhere in the house. The model of the EP-calculation does not let to precise in which room (utility room or main room) the air inlet is installed. The only effect considered in this study is the increase of the total airflow incoming. With this hypothesis, the excess air inlet induces an overconsumption of almost 3%. This result is not really significant. Nevertheless, depending of the localisation of the excess air inlet, it could induce a short circuit of the house sweep and therefore be responsible of a poor air renewal in some rooms. This energy impact should be supplemented with sanitary impact.

Air outlets are also often affected by dysfunctions (22% of cases). Indeed, in a single humidity-controlled ventilation system, outlet in the toilet are equipped with a system which momentarily increases airflow when someone uses the toilet. In most new houses, the system is a presence sensor running on batteries. The lack of battery is a common dysfunction: it represents 15% of dysfunctions concerning outlets (people often did not know they have to replace them). In this case, the outlet stays in the position where it was when the batteries have stopped: it could be either the lower airflow or the big airflow. Scenario 3 corresponds with the “worst” situation: the batteries of the two toilets outlets are fallen out of order when the outlets were in the big airflow position (it could happen!). In this case, the total exhaust airflow is more important than the predicted one. The impact of this dysfunction is significant: about 23% of over consumption for heating. It could induce an additional cost of more than 60 € each year, while batteries for 2 outlets cost about 10€. This situation is the “worst”, but in the other one, when the airflow is blocked in the lower position, the air renewal in the toilets will be insufficient. So, a lack of batteries will either induce an important additional cost each year, or lead to a moisture development in toilets. Therefore, it should probably be more relevant to pay 10€ and change the batteries.

The previous dysfunctions concern an over energy cost when the exhaust airflow is blocked at a high value. Nevertheless, is some cases, the poor quality of the ductwork prevents the airflow from reaching this value. The EP-calculation takes into account this quality with 4 different ductwork airtightness classes. Without any measurement, the worse class has to be used in the calculation. Scenario 4 includes several configuration, with classes varying for different positions of the ductwork leaks (in or out the heated volume). Figure 1 shows that a good ductwork airtightness should induce almost 4% of energy consumption gain. This gain is estimated with the hypothesis of a fixed exhaust airflow at the outlet (independent of the airtightness class). Therefore, with more leaks, there is an additional exhaust airflow through those leaks. With this hypothesis, the impact of the localisation of the leaks compared to the heated volume is significant: for a bad airtightness (class 2.5A) and a duct entirely in the heated volume, the overheating energy consumption could raise more than 13%. The EP-calculation do not estimate the over consumption of the fan needed to secure the airflow at the outlet, so this dysfunction impact might be higher. In practice, the exhaust airflow at the outlets is often not secured, and in this case, the impact of this dysfunction is a sanitary impact with a possible very low exhaust flow. Therefore, a bad ductwork could induce either an important energy consumption or a sanitary issue, or both.

Then, scenario 5, frequent for balanced ventilation system, is less frequent for single-flow ventilation systems: it deals with over ventilation. This dysfunction happens if the fan has not be well set. Various total exhaust airflow have been tested, the most important is a 60% of over ventilation. For this value, the ventilation may be responsible of a 16% increase of the energy consumption for heating, hence the importance of the fan setting.

## 3.2 How initial financial savings could induce significant losses

Some dysfunctions are due to design and installation, others to maintenance. The following part concerns dysfunctions due to initial financial savings. Indeed, fans and ventilation terminals are available in various models, at various prices. Scenario 6 is related to fan. For each of the three test houses, the fan which is foretold in their thermal study is a high-performance fan: the nominal power is 8 W. Some other lower performance fans exist for this type of ventilation system, for the same delivered airflow. For financial reasons (up to a 100 €-difference between fan prices for an initial 200€-price), it is possible than one of this fan is finally installed instead of the 8 W fan. Table 5 presents the impact of the fan choice on the total energy consumption $C_{pe}$ compared with the initial $C_{pe}$ (with an 8W-fan).

Table 5: Impact of a bad performance-fan on the total energy consumption (primary energy)

| **Fan Nominal power** | **Impact on the $C_{pe}$ (heating consumption)** [kWhpe.m$^{-2}$.year$^{-1}$] | | |
|---|---|---|---|
| | **House 1** | **House 2** | **House 3** |
| 12 W | 1% | 2% | 2% |
| 30 W | 8% | 9% | 8% |
| 45 W | 13% | 15% | 14% |

Those results prove the importance of the fan choice. Indeed, with a low-performance fan (45 W), the regulatory energy consumption can significantly increase (until 15% for the house 2). In practice, the impact on the energy bill is less important: until 11% (above 45€). Nevertheless, this additional cost for a 8W-fan is low enough to be quickly paid off: 2 years and 3 months only!

Moreover, the impact on the $C_{pe}$ could be critical: for house 2, with a 45W-fan, the recalculated $C_{pe}$ is almost equal to the limit value $C_{pe\ max}$. If an other dysfunction exists, the $C_{pe\ max}$ could therefore be overtaken. Then, the house would not respect the RT2012.

On this point, air inlet are also affected by financial choice. For example, scenario 2 corresponds with an initial 30% saving. In order to evaluate the energy and final economic impact of a first price installation, a combination of scenario 1 and 2 have be modeled (non-humidity controlled air inlet and a 45W-fan). Moreover, a dysfunctions combination is a current situation: according to Jobert, among all controlled dwellings, 29% get two non-compliances or more. Figure 3 presents results of this particular combination.

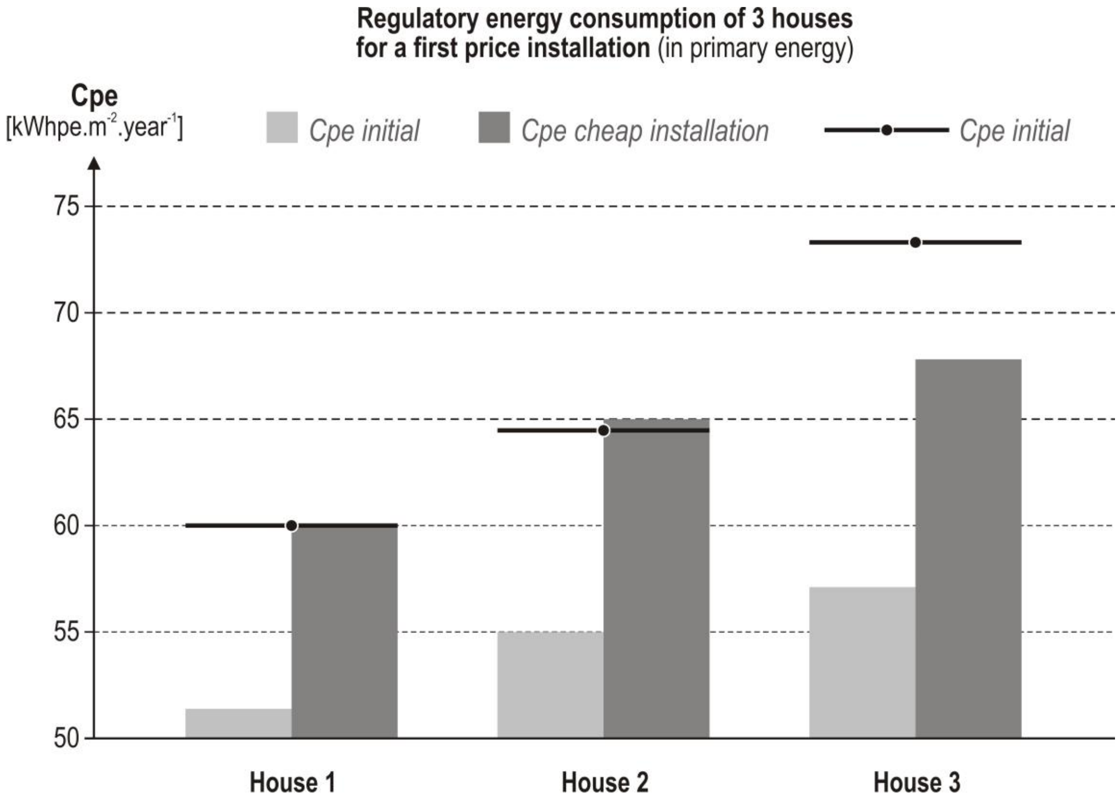

Figure 3: Regulatory energy consumption (primary energy) of 3 houses depending on the ventilation fan performances

In this probable situation, the regulatory $C_{pe}$ recalculated with the real equipment will exceed the limit value $C_{pe}$ max for two houses (1 and 2). In a first hand, energy consumptions would be significantly higher than the predicted ones, and in the other hand, the house would not respect the EP-regulation RT2012! Therefore, make some initial financial savings should rapidly induce many issues, including energy losses and poor indoor air quality.

# 4 CONCLUSIONS

Ventilation has to be understood as a principle and not just a system. A dysfunction of one element impact the whole buildings, and may increase the total primary energy consumption [Cep] by about 16% (22% of the heating consumption). Not only the energy bill may be significantly increased, but also the house might not respect the EP-regulation requirements. As ventilation systems dysfunctions are a main issue for single-family houses, a scheme as a quality management approach may increase ventilation quality. To that end, the VIA-Qualité project develop tools for each of the three main actors (designer, installers and inhabitants) in order raise awareness among them about the ductwork, products and maintenance quality.

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The sole responsibility for the content of this publication lies with the authors.

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