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Towards a better integration of indoor air quality and health issues in low-energy dwellings: Development of a performance-based approach for ventilation

Gaëlle Guyot

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THÈSE

Pour obtenir le grade de

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dans **l'École Doctorale SISEO**

Towards a better integration of indoor air quality and health issues in low-energy dwellings: Development of a performance- based approach for ventilation

Vers une meilleure prise en compte de la qualité de
l'air intérieur et de la santé dans les logements
individuels basse consommation : Développement
d'une approche performantielle de la ventilation

Thèse soutenue publiquement le **3 décembre 2018**,
devant le jury composé de :

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A mon étoile,

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Résumé

Mots clés : Ventilation, qualité de l'air intérieur, perméabilité à l'air, maison basse consommation, performance, santé

Les futures réglementations à l'horizon 2020 intégreront la notion de performance globale des bâtiments, incluant la qualité de l'air intérieur (QAI). Dans le domaine de l'énergie, les approches performantielles se sont développées afin de vérifier que le bâtiment respecte, à la conception, une consommation maximale d'énergie. Or, dans le domaine de la ventilation, les réglementations se basent généralement sur des approches prescriptives, fixant des débits de ventilation. Cette thèse vise donc le développement d'une approche performantielle afin de s'assurer, dès la conception, que la ventilation permet d'éviter un risque pour la santé des occupants.

Par ailleurs, dans un contexte de généralisation des bâtiments à quasi zéro énergie, la perméabilité à l'air est aujourd'hui de plus en plus intégrée dans les réglementations thermiques en Europe. Comme l'évaluation de la performance porte souvent sur l'efficacité énergétique, et rarement sur la QAI, l'impact de la présence de plusieurs zones, interconnectées par des défauts de perméabilité à l'air sur les cloisons intérieures (perméabilité intérieure), combinées à une non-uniformité de la perméabilité d'enveloppe, est une problématique rarement étudiée et traitée dans cette thèse.

Pour répondre à cette problématique, une campagne inédite de mesure des distributions de la perméabilité à l'air sur 23 maisons a permis de développer une base de données. Son analyse révèle que la perméabilité intérieure est non négligeable devant un détalonnage de porte, et que le type de structure (légère/lourde) a un impact considérable. A l'issue de ce travail, nous avons proposé des données d'entrées dans les modèles multizones sur ces distributions de perméabilité à l'air. Ensuite, un travail de quantification des impacts de ces distributions détaillées sur la QAI a pu être réalisé sur un cas d'étude modélisant les concentrations en CO₂, humidité et formaldéhyde dans une maison basse consommation. Elle est supposée équipée d'une ventilation simple-flux (SF), ou d'une ventilation double-flux (DF). Des impacts importants ont été mis en évidence. Pour évaluer la QAI, il est donc nécessaire de modéliser finement la perméabilité à l'air d'enveloppe et intérieure.

A l'issue d'un travail bibliographique intense, combiné à des analyses complémentaires, nous avons pu proposer une approche performantielle pour la ventilation à utiliser dans une étude réglementaire au stade de la conception. Nous avons proposé 5 indicateurs de QAI à prendre en compte *a minima*, incluant les doses reçues de CO₂, formaldéhyde et PM_{2.5}, deux indicateurs sur l'humidité portant sur l'évaluation du risque de condensation et la santé des occupants. Nous avons également proposé des scénarios d'occupation et d'émission en polluants à prendre en compte. Enfin, nous avons décrit le type de modèle multizone à mettre en œuvre, les modèles physiques et hypothèses associées, les conditions limites à utiliser.

Nous avons souhaité tester cette approche en l'appliquant sur une maison basse consommation servant de cas d'étude. Nous avons donc supposé être au stade de sa conception et devoir respecter

une hypothétique réglementation fixant des objectifs de performance sur la QAI. Nous avons ainsi illustré comment une telle approche permettrait de faire des choix clés au stade de la conception, comme le type de structure (aux vues de son impact sur les distributions de perméabilité), le type de système de ventilation, le niveau de pollution intérieure (en lien avec le choix de labels ou d'étiquetage par exemple), au regard de leur impact sur la QAI. En effet, dans notre cas d'étude, seule une ventilation double-flux combinée à une émission faible ou médium de formaldéhyde permet de respecter les objectifs de QAI. Nous avons également montré qu'une telle approche serait utile au stade de la conception pour mieux dimensionner la distribution des entrées d'air ou des bouches d'extraction, voir même les débits de ventilation, afin d'atteindre les objectifs de QAI.

Abstract

Key words: Ventilation, indoor air quality, air leakage, low-energy house, performance, health

In future building regulations 2020, building performance is going to be extended to global performance, including indoor air quality (IAQ). In the energy performance (EP) field, successive regulations pushed for a "performance-based" approach, based on an energy consumption requirement at the design stage. Nevertheless, ventilation regulations throughout the world are still based on prescriptive approaches, setting airflows requirements. This thesis should develop a performance-based approach to insure that ventilation is designed to avoid risks for occupant's health.

Given the European context with the generalization of nearly zero energy buildings, envelope airtightness is often included in EP-calculations, frequently through single-zone models with uniform air leakage. Because more consideration is often given to EP than to IAQ issues, impact of several zones interconnected by unevenly distributed leaks, on the envelope and on internal partition walls, is a rarely investigated issue. We propose to study it in this thesis.

Faced with this issue, we conducted an experimental study on multizone air leakages of 23 detached houses and developed an innovative database. The analysis of this database reveals that internal air leakage can become significant at door undercuts and that the type of building structure has a great influence. We proposed airleakage values and dispersion input data for multizone IAQ models. Then, through a multizone modelling of a low energy house case study, we quantified impacts of these airleakage distribution data on IAQ. We modelled CO₂, humidity and formaldehyde with two type of ventilation (exhaust-only or balanced). We highlighted strong impacts and concluded that detailed airleakage distributions should be used in IAQ performance assessment methods.

An extensive review work combined with complementary analysis allowed us to come up with the development of a performance-based approach for house ventilation to be used at the design stage in a regulatory calculation. We selected the use of five relevant IAQ performance indicators, based on CO₂, formaldehyde and PM_{2.5} exposures, and RH-based indicators assessing both condensation and health risks. We proposed also pollutant emission data and occupancy schedules to be used. Lastly, we described the multizone modelling laws and assumptions to be used, the physical models and associated assumptions, and the boundary conditions.

Importantly, we demonstrated that our proposed method was applicable, applying it to a low-energy house case study. We assumed being at the design stage of a house which should comply with a hypothetical regulation, requiring IAQ performance indicators and associated thresholds. We also demonstrated how such an approach could help at the design stage in key choices as the type of structure (regarding its impact on airleakage distributions), the type of ventilation system, the level of pollutant emissions. Indeed, in the case study studied case, only the balanced ventilation combined with low or medium-emission class of formaldehyde emissions allow to fulfill the IAQ requirements. We showed also that such an approach could help in the ventilation design, notably the distribution of the air inlets and/or outlets, or even the airflows, in order to secure the fulfillment of IAQ requirements.

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Abbreviations and definitions

IAQ: Indoor air quality

EP: Energy-performance

RT 2012: The most recent French building energy-performance regulation

Envelope airleakage: set of leaks located on the whole building envelope, separating the “outdoor” from the “indoor”

Internal partition walls airleakage: set of leaks located on internal partition walls, separating two rooms (two bedrooms, bathrooms, toilets, living-room, kitchen...)

Infiltrations: involuntary airflows pathing through envelope and internal partition walls airleakage

Ventilation airflows: voluntary airflows due to the ventilation system, excluding infiltrations

Trickle ventilator: ventilation component allowing the fresh air to enter in a room with an exhaust-only ventilation, usually located on a window, a rolling shutter casing or a wall

ACR: Air change rate per hour [h^{-1}], includes ventilation airflows and infiltrations

ELV: Exposure limit value

DCV: Demand-controlled ventilation

Dose: directly related to health this indicator is also called “cumulative exposure” or “exposure”. Used to define dose-response relationships.

A_{env} : Building envelope area excluding the lowest floor [m^2]

C_L : The air leakage coefficient [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{Pa}^{-n}$]

n_{50} : Air leakage rate at 50 Pa [h^{-1}]

Δp : Pressure difference [Pa]

q_{a4} : Building envelope air leakage rate at 4 Pa, normalized by the envelope area A_{env} [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$]

q_{50} : Air leakage rate at 50 Pa, normalized by the surface area of the measured wall [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$]

IQR: Interquartile range [-]

1

Introduction

1.1 Context and problem statement

Europe is on the way of mandating zero net energy homes, through the energy performance building directive (European Parliament, 2010). Such energy-efficient homes require a rethinking of their ventilation strategies, because of ventilation's large impact on the heat balance and associated conditioning energy in homes. For these high-performance homes, envelope airtightness treatment becomes crucial (Erhorn et al., 2008) and should be combined with efficient ventilation technologies.

Indoor air quality is another major area of concern in buildings which is directly linked to ventilation. Because people spend 60-90% of their life in indoor environments (homes, offices, schools, etc.) indoor air quality is a major factor affecting public health (Klepeis, 2001; "Communiqué de presse - Indoor air pollution: new EU research reveals higher risks than previously thought," 2003; Brasche and Bischof, 2005; Zeghnoun et al., 2010; Jantunen et al., 2011). Logue et al. (2011b) estimated that the current damage to public health in disability-adjusted life years (μ DALY) per person per year from all sources attributable to IAQ, excluding second-hand smoke (SHS) and radon, was in the range somewhere between the health effects of road traffic accidents (4,000 μ DALY/(pers.year) and heart disease from all causes (11,000 μ DALY/(pers.year). According to the World Health Organization (WHO, 2014), 99,000 deaths in Europe and 81,000 in the Americas were attributable to household (indoor) air pollution in 2012. Health gains in Europe (EU-26) attributed to effective implementation of the energy performance building directive, which includes indoor air quality issues, have been estimated at more than 300,000 DALYs per year.

The need of "performance-based" approaches for residential ventilation

In this context, in new labels and future building regulations, building performance should be extended to indoor environment quality, beyond energy performance. In the energy performance field, successive regulations pushed to a "**performance-based" approach**, based at least on an energy consumption requirement for heating and/or cooling at the design stage (Spekkink, 2005). Nevertheless, in the building ventilation field, regulations throughout the world are mainly still based on "**prescriptive" approaches**, such as airflows or air change rates requirements (Dimitroulopoulou, 2012). As the list of identified indoor pollutants is long and may still increase, it has been impossible to create definitive IAQ indicators for standards and regulations governing residential buildings (Borsboom et al., 2016). The committee chair of ASHRAE Standard 62-1989 (ASHRAE, 1989) has noted that the minimum ventilation requirement of 7.5 L/(s.pers) was based on body odor control (Janssen, 1989), and that this minimum was increased to 10 L/(s.pers) in many building types to account for contaminants other than human bio-effluents, such as building materials and furnishings. However, no specific methodology articulating the justification of this increase is noted. As a result, standards and regulations generally set ventilation rates based on comfort considerations and not on health criteria as suggested in the Healthvent project (Seppanen and et. al., 2012; Wargocki, 2012). The trouble with this approach is that it assumes that in addition to displacing human bio-effluents including odors, ventilation is a sufficient mean of controlling other contaminants (Matson and Sherman, 2004 and Persily, 2006). Against such prescriptive approaches, it is possible to develop **performance-based approaches** for residential building ventilation. Regarding the fact that prescribed ventilation rates are only an (unperfected) way to achieve a given IAQ, it could be imagined to require IAQ performance indicators instead of ventilation rates. The performance-based approach concept is illustrated on Figure 1.

"Turn left at the next traffic lights, then take the fourth street to the right, go right ahead at the first roundabout, turn to the right at the second roundabout and keep the left lane, then turn"



Spekkink, D. 2005. Key note presentation on PeBBu, CIB Conference, Helsinki, 2005

"To the airport!"



Spekkink, D. 2005. Key note presentation on PeBBu, CIB Conference, Helsinki, 2005

Figure 1. Illustration of (a) a prescriptive approach; (b) a performance-based approach. Source : (Spekkink, 2005)

"Performance-based" approaches for ventilation would insure that it is designed to avoid risks for occupant's health and building damages. Such an approach could be required at different scales:

1. At the ventilation system scale: for allowing the use of an innovative ventilation system instead of "reference" systems. "Reference" ventilation systems are usually defined as the widely used ventilation systems, or the ventilation systems directly providing the constant airflows required by the regulation. In this case, standardized input data and scenarii should be used,
2. **At the building scale: at the design stage of a building, input data from the given building should also be used.**

Such approaches could also be used at different stages of the building's construction:

1. At the design stage, as a design method;
2. **Later at the end of design stage, during the regulatory compliance stage, to assess the design. It could be called a design assessment method;**
3. At initial commissioning, or later once the building is occupied, as an in-situ performance assessment method.

If we compare to the energy performance field, the design method is the detailed energy simulation performed to optimize the energy consumption of the building, the design assessment method is the regulatory energy performance calculation based on simplified assumptions and a limited number of performance indicators, complete in-situ performance assessment methods are rare but could be based on several measurements (airleakage test, wall thermal conductivity, energy consumption, ...).

Facing a lack of data about the relevant method for ventilation, we propose in this PhD thesis to develop a performance-based approach for assessing ventilation performance at the building scale and at the end of the design stage, as does an energy performance regulatory calculation. We propose also to be at the regulatory compliance stage (number 2) as developed just above.

In order to develop such a performance-based approach, we need to address the following topics:

1. What are the relevant pollutants and/or parameters to use for calculating performance indicators and what indicators should be used?
2. What are the relevant input data to use regarding the occupancy and pollutant emission scenarii?

3. Lastly, what level of detail should we use for modelling airflows and pollutants throughout the house, concerning general modelling assumptions (multizone, weather data, ...), the airleakage distributions, the moisture buffering effect?

The following scheme proposed in Figure 2 gives an overview of this performance-based approach.

It is important to divide the inputs in two categories:

1. The ones which correspond to “standard” data, called “Standard conditions and scenarii”,
2. The ones which are data from a given building due to design choices on this building, called “Building design data”.

Each of these three steps constitutes a scientific barrier that we propose to come down in this PhD thesis.

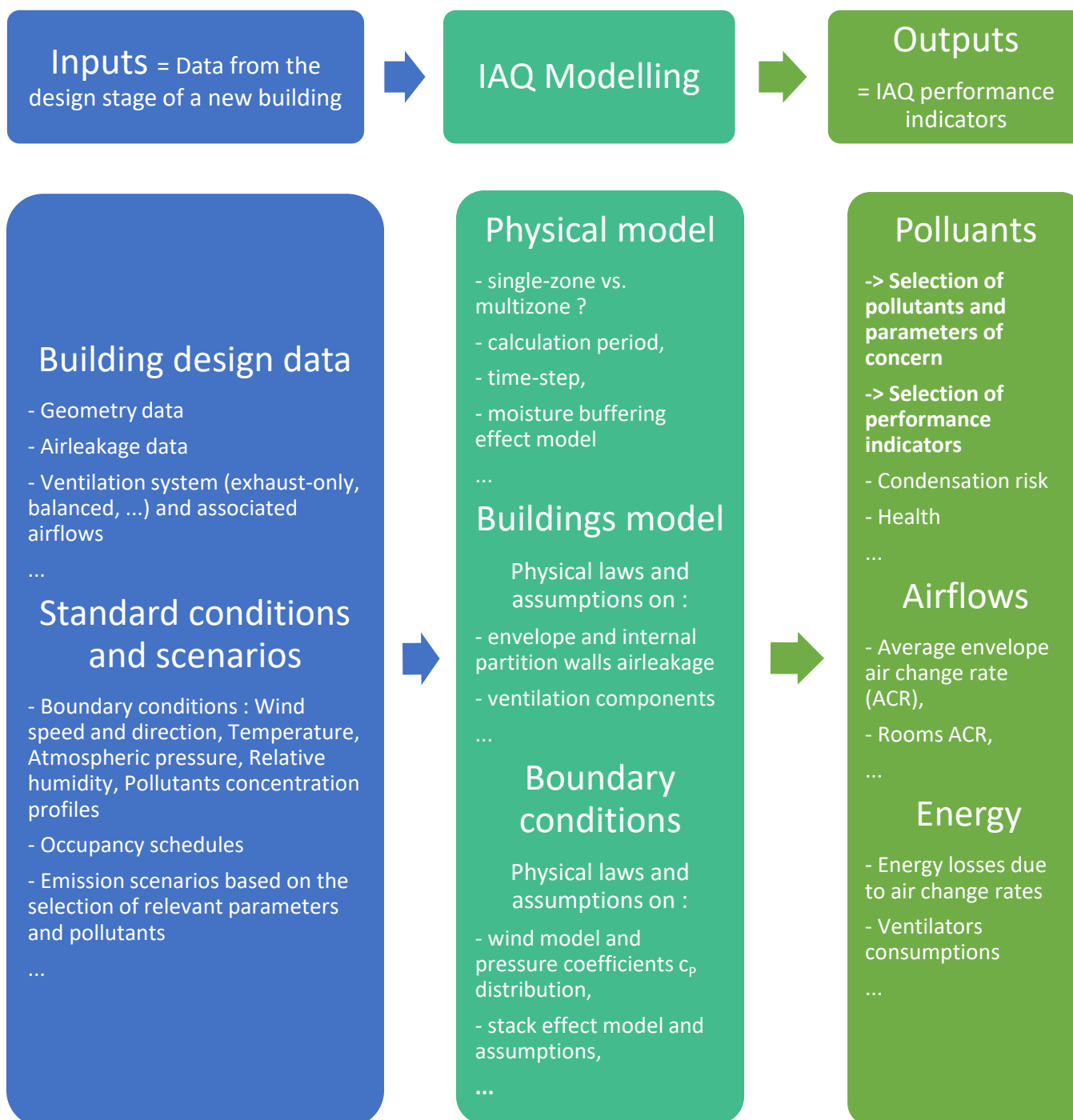


Figure 2. Scheme illustrating a performance-based approach for ventilation.

Impact of detailed airleakage distributions on ventilation performance

The last point presented above “3. Lastly, what level of detail should we use for modelling airflows and pollutants throughout the house”? includes the study of the impact of detailed airleakage distributions on the ventilation performance. Indeed, given the European context with the

generalization of nearly zero energy buildings in 2020, envelope airtightness is often included in energy performance (EP) calculations executed at the design stage of a building, generally through single-zone models with uniform envelope airleakage, as it is the case in France (JO, 2011). However, envelope air leakage is known to entail thermal losses, but also to modify theoretical voluntary airflow circuits in a building. Several authors confirmed that envelope airtightness promotes better IAQ in low-energy homes especially with mechanical ventilation, because the theoretical airflow circuits in buildings are better controlled (Boulanger et al., 2012b; Koffi, 2009; Laverge and Janssens, 2013). Indeed, airleakage interferes with theoretical mechanical ventilation airflows and thus can affect IAQ. Theoretically, general mechanical ventilation in French dwellings is based on fresh air inlets in bedrooms and in living room and exhaust air outlets in “humid” rooms (kitchen, bath, toilets) (Figure 3a). Ventilation in new homes in Middle and North-Europe, is very often based on such a whole-house ventilation strategy (Kolokotroni, 2008; Sowa, 2008; Wouters et al., 2008; Dimitroulopoulou, 2012). However, with exhaust-only ventilation systems, high airleakage on exterior walls of the humid rooms could short-circuit bedrooms, which could become under-ventilated. When this airleakage is unevenly distributed, IAQ impacts can be even stronger: if a room is very leaky (living room in Figure 3b), the other rooms can also be short-circuited and become under ventilated (bedrooms in Figure 3b). Nevertheless, this impact of unevenly distributed envelope airleakage is rarely investigated since it is often considered as evenly distributed in standards (CEN, 2007a; CEN, 2009) and in literature on ventilation performance (Boulanger et al., 2012b; Laverge et al., 2013; Laverge and Janssens, 2013).

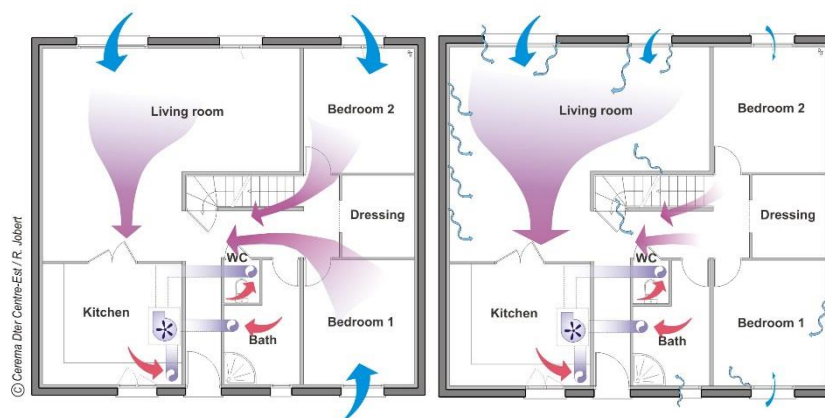


Figure 3. (a) Theoretical ventilation airflows in a dwelling and (b) Short-circuiting due to non-uniformly distributed envelope airleakage. Source: (Carrié et al., 2006).

Moreover, because more consideration is often given to energy performance than to IAQ issues, air leakage through internal partition walls is often disregarded. The rare authors considering this issue (Laverge et al., 2013; Laverge and Janssens, 2013; Roldan et al., 1987) take into account evenly distributed internal partition walls airleakage.

Some experimental studies showed however that envelope airleakage was not evenly distributed and that internal airleakage was unneglectable (Bossaer et al. 1998; Du et al. 2012; Guyot, Limoges, and Carrié 2012). As a result, additional research is needed both to get precise data on these uneven external and internal airleakage distributions and to quantify their impacts on IAQ as suggested by (Bekö et al., 2010; Koffi, 2009).

1.2 Thesis objectives and methodology

The two objectives of this thesis are:

1. Develop a performance-based approach for ventilation to be used at the design stage of a low energy house, including the three steps identified before as three scientific barriers to come down in this PhD thesis,
2. Quantify impacts of a multizone modelling taking into account uneven distributions of envelope and internal partition walls airleakage on this ventilation performance assessment.

Because this specific field has been shown as worthwhile for identifying both existing performance-based approaches for ventilation and performance indicators, the “smart ventilation” concept will be investigated in this thesis. Smart ventilation has been defined as “*a process to continually adjust the ventilation system in time, and optionally by location, to provide the desired IAQ benefits while minimizing energy consumption, utility bills and other non-IAQ costs (such as thermal discomfort or noise)*”(Durier et al., 2018). The demand-controlled ventilation (DCV) concept is a specific subset of smart ventilation. DCV systems generally use indicators of demand for ventilation, such as excess CO₂ or humidity, to control a ventilation system either by switching the airflows, or by continuously adapt them to the sensed parameter. Residential smart ventilation concept was investigated as a visiting researcher at the Lawrence Berkeley National Laboratory.

More specifically, we will perform an analysis of the building ventilation regulatory context in many countries in order to identify if some propose performance-based approaches. Indeed, analysis of those approaches could reveal emission scenarii, modelling laws and assumptions and indicators taken into account, which could inspire our work. This work has been published in *International Journal of Ventilation* (Guyot et al., 2018b).

We will also conduct a meta-analysis on the performance reported in 38 studies of various residential smart ventilation systems since 1983, in order to identify performance indicators used to assess the global performance of smart ventilation. As the advantages of using smart ventilation strategies are studied in this part of literature, often compared to traditional ventilation strategies, this is a worthwhile feedback to know which energy and IAQ performance indicators could be used. This work has been published in *Energy and Building* (Guyot et al., 2017).

Our review of both existing performance-based approaches and ventilation performance indicators in residential smart ventilation strategies will also be the starting point of this PhD work. It will be presented in the “*Part 2 - Review of existing performance-based approaches and ventilation performance indicators in residential smart ventilation strategies*”, based on these two published papers.

Once we will know more about performance-based approaches and used IAQ performance indicators, we will focus on the pollutant and airflows modelling issue. As soon as we model airflows in residential buildings, as introduced before, the airleakage becomes an essential input parameter to consider. If the energy performance calculations are generally based on single-zone models with uniform envelope airleakage, as it is the case in France (JO, 2011), we will see in Part 2 that multizone modelling were usually used in performance-based approaches for ventilation. Indeed, airleakage interferes with theoretical mechanical ventilation airflows and thus can affect IAQ in each room. We just referred in

the introduction to (Bekö et al., 2010; Koffi, 2009) who suggested that additional research was needed both:

1. to get precise data on these uneven external and internal airleakage distributions,
2. to quantify their impacts on IAQ.

To answer the point 1, we need firstly to get precise data on external and internal airleakage distributions. We will organize an experimental study on multizone air leakages in some twenty low-energy houses. We will measure the airleakage of each external and internal partition wall of the houses, with a high level of confidence. We will build corresponding airleakage database, analyze it, and identify airleakage values and dispersion data to be used as input data for multizone IAQ models. This work has been published in *Building and Environment* (Guyot et al., 2016) and will be presented here in the *Part 3 – Development of an original database from multizone airleakage measurements in twenty-three homes*.

In a second step to answer the point 2, in Part 4, we will use this data as input in a multizone modelling, in order to quantify impacts on several IAQ performance indicators. This part of the work has been submitted (G. Guyot et al., 2018a) and will be presented here in the *Part 4 – Impact of multizone airleakage modelling on ventilation performance and indoor air quality assessment in low-energy houses*.

Lastly, we will propose, in the *Part 5 - Towards performance-based approach for ventilation – proposed methodology*, a performance-based approach for assessing ventilation performance at the design stage of a residential building, as does an energy performance regulatory calculation. In order to develop such a performance-based approach, we will address the following topics:

1. Step 1: What are the relevant pollutants and/or parameters to use for calculating performance indicators and what indicators should be used?
2. Step 2: What are the relevant input data to use regarding the occupancy and pollutant emission scenarii?
3. Step 3: What level of detail should we use for modelling airflows and pollutants throughout the house, concerning general modelling assumptions (multizone, weather data, ...), the airleakage distributions, the moisture buffering effect?

In this Part 5 of the thesis, we will propose a method based on a literature review and on complementary analysis to answer each of these three questions, constituting an existing scientific barrier that we would like to come down. Then, we will apply the proposed performance-based approach on a case study to check its applicability.

2

Review of existing performance-based approaches and ventilation performance indicators in residential smart ventilation strategies

As introduced before, performance-based approaches have been used for assessing residential smart ventilation strategies, considered as innovative systems, in some regulations and standards through the world. The goal of such existing approaches is to allow the use of an innovative ventilation system instead of a reference system, often a constant airflow one. The authorisation can be considered either relatively to an IAQ regulation or standard, or to an energy performance regulation or standard. Such existing approaches include also an assessment of the IAQ and/or the energy performance provided by an innovative ventilation system, through calculation methodologies using standardized input data and performance indicators. The calculated indicators can be compared either to absolute given thresholds, or to values obtained with “reference” ventilation systems, to be sure they are at least “equivalent”, *i.e.*, they provide at least the same IAQ and/or energy performance. Our review of existing performance-based approaches to ventilation in some regulations levels emission and occupation scenarii, multizone modelling levels and performance indicators taken into account.

We will also review the literature focusing on IAQ and energy performance assessment of residential smart ventilation strategies. Especially because this part of literature focusses on comparing those smart strategies to traditional ones, and consequently uses a diverse range of performance indicators. For our purpose, this part of literature will also provide interesting data on the used IAQ performance indicators for ventilation performance assessment.

Our review of both existing performance-based approaches and ventilation performance indicators in residential smart ventilation strategies will also be the starting point of this PhD work. They are presented in this Part 2, based on two review papers published in *International Journal of Ventilation* (Guyot et al., 2018b) and in *Energy and Building* (Guyot et al., 2018a).

Performance based approaches in Standards and Regulations for smart ventilation in residential buildings: a summary review

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As ventilation systems become more sophisticated (or “smart”) standards and regulations are changing to accommodate their use. A key smart ventilation concept is to use controls to ventilate more at times it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. This paper discusses the favorable contexts that exist in many countries, with regulations and standards proposing “performance-based approaches” that both enable and reward smart ventilation. The paper gives an overview of such approaches from five countries. The common thread in all these methods is the use of metrics for the exposure to an indoor generated parameter (usually CO₂), and condensation risk. As the result, demand-control ventilation strategies (DCV) are widely and easily available on the market, with more than 20-30 systems available in some countries.

Keywords: Ventilation, indoor air quality (IAQ), energy performance (EP), residential buildings, DCV

Introduction

Energy-efficient homes have low envelope losses making ventilation and natural infiltration an increasing fraction of the overall energy use. Therefore, more effort is required on the treatment of air flows to reduce energy impacts is of increasing importance. For high performance homes, envelope airtightness treatment becomes crucial (Erhorn et al., 2008) and should be combined with efficient ventilation technologies.

Indoor air quality (IAQ) is another major area of concern in buildings which is influenced by ventilation. Indoor air quality is a major factor affecting public health because people spend

most of the time in residential buildings (Klepeis et al., 2001), especially in their bedrooms (Zeghnoun et al., 2010), and 60-90% of their life in indoor environments (homes, offices, schools, etc.) (Klepeis et al., 2001; “Communiqué de presse - Indoor air pollution: new EU research reveals higher risks than previously thought,” 2003; Brasche and Bischof, 2005; Zeghnoun et al., 2010; Jantunen et al., 2011). (Logue et al., 2011) estimated that the current damage to public health from all sources attributable to IAQ, excluding second-hand smoke (SHS) and radon, was in the range of 4,000–11,000 μ DALYs (disability-adjusted life years) per person per year. By way of comparison, this means the damage attributable to indoor air is somewhere between the health effects of road traffic accidents (4,000 μ DALYs/p/yr) and heart disease from all causes (11,000 μ DALYs/p/yr). According to the World Health Organization (WHO, 2014), 99,000 deaths in Europe and 81,000 in the Americas were attributable to household (indoor) air pollution in 2012. Health gains in Europe (EU-26) attributed to effective implementation of the energy performance building directive, which includes indoor air quality issues, have been estimated at more than 300,000 DALYs per year.

Today we ventilate our buildings to provide a healthy and comfortable indoor environment, with attention to health, moisture and odor issues. Indoor pollutant sources include outside air, occupants and their activities, and the furnishings and materials installed in buildings.

As the list of identified indoor pollutants is long and may still increase, it has been impossible to create definitive IAQ metrics for standards and regulations governing residential buildings (Borsboom et al., 2016). Consequently, IAQ performance-based approaches for ventilation at the design stage of a building are rarely used. Instead, prescribed ventilation rates have been used, assuming that at the same time they would control human bio-effluents, including odors, they would control also any other contaminant as well (Matson and Sherman, 2004). As a result, standards and regulations, such as ASHRAE 62.2-2016 and others in Europe (Dimitroulopoulou, 2012), often prescribe ventilation strategies requiring three constraints on airflow rates:

1. A constant airflow based on a rough estimation of the emissions of the buildings, for instance one that considers size of the home, the number and type of occupants, or combinations thereof;
2. Minimum airflows (for instance during unoccupied periods);
3. Sometimes also provisions for short-term forced airflows to dilute and remove a source pollutant generated by activities as cooking, showering, house cleaning, etc.

In order to conciliate energy saving and indoor air quality issues, interest in a new generation of smart ventilation systems has been growing. Thanks to “performance-based approaches”, such systems must often be compared either to constant-airflow systems (“equivalence approaches”) or to IAQ metrics thresholds.

This paper provides a review of performance-based approaches used in five countries for the assessment of smart ventilation strategies. We can identify two types of approaches. The United States and Canadian (CAN/CSA-F326-M91 (R2014) - Residential Mechanical Ventilation

Systems) standards specify ventilation systems on a building-by-building basis and allow a range of system designs - so long as they meet minimum requirements for airflow sound, etc. Other countries certify ventilation system designs that can then be applied to any building.

The present paper is a part of the project called “Smart Ventilation Advanced for Californian Homes” further developed in (Guyot et al., 2017b). This report includes a literature review on the suitability of common environmental variables (pollutants of concern, humidity, odours, CO₂, occupancy) for smart ventilation applications, the availability and reliability of sensors, the description of available control strategies. Next, a meta-analysis of 38 studies on smart ventilation used in residential buildings, develops the energy and indoor air quality performances, data on the occupant behaviour and on the suitability of a multizone approach for ventilation.

Smart ventilation and demand-controlled ventilation (DCV) definitions

The key smart ventilation concept is to use controls to ventilate more at times it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. The fundamental goal of this concept is to reduce ventilation energy use and cost while maintaining the same IAQ level (or improving IAQ) compared to a continuously operating system.

The concept of “Demand-controlled ventilation (DCV)” is a specific subset of smart ventilation. Such strategies have been widely used in scientific literature and in materials associated with available technologies over 30 years. Different definitions of DCV are available. According to the IEA Annex 18, DCV denotes continuously and automatically adjusting the ventilation rate in response to the indoor pollutant load (Mansson et al., 1997). (Limb M.J, 1992, p. 36) defines a DCV strategy as *“a ventilation strategy where the airflow rate is governed by a chosen pollutant concentration level. This level is measured by air quality sensors located within the room or zone. When the pollutant concentration level rises above a preset level, the sensors activate the ventilation system. As the occupants leave the room the pollutant concentration levels are reduced and ventilation is also reduced”*.

A recent meta-analysis of 38 studies of various smart ventilation systems with control based on either CO₂, humidity, combined CO₂ and TVOC, occupancy, or outdoor temperature shows that ventilation energy savings up to 60% can be obtained without compromising IAQ-even sometimes improving it (Guyot et al., 2017a). However, the meta-analysis did include some less-than favourable results, with energy over-consumption of 26% in some cases.

The concept of “smart ventilation” more recently developed in the LBNL is another subset of smart ventilation. It was developed in order to control fans to minimize energy use (Sherman and Walker, 2011; Walker et al., 2011; Turner and Walker, 2012; Walker et al., 2014). This smart ventilation concept uses the equivalent ventilation principle (Sherman and Walker, 2011; Sherman

et al., 2012) further developed in the paper, to allow for modulation of ventilation airflows in response to several factors, including outdoor conditions, utility peak loads, occupancy, and operation of other air systems. One incarnation of smart ventilation developed by LBNL is the “RIVEC” system that controls a ventilation fan based on real-time calculation of dose and exposure relative to a continuously operating fan. Figure 1 is an illustrative example showing operation of a RIVEC controlled fan that combines forced fan off times with response to operation of other fans.

Ventilation energy savings were estimated to be at least 40% by studying diverse climates (16 California climate zones), various home geometries and values for envelope airtightness to give a good representation of the majority of the Californian housing stock. This reflects absolute energy savings between 500 and 7,000 kWh/year per household with a peak power reduction up to 2 kW in a typical house (Turner and Walker, 2012).

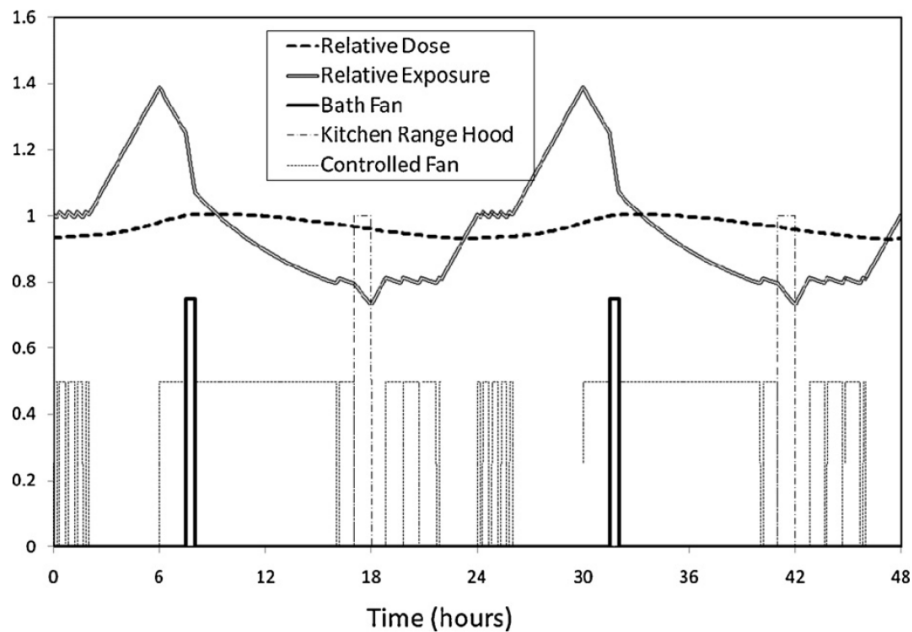


Figure 1 : Simulated controlled whole-house ventilation fan (continuous exhaust) with RIVEC and other household fan operation during the winter, source : (Sherman and Walker, 2011)

Overview on standards and regulations for residential buildings integrating smart ventilation

A number of ventilation standards and national regulations have progressively integrated an allowance for smart ventilation strategies and/or DCV systems in residential buildings. Simultaneously, energy performance regulations include the opportunity to claim credit in energy calculations for savings from such systems. In 2004 in the United States a federal technology alert

concluded that the HVAC systems in buildings should use DCV to tailor the amount of ventilation air to the occupancy level, for energy and IAQ reasons (Federal Technology Alert, 2004). Some years later, an update to the ventilation standard ASHRAE 62.2 (ANSI/ASHRAE, 2013) allowed the use of smart ventilation technologies. However, in the US, building energy codes and rating system do not explicitly include the effects of smart ventilation controls. In Europe, several countries enable the use of DCV systems in ventilation codes, including Belgium, France, Spain, Poland, Switzerland, Denmark, Sweden, the Netherlands, Germany (Savin and Laverge, 2011; Kunkel et al., 2015; Borsboom, 2015).

Smart ventilation and/or DCV systems must generally prove their IAQ performance through a performance-based approach, in order to comply with the ventilation regulation and get a credit in the energy-performance regulatory calculation.

Pushed by the international movement toward nearly-zero energy buildings, smart ventilation system success is not about to end. In Europe, two recently published directives n°1253/2014 regarding the eco-design requirements for ventilation units and n°1254/2014 regarding the energy labelling of residential ventilation units (European Parliament and the Council, 2014) are moving toward a generalization of low-pressure systems, DCV systems and balanced heat recovery systems by 2018. According this second directive, for central- and local-DCV systems, it will be possible to use a correction factor of 0.85 and 0.65, respectively, in the energy consumption calculation performed specifically for this labelling.

Given these opportunities, DCV strategies have been used at massive scale, notably in France and in Belgium, for more than 30 years. As of August 1st 2016, between 20 and 40 DCV systems have received an agreement in France, Belgium, and the Netherlands. Most of them are CO₂ or humidity-based strategies.

IAQ performance-based approaches for smart ventilation used in residential buildings

IAQ performance-based approaches could be used in many ways. Each country uses different indicators, calculated with different methodologies and compared to different thresholds, as shown in Table 2. The common thread in all of these methods is the use at a minimum, of the exposure to a pollutant generated indoors (very often the CO₂) and condensation risk. A minimum airflow rate for unoccupied periods is also often required.

In the United States, the equivalence principles in ventilation and indoor air quality described in (Sherman, 2004; Sherman et al., 2012) have been partially integrated in the current version of the ventilation standard ASHRAE 62.2 2016. Some state building regulations, such as the Title 24 energy-performance regulation in California, require compliance with this standard. This standard gives a method to calculate the minimum constant airflows for residential buildings. It also allows the use of variable volume mechanical ventilation, which could be: 1) ventilation averaged over short periods, 2) scheduled ventilation or 3) ventilation continuously controlled in real time. In the first strategy, total airflow rate equivalence is required over any three-hour

period. This allows for switching off the ventilation system during short periods if high airflow rates can be performed later. In any of the three cases, the equivalent ventilation principle is required: the annual exposure must be not higher than that produced by constant airflow systems. The calculations use single zone modelling, with a constant pollutant emission rate, and a time-step no longer than one hour. At each time step i , the relative exposure R_i is calculated from Equation 1 and Equation 2, and shall not exceed a value of 5 in order to avoid peak exposure. The annual average relative exposure must be less than one. The manufacturer, specifier or designer is supposed to certify that the calculation meets the requirements.

$$R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i} \right) e^{-Q_i \Delta t / V_{space}} < 5 \quad \text{if } Q_i \neq 0$$

Equation 1

$$R_i = R_{i-1} + \frac{Q_{tot} \Delta t}{V_{space}} < 5 \quad \text{if } Q_i = 0$$

Equation 2

$$R_0 = 1$$

Equation 3

Where Q_{tot} is the minimum constant ventilation rate calculated according to section 4.1 of the ASHRAE 62.2, Q_i is the real-time airflow in the variable mechanical ventilation system at time step i , Δt is the time-step used in the calculation, V_{space} is the volume of the space.

In France, manufacturers must follow a compliance procedure for DCV to ensure adequate ventilation. Once a system receives certification of compliance via this procedure, called “Avis technique”, it can be used in new dwellings according to its specifications. The agreement is a document of at least 30-60 pages which specifies how the system must be designed, how all the components of the system, including the inlets, outlets and ducts, must be installed, and precisely how the system must be commissioned and maintained. For each type and size of dwelling, the agreement gives the references of inlets and outlets and the input data for energy calculation. The procedure (CCFAT, 2015) describes the common scenario used to evaluate the DCV systems using the multizone software MATHIS (Demouge et al., 2011). Each room of the dwelling is modeled as single zone, with a time-step of 15 min. This procedure is based on the evaluation of humidity-based DCV systems having a widespread use for more than 30 years and thus must be adapted for other types of DCV systems. Typical input data given in the procedure include:

- External data: calculation period (October 1st-May 20th), outdoor CO₂ concentration, meteorological data and wind effects parameters. Only the heating season is considered

because it is assumed that window opening is influencing the CO₂ concentrations for the rest of the year. This approach is also used in the Belgian and Netherlands regulations;

- The dwellings: geometry of the 24 representative dwellings, airtightness of the dwellings and its distribution on the different facades);
- The occupancy scenario: metabolic emission rates of CO₂ and humidity, number of occupants, occupancy schedules, activity levels, and associated moisture emission rates;
- The ventilation components: trickle ventilators positioning, aeraulic characteristics of hygrovariable air inlets and outlets, effects of external and internal temperatures being taken into account as well, schedules for toilets exhausts, schedules for high-speed kitchen exhausts.

Firstly, the cumulative CO₂ exposure indicator E_{2000} (Equation 4) must be calculated and must be under 400,000 ppm.h in each room. This threshold is supposed to represent the mean cumulative exposure under a constant ventilation strategy, although the exact source of this number is not readily available in the literature.

$$E_{2000} = \sum_{t=0}^T C_{CO_2 > 2000}(t) * t < 400\ 000\ ppm.h$$

Equation 4

Where $C_{CO_2 > 2000}(t)$ is the absolute concentration in the room at t time-step, if it is higher than 2000 ppm.

Second, the number of hours when relative humidity is higher than 75%, $T_{RH > 75\%}$, must be calculated. This value is representative of the condensation risk (Equation 5).

$$T_{RH > 75\%} = \sum_{t=0}^T t < 600\ h\ in\ kitchen, 1000\ h\ in\ bathrooms, 100\ h\ in\ other\ rooms$$

Equation 5

Once both IAQ requirements are fulfilled, an “energy calculation” can be performed. This gives the conventional input data, the mean equivalent exhausted airflow ($m^3.h^{-1}$) and the total air inlet mean area (m^2), to be used in the energy performance (EP) calculation of each designed new dwelling. The EP calculation is a single zone modelling calculation. The detailed performance-based approach is performed once for each new DCV system, in order to be later taken into account in each dwelling EP-calculation as average values. The ventilation system may not be switched off during unoccupied periods, the trickle ventilators cannot be closed, and the total minimum airflow is set between 10 and 35 $m^3.h^{-1}$ according to the number of rooms in the building. The agreement is obtained for a 3-years period, after which it is recalculated in order to

take into account possible updates in regulations, agreement procedure, and available knowledge and technologies.

In Spain, the procedure is very close to the French one and shares the performance-based approach. Because of current regulations are expressed as constant ventilation flows, DCV systems must pass through a compliance procedure. Once a system receives agreement certificated of compliance, called "Documento de Idoneidad Técnica" (DIT), it can be used in new dwellings according to its specifications. The DIT is a document of about 30 pages that specifies how the system must be designed, how components of the system such as inlets, outlets and ducts, must be installed, and precisely how the system must be commissioned and maintained. For each type of dwelling and climate, the DIT gives the product number of air inlets and outlets, and the input data for energy calculations in the form of an equivalent reduction of constant ventilation flow rates specified in the current regulations. The DIT is adopted for a 5-year period and subject to yearly reviews. The compliance assessment involves reference scenarios: each room of the dwelling is modelled as single-zone with the multizone software CONTAM (Walton and Emmerich, 1994), with a time-step of 40 seconds. Standardized input data are given which include:

- External data: calculation period (all year), outdoor CO₂ concentration, meteorological data;
- The dwellings: geometry of the 14 standard dwellings, air infiltration is not considered;
- The occupancy scenario: metabolic emission rates of CO₂ and humidity, number of occupants, occupancy schedules, a schedule of their activities and associated moisture emission rates;
- The ventilation components: trickle ventilators positioning, aerologic characteristics of hygrovariable air inlets and outlets, schedules for toilets exhaust.

As a result, if the following IAQ indicators can be achieved, the annually averaged ventilation airflow can be implemented in the EP-calculation:

- Annual averaged CO₂ concentration must be lower than 900 ppm,
- Annual cumulative CO₂ exposure over 1600 ppm E₁₆₀₀ (see Equation 4) must be lower than 500,000 ppm.h in each room.

Future changes to the building code are being reviewed (Linares et al., 2014; Garcia and Linares, 2015; Linares et al., 2015). The changes aim to implement a performance-based approach with respect to IAQ requirements at the design stage of each new building. The proposed IAQ requirements are the same ones that are used in the current procedure for DCV. They would also be calculated using a multizone code like CONTAM, with prescribed input data concerning human CO₂ generation, proposed occupancy schedules, and occupancy rate selected according to the

national population and 2011 housing census. The minimum airflow during unoccupied periods will be set to 1.5 l.s⁻¹ in each room.

In Belgium, the procedure for residential buildings was similar to the French and the Spanish ones until 2015. In order to get a credit in energy calculation, each new system had to pass through an IAQ equivalence procedure before receiving an agreement called “ATG-E”, delivered by a national organization (UBATC), then consolidated through a Ministerial Order in each region. The equivalence procedure was described in (ATG and BCCA, 2012) and was also based on a multizone modelling, with CONTAM (Walton and Emmerich, 1994) using a time-step of five minutes. The standardized input data were both deterministic (geometry of the typical house, air leakage, moisture buffering parameters, indoor temperature, exterior climate file, calculation period from October to April) and stochastic (building orientation, wind shielding and terrain roughness, occupancy scenario and contaminant generation). Contaminants considered were CO₂, relative humidity and a tracer gas emitted in toilet and in bathrooms each time these rooms are occupied, for five minutes. 100 datasets were used per level of envelope air leakage ($v_{50}=0.6; 3; 6; 9$ and $12 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$). The reviewed system was then compared to the three reference systems defined in the regulation (A=natural, C=exhaust, D=balanced). The IAQ performance was evaluated through three indicators: the per-person cumulative CO₂ exposure indicator E'_{950} (Equation 6), the time per month critical thermal bridges were exposed to relative humidity over 80% from December 1st to March 1st, the exposure to the tracer gas.

$$E'_{950} = \sum_{t=0}^T (C_{CO_2 > 950}(t) - 950) * t$$

Equation 6

Where $C_{CO_2 > 950}(t)$ is the absolute concentration at which an occupant is exposed at t time-step, if it is higher than 950 ppm.

Once the IAQ indicators have been calculated they must be equal or better than the worst IAQ performing reference system. Then, the energy savings coefficient f_{reduc} is calculated from Equation 7, based on the heating season integrated ventilation heat loss E (MWh/year), excluding infiltration heat losses which are treated separately in the EP-calculation method. E_x is calculated for the studied smart system X . E_{ref} is the energy use of a system that has the same CO₂ exposure indicator as the system being rated and is determined as shown in Figure 2.

$$f_{reduc} = \frac{E_x}{E_{ref}}$$

Equation 7

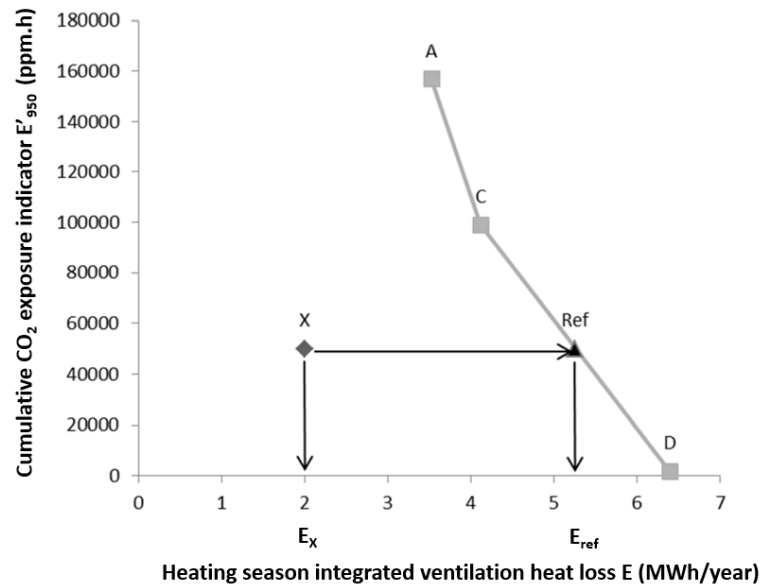


Figure 2 : Energy saving coefficient calculation for a DCV system X (ATG and BCCA, 2012)

In 2014, the Belgian regions considered DCV systems mature enough to be directly integrated in the EP-calculation method. A study (Caillou et al., 2014b) evaluated the 35 ATG-E approved systems. They improved the initial method by taking into account its limitations, such as the fact that the three reference systems defined in the regulation are not equivalent, which is illustrated on Figure 2. Authors added generation of a VOC pollutant emitted proportionally to the surface area of each room to the evaluation method and calculation of the cumulative exposure to this pollutant. Authors proposed classifying DCV systems according to the sensing type: type of sensor, type of spaces, local or centralized and the regulation type: exhaust only, supply only, balanced and local vs. centralized. For each class of DCV systems, they proposed standard values for the energy saving coefficient f_{reduc} . As a result, as of January 1st 2016, only the energy saving coefficient f_{reduc} given in the tables (Table 1) of an Ministerial Order (Moniteur Belge, 2015) can be used directly in the EP-calculation. This Order requires sensors to conform to the stipulations on accuracy and a minimum airflow over 10% of the minimum constant airflow for each room. Intermittent ventilation is allowed if the 15-minute average airflows is equal to this 10% requirement.

Type of detection in dry spaces	Type of regulation of air inlets in dry spaces	Local detection in humid spaces with regulation of air outlet Local regulation	Local detection in humid spaces with regulation of air outlet No local regulation	Other or no detection in humid spaces
CO₂-local : at least a sensor in each dry space	Local	0.35	0.38	0.42
	2 zones (night/day) or more	0.41	0.45	0.49
	Central	0.51	0.56	0.61
CO₂- partially local : at least a sensor in each bedroom	Central	0.60	0.65	0.70
CO₂- partially local : at least a sensor in the main bedroom + at least a sensor in the living room	2 zones (night/day) or more	0.43	0.48	0.53
	Central	0.75	0.81	0.87
CO₂-central : at least a sensor in the exhaust duct(s)	Central	0.81	0.87	0.93
Occupancy-local : at least a sensor in each dry space	Local	0.54	0.60	0.64
	2 zones (night/day) or more	0.63	0.67	0.72
	Central	0.76	0.82	0.88
Occupancy-partially local : at least a sensor in each bedroom	Central	0.87	0.93	1.00
Occupancy-partially local : at least a sensor in the main bedroom + at least a sensor in the living room	2 zones (night/day) or more	0.66	0.72	0.78
	Central	0.87	0.93	1.00
Other or no detection in dry spaces	No, local, per zone, or central	0.90	0.95	1.00

Table 1 : Energy saving coefficient f_{reduc} for all types of DCV systems (natural, exhaust-only, supply-only, balanced) used in residential buildings with a regulation of air inlets based on needs in dry spaces and/or with a regulation of air outlets based on needs in humid rooms (another table is available for exhaust-only systems with a regulation of air outlets based on needs in dry spaces)

In the Netherlands, for DCV systems used in residential buildings, it is possible to use correction factors on the ventilation airflow in the EP-calculation, based on the standard NEN 8088 (NEN, 2011). The standard provides standard energy reduction factors for quite a few DCV systems, ranging from 0.52 to 0.95. A complementary equivalence approach can be performed (VLA, 2013), using COMIS simulation software, in a semi-probabilistic approach (7 dwelling types, different occupant types, different airtightness levels, different wind exposure). The IAQ metric employed is the cumulative CO₂ exposure index requirement per person, LKI₁₂₀₀, calculated for the considered heating period September 29th-April 25th with Equation 8. For a new product type, manufacturers should submit their report to one of three predefined research institutes or consulting companies for review. At the end of the process, an agreement is published on the Dutch Association of Air Handling Equipment Manufacturers (VLA) website, and shortly thereafter a declaration of equivalence is published in the database of the Bureau of Control and Registration (Borsboom, 2015). A minimum air flow is prescribed according to the number and the type of occupants.

$$LKI_{1200} = \sum_{t=0}^T \left(\frac{C_{CO_2 > 1200}(t) - 1200}{1000} \right) * t < 30,000 \text{ ppm.h}$$

Equation 8

Where $C_{CO_2 > 1200}(t)$ is the absolute concentration at which an occupant is exposed at t time-step, if it is higher than 1200 ppm, or 800 ppm above the outdoor concentration.

Country	Person in charge	Ventilation Equivalence method	Calculated IAQ indicators	Credit in EP-calculation	Minimum airflow
USA (ASHRAE 62.2 2016)	The manufacturer, specifier or designer	Single zone modelling, $\Delta t < 1h$, constant pollutant emission rate	No specifically defined pollutant Yearly average relative exposure $R < 1$ At each time-step $R_i < 5$	No	Can be null if the total airflow rate equivalence is required over any 3-hour periods
France	The manufacturer for each (humidity) DCV system	Multizone modelling with MATHIS, $\Delta t = 15$ min, Conventional entry data	Per room, over the heating period: 1/CO ₂ cumulative exposure indicator $E_{2000} < 400,000$ ppm.h 2/Number of hours $T_{RH>75\%} < 600$ h in kitchen, 1000 h in bathrooms, 100 h in other rooms	Reduced average equivalent exhausted airflow (m ³ .h ⁻¹)	10-35 m ³ .h ⁻¹ according to the number of rooms in the building Switch off not allowed
Spain (<2017)	The manufacturer for each DCV system	Multizone modelling with CONTAM, $\Delta t = 40$ s, Conventional entry data	Per room, over the year: 1/ Yearly average CO ₂ concentration < 900 ppm 2/ Yearly cumulative CO ₂ exposure over 1600 ppm $E_{1600} < 500,000$ ppm.h	Reduced yearly average ventilation airflow	
Spain (future)	The designer of the building, of the base of information given by the manufacturer	A performance-based approach for all ventilation systems, using a software and conventional data at the design stage of each building	Per room, over the year: 1/ Yearly average CO ₂ concentration < 900 ppm 2/ Yearly cumulative CO ₂ exposure over 1600 ppm $E_{1600} < 500,000$ ppm.h	Reduced yearly average ventilation airflow	1.5 l.s ⁻¹ in each room during unoccupied periods
Belgium (< 2015)	The manufacturer for each DCV system	Multizone modelling with CONTAM, $\Delta t = 5$ min, conventional entry data both deterministic and stochastic	Per room, over the heating period: 1/CO ₂ cumulative exposure indicator E'_{950} 2/Monthly average RH $> 80\%$ on critic thermal bridges from December 1 st to March 1 st 3/Exposure to a tracer gas emitted in toilets and in bathrooms	An energy saving coefficient f_{reduc} is extrapolated	

			They must be at least equal that the worst performing reference system.		
Belgium (since 2015)	The person involved in EP-calculation and manufacturer for each DCV system	No-more existing. An advanced equivalence method has been performed by (Caillou et al., 2014) on all the 35 systems having an agreement.	No-more existing.	Published conventional energy saving coefficients used directly	10% of the minimum constant airflow for each room. An intermittent ventilation is allowed if the average on 15 minutes enables to comply with this 10%.
The Netherlands	The person involved in EP-calculation (standard approach) OR the manufacturer for each DCV system (equivalence approach)	For equivalence procedure : multizone code COMIS, in a semi-probalistic approach	Per person, over the heating period : Cumulative CO ₂ exposure over 1200 ppm: $LKI_{1200} < 30,000 \text{ ppm.h}$	Either, correction factors given in the standard for quite a few DCV systems OR Correction factors from the equivalence procedure	A function of the number of type of occupants

Table 2 : Overview of equivalence principles for smart ventilation and/or DCV in some residential building regulations

To our knowledge, only one study (Sherman et al., 2012) proposes consideration of an “IAQ equivalence” based on health-related metrics. The authors propose a method taking advantage of available data in previous work (Logue et al., 2011b, 2011a) and using the disability-adjusted life years (DALYs) metric. Based on disease incidence models, (Logue et al., 2011b) calculated the DALYs lost as a result of long-term exposure to indoor pollutants in residences and published values of the DALYs lost per incidence of disease. In this calculation, they used the unit damage estimate (UDE) value for each pollutant of interest. The “IAQ equivalence” also proposes use of these UDE_i values in order to set a DALY limit value (Equation 10) and then proposes checking that the combination of contaminant concentrations according to Equation 9 stays below this limit. (Sherman et al., 2012) evaluated this limit as 8,200 μ DALY per person per year for the pollutants in Table 3. It can be seen that $PM_{2.5}$ dominates this list. If radon, ozone, and $PM_{2.5}$ can be handled through prescriptive measures, the DALY limit decreases to 90 μ ALY/p/year. This approach is obviously limited, since it assumes that indoor contaminants of concern are clearly identified and prioritized. This equivalent methodology also needs to include acute exposure issues. Nevertheless, it could be integrated into evaluation methods for innovative smart ventilation systems, and even directly into the control of such systems with real-time sensors.

$$DALY = \sum_i Concentration_i * UDE_i$$

Equation 9

$$DALY_{limit} = \sum_i Standard_i * UDE_i$$

Equation 10

Compound	UDE $\left[\frac{\mu DALYS}{year * person} * \frac{m^3}{\mu g} \right]$	Chronic Standard $\left[\frac{\mu g}{m^3} \right]$	Chronic Standard damage $\left[\frac{\mu DALYS}{year * person} \right]$
Priority Pollutants			
1,3 Butadiene	0.02	0.06	0.001
1,4-dichlorobenzene	0.03	0.91	0.024
Acetaldehyde	0.3	3.7	0.96
Acrolein	190	0.02	3.7
Benzene	0.08	0.34	0.025
Formaldehyde	6.8	1.7	11.4
Naphthalene	0.47	0.29	0.14
Nitrogen Dioxide	0.70	40	27
$PM_{2.5}$	500	15	7,500
Other contaminants			
Ammonia	0.23	200	46
Ozone	1.4	147	200
Crotonaldehyde	1.02	N/A	N/A

Table 3: Indoor air contaminants – UDE_i and $Standard_i$ values in order to implement the IAQ equivalence principle according to Equation 9 and Equation 10 , source : (Sherman et al., 2012)

State of the art of the pollutant sensors used for smart residential ventilation

In smart ventilation strategies, sensors need to have a real-time output signal to allow the system to react and adjust the airflow. Selection of sensors for DCV applications should consider three criteria: Performance (whether the performance range can cover the typical IAQ range or guideline thresholds, whether resolution can meet the suggested level, and if the calibration frequency is not more than once a year), Cost and IAQ (the pollutant must be relevant and faced to an effective risk). The word “sensor” can refer to a single direct sensor or several components (filters, amplifiers, modulators of other signals). Many factors can affect sensor performance and should be considered in the choice of a sensor for smart ventilation applications, along with other factors such as size, extent of signal conditioning, reliability, robustness, maintainability, and cost (Bishop 2002).

An extensive Canadian review of the state of the art included sensors for CO₂, humidity, VOCs, formaldehyde, NO₂, SO₂, ozone, particulate matter and radon (Won and Yang, 2005) was updated in 2011 for formaldehyde sensors (Won and Schleibinger, 2011). Suggested performance and specifications of available sensors are summarized in Table 4 and Table 5, authors recommending that: 1) sensor minimum detection thresholds should be equal to the lower concentrations expected inside buildings, 2) sensor resolution and maximum drift between calibrations should be less than 10% of a typical indoor concentration, and 3) 30 minutes is a typical ventilation time constant and acceptable sensors should reflect this.

Table 4: Suggested performance levels of sensors for DCV (Won and Yang 2005)

Pollutants	Range of IAQ guidelines *	Typical range indoors	Sensor minimum detection limit	Sensor Resolution
CO ₂	800 - 3500 ppm	350 - 2000 ppm ** (often < 1000 ppm) **	350 ppm**	≤ 50 ppm **
Humidity (water vapour)	30 - 80% RH	10 - 80% RH ** (0.002 - 0.015 absolute humidity) **	10% RH **	≤ 5% RH **
NO ₂	0.002 - 0.13 ppm	0.01 - 0.05 ppm	2 ppb	≤ 1 ppb
SO ₂	0.005 - 0.15 ppm	0.0001 - 0.06 ppm	1 ppb	≤ 0.5 ppb
O ₃	0.03 - 0.06 ppm	0.002 - 0.06 ppm	2 ppb	≤ 1 ppb
VOCs (individual)	0.001 - 1 ppm	< 0.2 ppm	1 ppb	≤ 0.5 ppb
Formaldehyde	0.02 - 0.08 ppm	0.1 - 0.8 ppm	20 ppb	≤ 10 ppb
TVOC	0.8 – 2.5 ppm ***	0.02 - 1 ppm (usually < 0.2 ppm)	10 ppb	≤ 3 ppb
Particulate matter	20 - 180 ug/m ³	10 - 100 ug/m ³ **	10 ug/m ³ **	≤ 0.05 ug/m ³ **
Radon	2.7 - 5.4 pCi/L	1.3 pCi/L	1.3 pCi/L	≤ 0.7 pCi/L

* Table 3

** Fisk & De Almeida (1998)

*** The conversion was made from mg/m³, assuming the molecular weight of 100 at 23 °C.

Table 5: General specifications of commercial sensors (Won and Yang 2005)

Pollutants	Detection Range	Detection Limit	Accuracy	Resolution	Price (CAD\$)	Calibration	Method
CO ₂	0-5,000 ppm		±50 ppm or ±5%	1 ppm	~ \$500	Not required, but calibration every 5 years is recommended	Non-dispersive infrared (NDIR)
Humidity (RH)	0-90% RH		±2-3% RH	0.1%	< \$500	Not required, or once every 2 years	Thin film capacitive sensor
Humidity (dew point)	-20 to 50°C		±2°C		\$700	Not required, or once every 1 or 2 years	Calculated from RH measurements w/ thin film sensor
NO ₂	0-20 ppm		±2-5%	0.1 ppm	\$500 - > \$1,000	Not required, or once every 6 months or 1 year	Electrochemical
	0-0.05/0.2 ppm	50 ppt			>= \$10,000		Chemiluminescence
SO ₂	0-20 ppm		±2-5%		\$1,000-\$2,000	"	Electrochemical
O ₃	0-1 ppm		±2-5%		\$1,000-\$2,000	Once every 6 months or 1 year	Electrochemical
	0-0.17 ppm			1 ppb	\$1,000-\$2,000		Metal oxides
TVOC	0.02-20 ppm		±25%		\$5,000 (w/ T & RH)	Not required or every 6 months or 3 years	PID
Formaldehyde	0-2/10 ppm		±5%	0.01 ppm	\$2,000 - \$4,000	Not required, every 1 year	Electrochemical
A set of VOCs	low ppb - low ppm	low ppb			\$20,000 - \$35,000		An array of QCM, QMB, MOS, &/or SAW
Particle	0.3 - 25 µm	37-74 ppb*			\$4,000-4,500 (hand-held) > \$10,000 (portable)		Light scattering
	0.3 - 5 µm	5-55 ppb*			\$2,000-4,000		
Radon	0-1,000 pCi/L			1 pCi/L	\$150 - \$4,000	Once every 6 months or 1 year	Various

* The number concentration in Table 17 was converted to the mass concentration, assuming all particles have a size of 1 µm and a density of 1 g/cm³

CO₂ sensor technologies are not new; DCV strategies have existed for more than 30 years. Available technologies are mostly non-dispersive infrared sensors, but also include photoacoustic CO₂ sensors. Fisk (2010) studied the accuracy of 208 single-location CO₂ sensors in 34 commercial buildings. Even if the average errors were small (i.e., 26 ppm and 9 ppm, respectively, at 760 and 1,010 ppm), they found occasional respective absolute of errors of 118 at 760 ppm (16%) and 138 at 1,010 ppm (14%). Authors showed that there were also statistically significant differences between different technologies and manufacturers, and that sensor age was not statistically significant. These observations were confirmed by (Shrestha and Maxwell 2009), which reported numerous errors greater than 75 ppm; cases of errors greater than 200 ppm were not uncommon.

Unlike other pollutant sensors, CO₂ sensors can be considered quite easy to calibrate, since gas mixtures with necessary CO₂ concentrations can be accurately and readily manufactured using pure CO₂.

In the Belgian regulation for DCV strategies, a CO₂-based DCV system must include CO₂ sensors with a maximum uncertainty of 40 ppm + 5% of the target value, in the 300 ppm—1,200 ppm range (Moniteur Belge 2015). The non-residential requirements of California's Title 24 regulations state that "*the CO₂ sensors must be factory certified to have an accuracy of no less than 75 ppm over a five-year period without recalibration in the field.*"

Costs were evaluated in 2011 (Mortensen 2011) and found to be approximately 3000 DKK\$ (~\$450 US, ~400 EUR).

Humidity sensors are not new either, as such DCV strategies have been used at large scale, notably in France, for more than 30 years. Won and Yang's review (2005) refers to a previous study (Roveti 2001) that reviews the wide variety of sensors available on the market. In France, for more than 30 years, the market has largely been dominated by humidity-based DCV systems with mechanically variable inlet and outlet cross-sections (Savin, et al. 2014). Advanced materials are used, such as polyamidic fibre, which varies in length with the relative humidity. Polyamidic fibres are not classical sensors, but they could be described as "sensor-actuators"—worthwhile in a whole house ventilation strategy, but not interesting just as sensors. The proper operation of this type of inlet/outlet has been demonstrated in laboratories and the field by the project Performance (Air, H. 2010; Bernard 2009), through measurements over two complete heating seasons in 31 new occupied apartments. Depending on the manufacturer, lifetimes could be up to 30 years, including a warranty of approximately 10 years, without need for recalibration. These products are used not only in France but also in other European countries such as Spain, Poland, and Germany.

Belgian regulations for DCV strategies state that a relative humidity DCV system must include relative humidity sensors, each with a maximum uncertainty of 5% of the target value, in the 10%—90% RH range (Moniteur Belge 2015).

In their market survey, Won and Yang (2005) found that humidity sensors were usually combined with temperature sensors. The average measurement range was found to be between 0% and 90% with an accuracy of $\pm 2\%$ – 3% . A majority were thin film capacitive sensors, with a cost below that of CO₂ sensors (\$500 CAD, ~\$400 US, ~350 EUR). The humidity sensor-actuators described above are not reported in this market survey and are very low-cost (<20 EUR) with a long warranty.

VOC sensing in demand-controlled ventilation is relatively new because, until recently, VOCs could not be measured separately; multi-gas sensors were used instead. Won and Schleibinger (2011) noted cross-sensitivity as a major issue for VOC sensors. Datasheets published by manufacturers allow quantification of this cross-sensitivity issue. (Won and Schleibinger 2011) concluded that no commercial VOC sensor was yet precise and specific enough for ventilation applications. Kumar, et al. (2016) reviewed compact, light-weight, inexpensive sensors up to \$500 USD, with some under \$100 USD measuring carbon monoxide, benzene, and VOCs. Advanced technologies have been reviewed (Kumar, et al. 2016), including a miniaturized gas chromatography system for monitoring single volatile compounds in indoor air (Zampolli, et al. 2005). In Belgium, those wishing to employ a VOC sensor in bathrooms in a DCV system must prove that there is a correlation between the measured signal and human occupancy (Moniteur Belge 2015). Before beginning to study implementation of such a sensor on a large scale, Caillou, et al. (2014b) consulted several international experts in the field. In 2014, VOC-sensing technology was considered mature enough to be integrated into DCV technologies. A commonly cited problem is the difficulty associated with directly controlling and calibrating such a sensor, as opposed to a CO₂ sensor, for instance.

Other types of sensors such as formaldehyde, particle, NO₂, microelectronic mechanical sensors, nanosensors, multiple-parameter sensors, electronic nose, ozone, sulfur dioxide, and radon were described in Won and Yang's market survey (2005) and are not reported here because of their very limited use in residential applications.

Others topics are subjects of interest for smart ventilation performance and are developed in (Guyot et al., 2017b): occupancy sensors, data transmission, type of control (centralized or per-zone), the number and location of sensors, and control strategy algorithms.

Conclusions

This paper summarizes the strategies used in Europe and the US for development of smart ventilation strategies, such as demand-control ventilation strategies. The paper gives an overview of the regulations and standards proposing “performance-based approaches” in five countries to promote the use of smart ventilation strategies. The common thread in all of these methods is the use, at a minimum, of the exposure to a pollutant generated indoors (very often the CO₂) and condensation risk. As a result, more than 20 compliant DCV systems are available in countries such as Belgium, France and the Netherlands.

From this summary we found that there are areas of commonality between some countries:

- the use of cumulative CO₂ above a certain limit
- the use of mean CO₂ over a year (or other lengthy period)
- time above relative humidity thresholds
- simple pre-calculated multipliers for use in energy calculations.

However, IAQ Metrics vary from country to country and even if they have metrics in common (e.g., cumulative CO₂ above a certain level) the levels and target values are different. Similarly, the implementation in energy calculations also varies (e.g., using different times of the year for evaluation purposes). These differences make discussions about appropriate ventilation levels difficult, adds burden to manufacturers who have to go through multiple product approval procedures and it is a restraint on ventilation system innovation due to having to address multiple performance targets. Therefore, there is the need for a common metric, associated to a common evaluation method and the use of common target values. There is also a clear potential for the use of real-time controllers for IAQ but changes to energy calculation procedures would be required.

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Smart ventilation energy and indoor air quality performance in residential buildings: a review

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ABSTRACT

To better address energy and indoor air quality issues, ventilation needs to become smarter. A key smart ventilation concept is to use controls to ventilate more at times it provides either an energy or indoor air quality (IAQ) advantage (or both) and less when it provides a disadvantage. A favorable context exists in many countries to include some of the existing smart ventilation strategies in codes and standards. As a result, demand-controlled ventilation (DCV) systems are widely and easily available on the market, with more than 20 DCV systems approved and available in countries such as Belgium, France and the Netherlands. This paper provides a literature review on smart ventilation used in residential buildings, based on energy and indoor air quality performance. This meta-analysis includes 38 studies of various smart ventilation systems with control based on CO₂, humidity, combined CO₂ and total volatile organic compounds (TVOC), occupancy, or outdoor temperature. These studies show that ventilation energy savings up to 60% can be obtained without compromising IAQ, even sometimes improving it. However, the meta-analysis included some less than favorable results, with 26% energy overconsumption in some cases.

BACKGROUND

The present review paper is a part of the project called “Smart Ventilation Advanced for Californian Homes” (SVACH) further developed in the Lawrence Berkeley National Laboratory (LBNL) report (Guyot et al., 2017). This report addresses several aspects of smart ventilation: the suitability of various environmental variables for use as inputs in smart ventilation applications, the availability and reliability of the sensors used to measure these variables, a description of relevant control strategies, an overview of the regulations and standards proposing “equivalence methods” in order to promote the use of smart ventilation strategies, the available systems on the market in different countries, and a summary of

ongoing developments in research areas related to ventilation, including IAQ metrics and feedback from on-site implementations.

Through updates to California building codes, California is leading the way in reducing energy use in residential buildings, and is even on the way to mandating zero net energy homes. This is also the case in other municipalities, in Europe, for example, which has issued the energy performance building directive (European Parliament, 2010). Such energy-efficient homes require rethinking their ventilation strategies, because of ventilation's substantial impact on the heat balance and associated conditioning energy in homes. For these high-performance homes, envelope airtightness treatment becomes crucial (Erhorn et al., 2008) and should be combined with efficient ventilation technologies.

Indoor air quality is another major area of concern in buildings and is influenced by ventilation. Because people spend 60–90% of their life in indoor environments (homes, offices, schools, etc.), indoor air quality is a major factor affecting public health (Klepeis et al., 2001; European Commission 2003; Brasche and Bischof, 2005; Zeghnoun et al., 2010; Jantunen et al., 2011). (Logue et al., 2011b) estimated that the current damage to public health in disability-adjusted life years (μ DALY) per person per year from all sources attributable to IAQ, excluding second-hand smoke and radon, was in the range between the health effects of road traffic accidents (4,000 μ DALY/p/yr) and heart disease from all causes (11,000 μ DALY/p/yr). By way of comparison, this means that, according to the World Health Organization (WHO, 2014), 99,000 deaths in Europe and 81,000 in the Americas were attributable to household (indoor) air pollution in 2012. Health gains in Europe (EU-26) attributed to effective implementation of the energy performance building directive, which includes indoor air quality issues, have been estimated at more than 300,000 DALYs per year.

As a result, interest in a new generation of ventilation systems has been growing. “Smart ventilation” strategies, including demand-controlled ventilation (DCV), usually denote the use of controls to ventilate more when doing so provides an energy or IAQ advantage (or both) and less when it provides a disadvantage, relative to a “dumb” base case. DCV strategies have been considered in the literature (Laverge et al., 2011) as a cost/energy and IAQ measure, including in existing buildings. DCV strategies have the potential for energy reductions for all ventilation systems.

A favorable regulatory context exists in many countries to develop such strategies (Guyot et al., 2017). Consequently, more than 20 DCV systems with an agreement are available in countries such as Belgium, France and the Netherlands.

Ventilation should not be seen as a panacea: to achieve good indoor air quality, source control and reduction must be considered as the starting point (Mansson et al., 1997; Sherman and Hodgson, 2002; Wargocki, 2012; Borsboom et al., 2016). The history of combustion devices changing from open fireplaces to sealed modern fireplaces is a good illustration of a response to the need for source reduction (Matson and Sherman, 2004). Public policies that push the development of low emitting building materials and furnishings is another example: Composite wood product airborne toxic control measure (California Environmental Protection Agency, 2011) and compulsory labeling of VOC emission of all construction products and decorative products installed indoors (French Ministry for Ecology, 2011). While source reduction is key in reducing pollutant levels, this paper limits its scope to ventilation system design.

As the list of identified indoor pollutants is long and may still increase, it has been impossible to create definitive IAQ metrics for standards and regulations governing residential buildings (Borsboom et al., 2016). Instead, prescribed ventilation rates have been used. The trouble with this approach is that it assumes that in addition to displacing human bio-effluents including odors, ventilation is a sufficient means of controlling other contaminants (Matson and Sherman, 2004 and Persily, 2006). The committee chair of ASHRAE Standard 62-1989 noted that the minimum ventilation requirement of $7.5 \text{ L}\cdot\text{s}^{-1}$ per person was based on body odor control (Janssen, 1989), and that this minimum was increased to $10 \text{ L}\cdot\text{s}^{-1}$ per person in many building types to account for contaminants other than human bio-effluents, such as building materials and furnishings. However, no specific methodology articulating the justification of this increase was noted. As a result, standards and regulations generally set ventilation rates based on comfort considerations and not on health criteria, as suggested in the Healthvent project (Seppanen and et. al., 2012; Wargocki, 2012).

SMART VENTILATION

The key smart ventilation concept is to use controls to ventilate more at times it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. The fundamental goal of this concept is to reduce ventilation energy use and cost while maintaining or improving IAQ relative to a continuously operating system.

Demand-controlled ventilation (DCV)

The DCV concept is a specific subset of smart ventilation. DCV systems generally use indicators of demand for ventilation, such as excess CO_2 or humidity, to control a ventilation system. Such strategies have been widely used in the scientific literature and in materials associated with the technologies available over the past 30 years. DCV has been defined in a variety of ways. According to the IEA Annex 18, DCV denotes continuously and automatically adjusting the ventilation rate in response to the indoor pollutant load (Mansson et al., 1997). (Limb M.J, 1992, p. 36) defines a DCV strategy as “a ventilation strategy where the airflow rate is governed by a chosen pollutant concentration level. This level is measured by air quality sensors located within the room or zone. When the pollutant concentration level rises above a preset level, the sensors activate the ventilation system. As the occupants leave the room the pollutant concentration levels are reduced and ventilation is also reduced.”

Several types of DCV are currently available in the literature and on the market depending on the type of building regulation, the type of sensing combinations, and the types of control algorithms. For instance in Belgium (Caillou et al., 2014b; Moniteur Belge, 2015), DCV systems have been classified according to measured IAQ-related parameters such as CO_2 , relative humidity, occupancy; type of space(s) (humid and/or dry); local vs. centralized control; sensor location (distributed vs. central), and airflow direction (exhaust only, supply only, balanced). Here we disaggregate by airflow direction because this is key for the system installation and evaluation at the design stage.

Balanced DCV systems

Balanced DCV system control can be centralized or zoned and decentralized in each room, either by the use of a supply fan in each dry room or by the presence of dampers controlling airflow in each space. An

important point is that the ventilation system must be able to balance the exhaust and supply continuously.

Exhaust-only DCV systems

Exhaust-only DCV system controls can also be centralized or decentralized. In a tight home the distribution of air intakes could be controlled for zonal ventilation with either central or multiple exhausts. In leaky homes this strategy is less effective (infiltration would counteract decreased airflow through air inlets). These systems can be centrally regulated by measuring (CO₂ for instance) in dry spaces and adjusting centralized equipment accordingly, without regulation of the air inlets in these spaces. Other technologies exist, sometimes including additional exhausts in bedrooms that compensate for under-ventilation due to airtightness (Caillou et al., 2014b).

Residential Integrated Ventilation-Energy Controller (RIVEC)

With the Residential Integrated Ventilation-Energy Controller (RIVEC), the LBNL has more recently been developing another subset of smart ventilation. It was developed in order to control fans to minimize energy use (Sherman and Walker, 2011; Walker et al., 2011; Turner and Walker, 2012; Walker et al., 2014). This smart ventilation concept uses the equivalent ventilation principle (Sherman, 2004) to allow for modulation of ventilation airflows in response to several factors, including outdoor conditions, utility peak loads, occupancy, and operation of other air systems. Equivalent exposure compares the exposure for the system being evaluated to that from a continuous ventilation system (assuming a continuously generated pollutant). This generic approach allows for any smart ventilation strategy to have real-time control by targeting a relative exposure of unity. This has been integrated into ASHRAE Standard 62.2 (ANSI/ASHRAE, 2013,2016) as an optional compliance path. This concept was further developed (Sherman et al., 2011) to be applied under a variety of ventilation rates, emission rates, and the evaluation periods for the dose of pollutants.

One current update of the RIVEC (Sherman and Walker, 2011; Walker et al., 2011) is a real-time whole-house ventilation system. Figure 1 is an illustrative example showing the operation of a RIVEC-controlled fan that combines forced fan off times with the response to the operation of other fans. RIVEC works by continuously calculating pollutant dose and exposure relative to a continuous ventilation system. It is able to:

1. Use timers or temperature sensors to provide ventilation when the impact is the smallest – typically shifting ventilation from times of high temperature differences to times of low temperature difference. This also results in significant peak-demand reduction (Turner et al., 2015), which increases grid reliability and reduces costs if time-of-use energy rates are in effect.
2. Account for operation of other air-moving equipment, such as kitchen and bathroom exhaust fans and clothes dryers.
3. Reduce ventilation during unoccupied times.
4. Ventilate more at times to compensate for other times when ventilation is reduced.
5. Account for natural infiltration contributions to total ventilation.
6. Respond to peak demand signals from utilities.
7. Change ventilation times to reduce entry of outdoor pollutants when their levels are high.

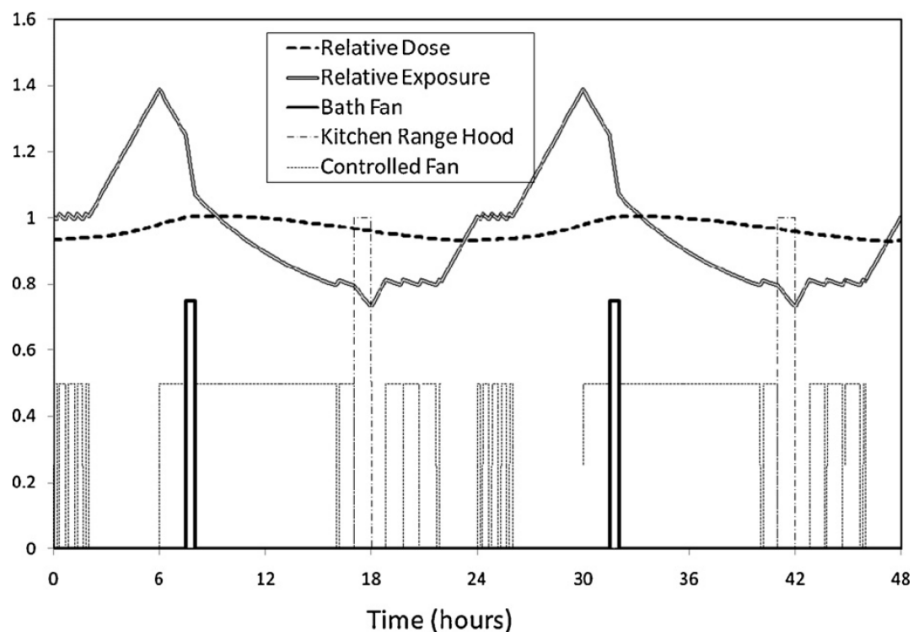


Figure 1: Simulated controlled whole-house ventilation fan (continuous exhaust) with RIVEC and other household fan operation during the winter; source: (Sherman and Walker, 2011)

In smart ventilation strategies, the type of measurements used can also depend strongly on the quantity being measured (CO_2 , RH, pollutants, occupancy), the type of measuring technology, the type of spaces (humid and/or dry), the type of airflow control (mechanical or electronic inlet and outlet cross-sectional area, direct control of the fan speed, or control of dampers). The type of control algorithm (for example, the value of the set-points and the rules for control between set-points) is also an important topic that can have a substantial impact on IAQ and energy performance.

REVIEW PROCEDURE

In this paper, we analyzed field and modeling studies on energy and/or IAQ benefits of residential smart ventilation from 1979 to 2016. The summaries presented above are instructive and provide a valuable resource to initiate the current work even though many of the summarized studies are for non-residential buildings.

As part of the International Energy Agency Annex 18, (Raatschen, 1990) reviewed 31 papers from 1979 to 1989, including four studies on implementation of DCV systems in homes (Anon, 1983; Barthez and Soupault, 1984; Nicolas, 1985; Sheltair scientific Ltd., 1988). A further review (Fisk and De Almeida, 1998) on sensor-based demand-controlled ventilation combined 13 other papers from Annex 18 including six case studies on implementation of DCV systems in homes (Mansson, 1993), together with 15 additional papers published before 1997, including only one on a residence (Kesselring et al., 1993). The vast majority of these studies considered only relative humidity-based control, and in some rare cases CO_2 -based control. A recent review of sustainable, energy-efficient and healthy ventilation strategies in buildings (Chenari et al., 2016) devoted a large section to DCV systems, including 15 additional papers from 2004

to 2013. Four of these concern smart ventilation in residential buildings (Jreijiry et al., 2007; Laverge et al., 2011; Nielsen and Drivsholm, 2010; Pavlovas, 2004). Between these three existing reviews there are 15 papers on smart ventilation, all DCV, in residential buildings.

In the present review, we analyzed 23 additional studies of interest on residential smart ventilation: 13 cover various smart ventilation systems based either on CO₂ control or on humidity control; one presents a combined CO₂- and TVOC-controlled ventilation system; three study occupancy-based smart ventilation systems; three study outdoor temperature-controlled smart ventilation; and three concern other smart ventilation strategies based on the RIVEC.

The results of these 38 studies are summarized in a table at the end of the article. We must stress that it is very difficult to compare performance results between different studies, for at least four reasons:

- 1- Differences in the types of smart ventilation strategies used: there is often a lack of precise data on the type and location of sensors, the method of air flow regulation and the type of ventilation system.
- 2- A lack of information on the conditions of the studies (climate, occupancy, energy performance level, range of ventilation rates, building materials emission and absorption characteristics). A study can give poor results for given conditions, but this does not necessarily mean that the ventilation system is bad.
- 3- Differences in measuring IAQ-related parameters: there is neither a single parameter or set of parameters common in these studies, nor a universal method to calculate the indicators. There are often differences on the metrics used to evaluate the IAQ parameters. For instance, the average CO₂ concentration is often given without information on either the location of the measurement (which room) or the averaging time used (1 day, 1 week, 1 year).
- 4- Differences in reference cases: reference cases, including reference airflow rates, are different in each standard or code to which each building regulation refers.

Despite these differences it was possible to find commonalities and derive general guidance from the reviewed papers. Table 2 contains a summary of all the studies reviewed in this paper.

PERFORMANCE OF HUMIDITY- AND/OR CO₂-CONTROLLED SMART VENTILATION SYSTEMS

Historically, humidity and CO₂ have been used as indicators of IAQ and therefore used to control DCV systems. Humidity is one of the prioritized pollutants of concern (Borsboom et al., 2016). CO₂ is often used in DCV strategies, not to prevent negative health effects directly attributed to it, but because it can be representative of other parameters such as concentrations of bio-effluents (Zhang et al., 2016) or ventilation rates. The only health threshold on which several studies converge is an exposure of 10,000 ppm for 30 min, corresponding to respiratory acidosis for a healthy adult with a modest amount of physical load (ANSES 2013), far from concentrations observed in indoor environments. Nevertheless, CO₂ exposure has often been used in the literature, describing a time-integrated concentration.

The following reviews focus on these control strategies. Note that these studies did not measure any pollutants such as particles, formaldehyde, NO₂, etc.; however, the control strategies were used also because sensors for humidity and CO₂ are easily available at an affordable price.

Until the beginning of the 1990s, the literature we reviewed (Anon, 1983; Barthez and Soupault, 1984; Nicolas, 1985; Sheltair scientific Ltd., 1988; Wouters et al., 1991; Moffat et al., 1991; Mansson, 1993; Kesselring et al., 1993) contained mainly case studies, reporting a wide range of energy savings (0%–60%), with small to moderate IAQ improvements. Although all the data required to account for these large differences are rarely available, several explanations for the differences can be identified, including type of DCV system, the advancement of these technologies, and outdoor climate (for humidity-controlled DCV).

(Parekh and Riley, 1991) studied the implementation of a relative humidity (RH)-based DCV system in two houses. The whole-house ventilation system had inlet and exhaust grilles with a cross-sectional area modulating in response to the RH level in the room. They observed only 6% energy savings (calculated over a short time period, which could reduce the savings calculated) and concluded that the IAQ was poor, especially in the bedrooms, which had a CO₂ concentration greater than 1200 ppm. They highlighted the fact that a high level of air leakage in their setup would reduce the influence of the ventilation system on total building air flow rates and IAQ. As a result, DCV system performance may be underestimated.

(Nielsen, 1992) monitored the performance of a humidity-based DCV system installed in a new single-family house in Denmark occupied by two retired people for around 21 h a day over 1 month. The system is described as injecting air in each room, including the kitchen and bathroom, with exhausts in the bathroom and in a laundry room connected to the kitchen. A regulating damper in the inlet duct of each room regulates the air volume in response to temperature and relative humidity measurements. Sensors are located in each room and in the inlet duct. Two criteria control the operation of the ventilation system: first, relative humidity must remain under 45% in order to avoid house dust mite growth; and second condensation on double-pane glass windows must be avoided. Additionally, the authors set the minimum airflow rate at 10 L.s⁻¹, and the maximum airflow rate at 35 L.s⁻¹. The controller makes a decision about changing air flow to maintain these criteria every 1 min. As a result, the total airflow rate could be reduced to 39% below the Danish code requirement, with a RH of 45% exceeded about 10% of the time, and 47% exceeded only 1–5% of the time. No condensation was observed, or predicted based on RH results, over the monitoring time. CO₂ concentrations were lower than 1200 ppm 98% of the time.

(Nielsen and Ambrose, 1995) monitored the performance of a humidity-controlled ventilation system in 16 apartments for 3 months and compared results with a group of 16 identical apartments equipped with constant airflow ventilation. In most of the apartments, the balanced DCV system consists of “on-off” supplies controlled by capillary hygrostats in each bedroom, and exhausts in the bathroom and kitchen automatically regulated by a motor-driven exhaust air damper. The opening of inlet valves has no impact on total exhaust airflow but distributes the air supply between the bedrooms. RH set points are set at 40% in bedrooms and 45% in the other rooms. For outdoor air temperatures less than 1°C, a constraint that is a function of indoor RH and outdoor temperature measurements is added to avoid condensation on windows. The resulting maximum reduction in the total airflow rate was 35%, obtained at an outdoor temperature of 1.5°C. For outdoor temperatures greater than 9°C, the airflow was constant because the outdoor air had no dehumidification potential compared to the indoor air. The mean RH did not exceed 43%, and was slightly lower in bedrooms equipped with DCV. No condensation on windows was recorded.

(Afshari and Bergsøe, 2003) present a 5-year project on the evaluation and development of innovative energy and ventilation strategies. They calculated energy savings of 20–30% of ventilation-related energy, for a RH-controlled ventilation system confirmed by measurements on a test apartment. In this apartment, they simulated two-person occupancy and emissions of materials and furnishings (N_2O tracer) in the living room. They first installed a standard exhaust-only ventilation system delivering a constant rate of $35 \text{ L}\cdot\text{s}^{-1}$ ($20 \text{ L}\cdot\text{s}^{-1}$ in the kitchen and $15 \text{ L}\cdot\text{s}^{-1}$ in the bathroom). Next, they installed RH-controlled exhausts and passive RH-controlled inlets. The base flow rates were $10 \text{ L}\cdot\text{s}^{-1}$ in humid rooms. A relative humidity of 45% activated a high rate of $50 \text{ L}\cdot\text{s}^{-1}$ in the kitchen and $20 \text{ L}\cdot\text{s}^{-1}$ in the bathroom. As a result, even with a higher exhaust rate in the kitchen some of the time, the home ventilation rate was reduced to 20–30% of the reference case. The maximum CO_2 concentration in the living room is reduced by 10% and the concentration in the living room of pollutants emitted by materials and furnishings stays at the same level when the building is occupied and can be reduced by 50% the rest of the time. The maximum CO_2 concentration in the bedroom is doubled from 600 to 1200 ppm.

(Pavlovas, 2004) modeled a typical Swedish apartment equipped with four types of exhaust-only ventilation with the IDA Climate and Energy software. The four types of ventilation were:

- 1) A reference system providing a constant airflow rate,
- 2) A CO_2 -based DCV system with sensors in humid rooms (kitchens and bathrooms),
- 3) A humidity-based DCV system with sensors in humid rooms,
- 4) An occupancy-based DCV system.

In all systems, the exhaust airflow rate varies from a base flow of $10 \text{ L}\cdot\text{s}^{-1}$ up to $30 \text{ L}\cdot\text{s}^{-1}$ when needed. Different set points were tested: 800, 1000, and 1200 ppm for CO_2 -based control, and 60, 70, and 80% for the maximum humidity threshold. The position of interior doors (closed or open) was also tested. Authors judged air quality through both CO_2 concentrations and high humidity levels. Both CO_2 - and occupancy-based DCV resulted in similar CO_2 concentrations but increased the risk for high humidity levels. The RH-based DCV increased CO_2 concentrations. Both CO_2 and RH strategies resulted in more than 50% annual heating demand savings, and the occupancy-based system about 20% energy savings. The greatest energy savings, without compromising indoor air quality, were obtained with the following set-points: 1200 ppm for the CO_2 concentration and 80% for the high relative humidity threshold.

(Jreijiry et al., 2007) developed and tested a demand-controlled hybrid (combined passive stack and mechanical) ventilation system for residential buildings as a part of the European RESHYVENT project. Yearly simulations were performed in a house located in four climates equipped with two different DCV systems, based on CO_2 or on occupancy in the dry rooms. The air flow in the passive stack is calculated based on the indoor-outdoor temperature difference and an air flow resistance model of the stack. In each system, occupancy is detected in the toilets, humidity is detected in the bathroom and kitchen, and temperatures of exhaust and outdoor air are used. Air inlets and exhaust grilles can be modulated to eight different positions. Every 10 min, a control algorithm adjusts the fan speed in response to the calculated passive stack air flow. In the CO_2 -based DCV strategy, inlets and grilles open, based on humidity and CO_2 concentrations. Both strategies have economizer and night-cooling functionality in their algorithms. The results were compared to a single-exhaust ventilation system, considered as the reference system. In all the climates, when compared to the reference system, authors noted no significant difference on the summer thermal comfort and the energy consumption for heating. Nevertheless, they highlighted strong impacts on CO_2 exposure in occupied dry rooms and on electrical consumption of the fan. The hybrid

smart system reduced the exposure to CO₂ at least by a factor of 2 and the electrical consumption of the fan by 90%.

(Van den Bossche et al., 2007) modeled an exhaust-only RH-based DCV system in a typical Belgian house equipped with self-regulating trickle ventilators with CONTAM and compared the results with an exhaust-only constant airflow ventilation system. They simulated four-person occupancy and used outdoor data from a reference year in Uccle, Belgium. The nominal ventilation exhaust rates were 50 m³.h⁻¹ in the kitchen and 25 m³.h⁻¹ in the bathroom. In the DCV strategy, humidity sensors in the humid rooms controlled airflow to 20%–100% of the nominal airflow for a relative humidity range of 30–100%, with a linear relationship between the two set-points. Also, motion sensors in humid rooms ensured minimum airflows for a 20- to 30-min period after the last detection of occupancy.

They showed that IAQ, estimated either by the time spent in each CO₂-IDA class of the EN 13779 standard (CEN, 2007) or by the LKI₁₂₀₀ index of the Dutch standard NEN 8088 (NEN, 2011), was slightly lower for the DCV system studied. This IAQ metric is the cumulative CO₂ exposure index requirement per person calculated with Equation 1 for the heating period considered, September 29th to April 25th. The other indicator used was the percentage of time when relative humidity failed to stay in the 30–70% range. This indicator was found to be very sensitive to envelope airtightness. In the bathroom and bedroom of an airtight house ($n_{50}=0.6$ h⁻¹), the DCV system studied maintained the space in this range only for 67% of the time, while the reference system succeeded 90% of the time. For a leaky house with average airtightness ($n_{50}=11.2$ h⁻¹), they observed no difference in performance. The energy savings potential was calculated at around 1100–1200 kWh, which is 27% for the airtight houses and 14% for average airtightness. They also studied the moisture-buffering effect and showed that it did not affect DCV energy performance, with only 0.75% extra energy demand.

$$LKI_{1200} = \sum_{t=0}^T \left(\frac{C_{CO_2>1200}(t) - 1200}{1000} \right) \cdot t < 30 \text{ kppm.h}$$

Equation 1

where $C_{CO_2>1200}(t)$ is the absolute concentration at which an occupant is exposed at t time-step, if it is higher than 1200 ppm, or 800 ppm above the outdoor concentration.

(Woloszyn et al., 2009) studied the performance of a humidity-based DCV system for residential buildings, comparing four heat, air, and moisture simulation software, and taking into account the moisture buffering effect. For a whole-house exhaust-only ventilation system with exhaust airflow depending on RH, they showed a mean ventilation rate reduction of 30–40% with 12–17% energy savings in the cold period, compared to a constant airflow exhaust-only ventilation system. They highlight that these gains were achieved while keeping the peak RH values the same. CO₂ concentrations were estimated to be greater than 1200 ppm around 33% of the time during the cold period. They also conclude that it should be suitable to optimize such systems, combining RH- and CO₂-based strategies, in order to reduce CO₂ concentrations as well.

Measurements over two complete heating seasons were taken in 31 new occupied apartments equipped with humidity-based inlet and outlet DCV systems (Air H, 2010; Bernard, 2009). For more than 30 years the market in France has largely been dominated by such humidity-based DCV systems with a

mechanically variable inlet and outlet cross-sectional area (Savin et al., 2014). They use advanced materials such as polyamide fiber, which varies in length with the relative humidity. They are not classical sensors but could be described as sensor-actuators: the dimensional changes are used directly to adjust vent opening. The variables measured included outdoor and indoor variables (CO₂, temperature, and humidity), and ventilation parameters (pressure, inlet cross-sectional area, airflows through the trickle ventilators, and exhaust air outlets). They were captured every minute. The measurements validated the theoretical IAQ performance modeled by the software used in the French certification of compliance for DCV systems (CCFAT, 2015). Manufacturers must follow this compliance procedure for DCV to ensure adequate ventilation. Cumulative CO₂ exposure, even in high-occupancy bedrooms (four adults), and condensation risk were very low in the vast majority of homes. IAQ was better in bedrooms during the night than it was with fixed air inlets, even if IAQ indicators were acceptable in both cases. Average ventilation airflow was measured at around 30% lower than with the fixed ventilation rates required by the airing regulations, accounting for an approximately 0.5 air change rate per hour. The authors extrapolate this result to homes with more standard occupancy patterns and obtained a reduction of average ventilation airflow of around 50–55%. Energy savings on ventilation motor consumption were estimated between 35 and 50%.

(Nielsen and Drivsholm, 2010) studied a simple DCV approach for homes with control based on measurements in the air-handling unit that modulated the fan speed between two levels. This strategy was implemented in a new Danish single-family house occupied by two adults and two children and equipped with a single ventilation system. Measurements were taken with and without the new control strategy. The high-speed fan is set at 100% of fan capacity and is based on the flow rate required by the Danish building code (216 m³.h⁻¹ or 0.43 l.s⁻¹.m⁻² for the house tested); the low speed is 40% of the speed at the high-flow rate. A difference of 100–150 or 200 ppm between CO₂ concentrations measured between the exhaust and outdoor air indicates that the building is occupied and activates operation at high speed. A difference of 2 g/kg in absolute humidity also activates the high-speed fan, which takes into account the fact that in the Danish climate the outdoor temperature is below 5°C over 3000 h per year. The results show an optimum at a CO₂ concentration difference set-point of 150 ppm. At this setting, the ventilation rate can be set to “low” 37% of the time, mostly during unoccupied periods, without significant change in the IAQ performance, based on CO₂ and humidity, compared to the fixed rate ventilation strategy. The corresponding energy savings have been estimated at 35% of the fan’s electricity consumption and 23% of the heating needs. Measurements of the fan speed throughout the week show that the control strategy closely followed the unoccupied schedules during the daytime.

(Laverge et al., 2011) tested the performance of four approaches for DCV in a typical Belgian house: 1) humidity-controlled in the humid rooms with an “on-off” strategy based on the RH measured in the exhaust air with a set point of 70%, 2) occupancy-controlled, with an “on-off” strategy on the fan running once 20 min of occupancy is detected, 3) CO₂-controlled in the dry rooms with air inlets reduced to 10% opening if the CO₂ concentration is lower than 1000 ppm in the room, 4) the three approaches combined. Multi-zone modeling was performed with CONTAM and the results were compared to reference exhaust-only constant flow rate ventilation. Two IAQ indicators were used: 1) The mean excess CO₂ concentration over 1000 ppm to which an occupant is exposed during the heating season and 2) the exposure to a tracer gas emitted in rooms with a toilet (efficiency of the exhaust in removing humidity at the source). The total heating-season-averaged heat loss through ventilation savings were in the range of 25% (only one control parameter) to 60% (three combined). CO₂ detection in dry rooms was found to be more robust than in the

other rooms. Reducing inlet size effectively moves the responsibility for aeraulic management to the fan, more than wind or the stack effect. Complementary analyses with different levels of envelope airtightness confirmed this analysis. The CO₂ indicator results were better with CO₂ and occupancy control. Exposure to the toilet room tracer gas under all strategies was similar.

In a recent study evaluating different control algorithms mainly based on the 35 DCV systems available on the Belgian market, (Caillou et al., 2014b) calculated energy savings between 0 and 40%, varying by type of system, only for the systems fulfilling the IAQ requirements. The most IAQ-friendly and energy-efficient systems are locally regulated and combine exhaust controlled by relative humidity in each humid room and a supply (through air supply inlets in a balanced system or through trickle ventilators in an exhaust-only system) controlled by CO₂ in each dry room. The less IAQ-friendly and energy-efficient systems are those with only RH-regulated exhaust in humid rooms and no control on the air inlets. Most energy saving coefficients are given in Table 1. These results are published in a Ministerial Order (Moniteur Belge, 2015) to be used directly in the energy performance calculations. The energy savings coefficient f_{reduc} is calculated from Equation 2, based on the heating season integrated ventilation heat loss E (MWh/year), excluding infiltration heat losses, which are treated separately in the EP calculation method. E_x is calculated for the smart system X studied. E_{ref} is the energy use of a system that has the same CO₂ exposure indicator as the system being rated and is determined as shown in Figure 2. The per-person cumulative CO₂ exposure indicator E'_{950} (Equation 3) is calculated starting from the absolute concentration at which an occupant is exposed at t time-step, if it is higher than 950 ppm.

$$f_{reduc} = \frac{E_x}{E_{ref}}$$

Equation 2

$$E'_{950} = \sum_{t=0}^T (C_{CO_2 > 950}(t) - 950) * t$$

Equation 3

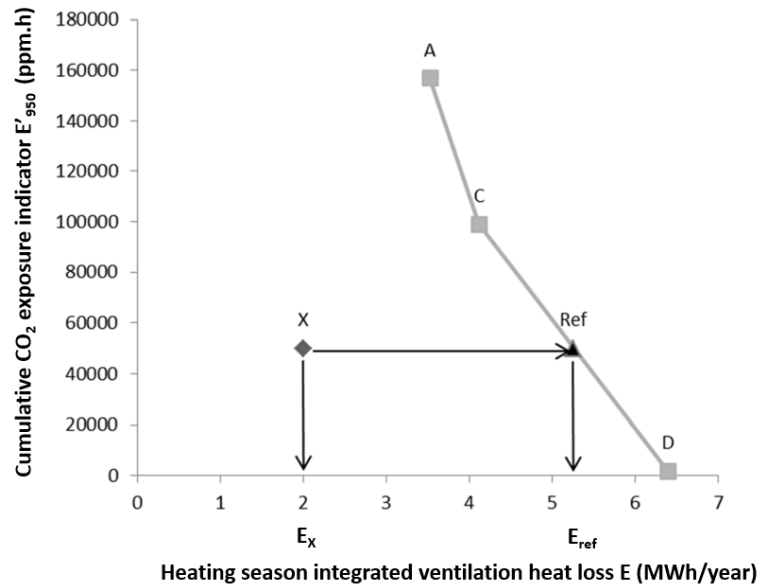


Figure 2: Energy saving coefficient calculation for a DCV system X (ATG and BCCA, 2012)

Type of detection in dry spaces	Type of regulation of air inlets in dry spaces	Local detection in humid spaces with regulation of air outlet		Other or no detection in humid spaces
		<i>Local regulation</i>	<i>No local regulation</i>	
CO ₂ -local: at least 1 sensor in each dry space	Local	0.35	0.38	0.42
	2 zones (night/day) or more	0.41	0.45	0.49
	Central	0.51	0.56	0.61
CO ₂ -partially local: at least a sensor in each bedroom	Central	0.60	0.65	0.70
CO ₂ -partially local: at least 1 sensor in the main bedroom + at least 1 sensor in the living room	2 zones (night/day) or more	0.43	0.48	0.53
	Central	0.75	0.81	0.87
CO ₂ -central: at least 1 sensor in the exhaust duct(s)	Central	0.81	0.87	0.93
Occupancy-local: at least 1 sensor in each dry space	Local	0.54	0.60	0.64
	2 zones (night/day) or more	0.63	0.67	0.72
	Central	0.76	0.82	0.88
Occupancy-partially local: at least 1 sensor in each bedroom	Central	0.87	0.93	1.00
Occupancy-partially local: at least 1 sensor in the main bedroom + at least 1 sensor in the living room	2 zones (night/day) or more	0.66	0.72	0.78
	Central	0.87	0.93	1.00
Other or no detection in dry spaces	No, local, per zone, or central	0.90	0.95	1.00

Table 1: Energy saving coefficient f_{reduc} in Belgium for natural, exhaust-only, supply-only, balanced DCV systems with a regulation of air inlets based on needs in dry spaces and/or with a regulation of air outlets based on needs in humid rooms (another table is available for exhaust-only systems with a regulation of air outlets based on needs in dry spaces)

Another recent study was based on 1 year of measurements in 62 homes in The Netherlands (van Holsteijn and Li, 2014), some of which were equipped with CO₂-based DCV systems. They used as an IAQ indicator the cumulative CO₂ exposure index requirement, LKI₁₂₀₀, Equation 1. Depending on the location of the sensors, they showed a range of performance for the DCV systems. If RH and CO₂ sensors were all linked to a mechanical supply and/or exhaust air component in the rooms where the sensors performed measurements, good performance was observed. In the other cases, energy performance and IAQ can be worse than in constant airflow reference systems. Reference systems for single-exhaust ventilation had a mean energy performance of 119 MJ/m²/heating season and an IAQ performance of 244 kppm/person. Systems with only CO₂ sensors in the living room decreased the performance based on these two indicators by 21% and 11%, respectively. Systems with RH and CO₂ sensors in all the rooms increased performance based on these two indicators by 31% and 70%, respectively. The reference system for balanced ventilation had a mean energy performance of 24 MJ/m²/heating season and an IAQ performance of 68 kppm/person. Systems with only CO₂ sensors in two zones increased energy performance by 24% and decreased IAQ by 54%. Systems with RH and CO₂ sensors in all the rooms and supply in the connecting spaces increased energy performance by 45% and decreased IAQ by 11%. Much higher performance was observed for systems with RH and CO₂ sensors in all the rooms.

PERFORMANCE OF OTHER SYSTEMS: BEYOND CO₂ AND HUMIDITY

Some other smart ventilation strategies are based on other pollutants, occupancy, or outdoor temperature. More recently concerns about constantly emitted pollutants (e.g., VOCs including formaldehyde) mean that occupant-only-related indicators may be considered inadequate to control smart ventilation strategies.

(Fisk and De Almeida, 1998) recommended using VOC sensors in conjunction with CO₂ sensors. They highlighted the difficulties of doing this resulting from the high variability in toxicity of different VOCs as well as the lack of data on acceptable levels for mixtures of VOCs. Nevertheless, they consider that VOC-based DCV strategies could at least avoid peak exposure during scheduled activities such as painting or installation of carpeting. As more than 300 VOCs have been measured in indoor air, the total VOC (TVOC) concentration is often used in the literature and sensor technologies to simply characterize the total concentration with a single parameter. It is calculated from the measurement of one or several VOCs. Several authors have highlighted the lack of a precise definition for this variable and of a standardized procedure for its calculation (Mølhave, et al. 1997).

In an example of VOC-based system design, a standard Korean multi-zone apartment has been modeled with CONTAM and EnergyPlus at a 1-h time step, equipped with a whole-house balanced DCV system either based on CO₂ demand or on TVOC demand (Seong, 2010). The control strategy investigated is an “on-off” strategy, with a base airflow rate fixed at the reference in the Korean regulation, 0.7 h⁻¹. The location of the sensors is not given. TVOC generation rates were modeled based on data measured by the Korean Ministry of the Environment. They differ for each room and include first an emission rate per floor area, then finishing and product (furniture, bed mattress, chest of drawers, desk, personal computer, chair, kitchen unit, shoe rack, TV) emissions. The TVOC exposure is not calculated and thus it is difficult to

compare the performance results. The CO₂-based DCV strategy keeps the home under 1000 ppm and at low TVOC concentrations most of the time, albeit with some peaks, remaining in the 150–800 µg.m⁻³ range. The authors compare this range to the initial concentration set to 1000 µg.m⁻³, the concentration obtained without any ventilation system 4000 µg.m⁻³, and the one obtained when ventilated by the Korean standard, 600 µg.m⁻³. The energy savings are estimated at 17%. The TVOC-based DCV strategy maintains CO₂ concentrations under 2200 ppm, and TVOC concentrations of 400–800 µg.m⁻³. It showed energy savings estimated at 26%.

The performance of occupancy-based smart ventilation systems has been demonstrated in some modeling and field studies.

Through a preliminary TRNSYS-modeling study, (Römer and van Ginkel, 2003) demonstrated energy savings of about 15% for a low-energy house equipped with a ventilation system based on a night-time strategy. In this strategy, base airflows during the night are multiplied by a factor of two in bedrooms and reduced by the same factor in the other rooms. Another strategy consisted in dividing the base airflows by a factor of two when rooms were unoccupied. Based on a typical schedule for a four-person family, they calculated 20% energy savings. Such a balanced occupancy-based ventilation system was installed in a low-energy test house. If the relative humidity in a room exceeded 70% or the indoor temperature exceeded the comfort temperature, the high airflow rate was also activated. Movement detection in a room manages the opening of ventilation valves until the prescribed levels of temperature and RH are reached. The authors measured a 50–80% reduction in the kitchen air change rate, no change in the bedroom air change rate, and an increase of 160% of the living room, compared to the constant air change rate. No information is given in the paper about the total airflow reduction.

Based on the LBNL smart ventilation studies background for chronic and acute exposure evaluation, (Mortensen et al., 2011) studied the optimization of the performance of a whole-house ventilation strategy with two fan speeds. They studied variations in the emission ratio – defined as the ratio between all pollutant source strengths and background pollutant source strength, the low ventilation factor – defined as the ratio between the low ventilation rate and the ventilation rate of the equivalent constant rate system; and this equivalent constant rate. The results show that the performance can always be optimized given the occupancy time and emission characteristics. The low-ventilation factors were 0.13–0.4 at peak effectiveness, and all the systems had a high-to-low flow airflow ratio of 2.5–5. They also calculated the ratio of acute to chronic exposure and showed that it was always less than 3, which means such DCV systems provide acceptable peak exposure. They showed that for a home occupied for 16 consecutive hours, the total ventilation rate is reduced by about 12% for a constant rate of 0.5 h⁻¹ and an emission ratio of 1.5. When occupant pollutant emissions are dominant, the airflow reductions can be more than 18% and would be reduced to 9% when there is no contribution from occupants.

In a recent modeling study of a new three-level house in Sweden, (Hesaraki and Holmberg, 2015) studied the IAQ and energy impact of a whole-house exhaust-only DCV system based on occupancy schedules. The whole-building airflow rate is 60 L.s⁻¹ (0.75 L.s⁻¹m⁻²) and is switched to 16 L.s⁻¹ (0.1 L.s⁻¹m⁻²) during unoccupied periods (8 am to 6 pm). The authors studied the impact of using the low rate for 4, 6, 8, or 10 h, starting from 8 am. Compared to the reference constant airflow system at 60 L.s⁻¹, the mean age of air at 6 pm (when the occupants return) increases by 5.5, 22.2, 50, or 105.5%, respectively; the VOC concentration at 6 pm increases by 4, 20, 65, or 211%, respectively, in the last case going over the threshold value to 0.1 ppm, while the CO₂ concentration stays below the 1000 ppm threshold value

considered. For the acceptable IAQ system with 8 h unoccupied, the heating energy savings was estimated at 20% and fan consumption 30%. As a result, the total building energy consumption was reduced by 10%, from 52 to 47 kWh.m⁻². Similar good savings were also observed in (Laverge et al., 2011).

The performance of outdoor temperature-controlled smart ventilation systems has been demonstrated in a number of recent modeling studies, sometimes in conjunction with hybrid ventilation systems.

The use of the RIVEC was studied to optimize hybrid and passive ventilation strategies in single-family homes (Turner and Walker, 2013). In this study, RIVEC first determines the available airflow rate in a designed passive stack (the signal could be given from a pressure probe or other airflow meter). This passive stack airflow is limited to 100% of the ASHRAE 62.2 minimum requirement to prevent excess energy use in extreme weather. If the airflow is not sufficient to meet the IAQ equivalence requirements, RIVEC turns on the whole-house exhaust fan. As a result, the authors showed that there was room to optimize hybrid ventilation systems with accurate sizing of the passive stack and smart ventilation strategies.

(Less et al., 2014) recently used RIVEC to study an outdoor temperature-controlled ventilation strategy allowing ventilation to be switched off when the stack effect alone was sufficient to provide equivalent air change rates. Simulations were performed in all climate zones in the United States, for two house geometries and under envelope airtightness levels in the range of 0.6–10 air changes at 50 Pascal (ACH₅₀). Four control strategies were studied to optimize the solution:

1. Infiltration-dependent: the fan is turned off if the stack effect provides the target airflow;
2. Infiltration-dependent2: the fan is turned to half-flow if the stack effect provides 50% of the target airflow;
3. Infiltration-independent: the fan is turned off each time the outdoor temperature drops below 5°C;
4. Infiltration-independent-25th: the fan is turned-off each time the outdoor temperature drops below the 25th percentile of the coldest hours determined from TMY data files.

The simplest strategy, with the cut-off set to 5°C, was the most efficient one across a variety of climate zones. However, this approach of accounting for natural infiltration is limited in tighter homes. Houses tighter than 3 ACH₅₀ were never able to reach natural infiltration air change rates equivalent to ASHRAE 62.2 (note that the natural infiltration airflows were still accounted for in the controls). For leakier houses in severe climates, such strategies can become effective and reach annual HVAC energy savings in the range 100–4000 kWh. Fans should be oversized by 5–150%, with an average of 34%.

(Lubliner et al., 2016) further investigated this type of low-cost temperature-based smart ventilation control system (less than \$80) on two houses, using REGCAP and EnergyGauge USA energy software and a field-testing campaign lasting several months in two climates. Weekly testing in these houses allowed them to set the outdoor temperature set-point for each house. As a result, they obtained energy savings between 73 and 230 kWh/year. They also demonstrated the importance of the location of the temperature sensors. They observed no significant impact on CO₂ and humidity. Occupancy, window opening, and wind effects were found to have significant effects on CO₂ and humidity.

IMPACT OF DIFFERENT CONTROL STRATEGIES FOR SMART VENTILATION PERFORMANCE

Other control strategies for smart ventilation systems were also studied during the development of the RIVEC (Sherman and Walker, 2011). This update to their previous work consisted of an intermittent ventilation strategy controlled by the operation of other air devices in the house and with a switch-off during the 4-h period of peak energy demand. The theoretical background still assumes a continuously occupied home with a constant emission rate. The authors propose controller logic with a set of actions at each time step, fixed primarily at 10 min. The controller:

1. determines the current ventilation rate taking into account exogenous ventilation airflows and separating exhaust, supply, and balanced flows;
2. estimates the current IAQ from relative exposure and relative dose calculated with the constant emission rate assumption;
3. turns on or off the whole-house ventilation system, according to a detailed control algorithm dividing the day into four periods: a 12-h base period, a 4-h pre-peak shoulder period, a 4-h peak period (off), a 4-h post-peak period.

Simulations were performed with a 1-min time step with the REGCAP simulation tool (Walker and Sherman, 2006) on a typical new Californian home in three climate conditions (mild, warm, and cold mountain). This smart ventilation strategy was modeled with four ventilation types: continuous exhaust, heat recovery ventilator, continuous exhaust with a central fan integrated supply, and continuous supply. They observe an up to 14% decrease in the annual average relative dose and a peak relative exposure no more than 11% above the target limit, even with a 4-h shutoff period. Energy savings, including heating gas savings and electricity savings (cooling + fans), were estimated between 11 and 61%. Energy savings recalculated considering equivalent IAQ (and not better IAQ as originally observed) were between 20 and 64%.

A RIVEC prototype was field-tested in an occupied house in Moraga, California, equipped with an economizer (Walker et al., 2011). The field test was divided into three periods: 3 weeks of operation of the RIVEC system, 6 days with the whole-house ventilation system turned off, and 2 days with the whole-house system operating without RIVEC. Experimental data were combined with a modeling approach to estimate the energy savings over the year, in three California climate zones (temperate, Oakland; warm, Fresno; cold mountain, Mount Shasta). Modeling showed a potential of 13–44% (1000 kWh) annual ventilation energy savings, while preserving IAQ and eliminating 100% of the peak power associated with ventilation. RIVEC reduced the run time of the fans by up to 71% for a home with an economizer. The whole-house fan must be oversized by 25% to allow it to provide sufficient off-peak ventilation rates.

The RIVEC was then further developed to be more robust, with only two periods in the day (eliminating the pre- and post-peak periods), and to take into account varying occupancy in the control algorithm (Turner and Walker, 2012, 2013). These further modeling investigations looked at diverse climates (16 California climate zones), various home geometries, four mechanical ventilation systems, and two passive or hybrid systems and envelope airtightness levels to give an accurate representation of the majority of the California housing stock. The authors concluded that ventilation energy savings were typically 40% while maintaining, or even going beyond, the IAQ equivalence of ASHRAE 62.2, and without allowing

unacceptable acute exposure to constantly emitted pollutants. This results in absolute energy savings from 500 to 7000 kWh/year per household. These energy savings are robust across climates as well as house geometric and airtightness levels. The peak power is also significantly reduced up to 2 kW for a typical house.

Another aspect of smart ventilation is that it is designed to control exposure to outdoor pollutants – typically particles and ozone. RIVEC was used to simulate a smart ventilation strategy that switched off the ventilation fan during outdoor ozone level peaks in a typical single-family house located in two places in California (Walker and Sherman, 2013). They demonstrated reductions of 10–40% in indoor-to-outdoor ozone ratios compared to continuously operating ventilation systems for a typical new Californian home (with a specific leakage area of 4).

CONCLUSIONS AND OBSERVATIONS

With smart ventilation strategies, including demand-controlled ventilation (DCV) strategies, the concept consists in using controls to ventilate more at times when it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. This can be done in a manner that provides improved home energy and IAQ performance. A favorable regulatory context exists in many countries to develop such strategies. As a result, more than 20 DCV systems with an agreement are available in countries such as Belgium, France and the Netherlands.

This article begins to address the fact that under the umbrella of “CO₂-based DCV systems” or “humidity-based DCV systems” or “smart ventilation systems,” there can be a wide variety of systems and strategies, with differences in the type of sensors, type of regulations, type of control algorithms, etc. To correctly analyze the performance of such systems, it is also very important to clearly define them and give a precise description of how they work.

Through this meta-analysis of 38 studies of various smart ventilation systems with control based on CO₂, humidity, combined CO₂ and TVOCs, occupancy, outdoor temperature, or other control strategies, we learned that:

- demand-controlled ventilation based on CO₂ or humidity is well established in some countries with standardized performance calculation procedures and readily available controls and ventilation systems;
- there is clearly a potential for improved indoor air quality using smart ventilation strategies;
- significant energy savings up to 60% can be obtained, with less favorable results including 26% overconsumption in some cases.

The low number of studies reviewed, 38 since 1983, suggests that smart ventilation is still an emerging technology. In this review highlighting the lack of data on ventilation strategies controlled by other parameters than humidity or CO₂, we identified issues that require greater understanding:

- What are the relevant pollutants to sense for residential ventilation control and can we sense them with sufficient accuracy and reliability for control?

- Can we ignore building and materials pollutants when homes are unoccupied? Can we ignore outdoor pollutants? Current regulations and the demand-controlled ventilation systems reviewed do not account for these effects.
- Can we reliably detect occupancy so as to realize the potential savings?

As a perspective for the future for real-time controllers like RIVEC compared with current DCV approaches, we would also suggest research in those areas, in order to:

- develop better indoor air quality metrics for residential ventilation control including the use of accurate and reliable sensing devices;
- better understand the differences between contaminant sources between occupied and unoccupied dwellings;
- include air cleaning in ventilation controls.

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Table 2: Summary of the studies surveyed on energy and IAQ performance of smart ventilation strategies in residential buildings. For supplementary material.

Reference Country	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
(Anon, 1983) <i>France</i>			Balanced + whole house + short-term supplementary airflows in kitchen	RH-controlled extraction grills + RH-controlled supply	Average RH controls supply and extract airflow rates	Cost of 230€ for a 3 BR-flat Sensors, air inlets, and exhaust tested for several years in two independent laboratories	Less condensation	50–60%
(Barthez and Soupault, 1984) <i>France</i>	Apartment	Modeling + experimental	Single exhaust + whole house + short-term in kitchen	CO ₂ + no sensor in other rooms	Control a 2-speed fan	Good relationship between CO ₂ and occupancy but no conclusion between CO ₂ and RH	CO ₂ between 400 and 750 ppm Relative humidity around 60%	- 60% of the total airflow modeled and measured
(Nicolas, 1985) <i>France</i>	Residential	Modeling	Single exhaust + whole house + short-term supplementary airflows in kitchen	Mechanical RH + Mechanical RH	Sections = mechanical function of RH	Performance varies according to air leakage level, climate, occupancy scenarios	/	- 30% of the total exhaust airflow, 10% heating energy savings
(Sheltair Scientific Ltd., 1988) <i>Vancouver, Canada</i>	1 House	Monitoring campaign for 1 week	Single exhaust + whole house	Mechanical RH	Sections = mechanical function of RH	Could be more effective in a drier climate. Accuracy measurement problems	RH constant, contrary to the CO ₂	0%, Explained by leaks on the boiler heater
(Parekh and Riley, 1991) <i>Ottawa, Canada</i>	2 Houses	Monitoring campaign 6-month duration	Single exhaust + whole house	Mechanical RH Mechanical RH	Sections = mechanical function of RH	Impact of air leakage highlighted	Poor IAQ, especially in the bedrooms	6% Energy savings
(Mansson, 1993) (Wouters et al., 1991) <i>Namur, Belgium</i>	9 Reference flats + 9 with RH DCV in a 9-storey building	Monitoring campaign 110 days in 3 periods	Natural + whole house (shunt ductworks in humid rooms)	RH-controlled extraction grills + RH-controlled grills	Sections = mechanical function of RH	Same “CEC” project as the following 2 studies No measure in the bed- and living-rooms	% Of time CO ₂ under 1000 ppm and 1500 is lower with DCV	**Improvement

Reference Country	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
(Mansson, 1993) (Wouters et al., 1991) <i>Schiedam, The Netherlands</i>	7 Ref flats + 7 with RH DCV in a 10-storey building	Monitoring campaign 72 days in 3 periods	Natural + whole house (shunt ductworks in humid rooms)	RH-controlled extraction grills + RH-controlled grills	Sections = mechanical function of RH	No measure in the bed- and living-rooms Poor results explained by the excessively small existing ducts	No improvement	**No improvement
(Mansson, 1993) (Wouters et al., 1991) <i>Les Ulis, France</i>	10 Ref flats + 10 with RH DCV in a 5-Storey building	Monitoring campaign 143 days in 3 periods	Natural + whole house (shunt ductworks in humid rooms)	RH-controlled extraction grills (except in kitchen) + RH-controlled grills	Sections = mechanical function of RH	No measure in the bed- and living-rooms Airtight building with appropriate size of existing ducts explains the good results	CO ₂ and RH correlate well	** 30% during a heating season
(Mansson, 1993) <i>Torino, Italy (2700 HDD)</i>	9 Rooms of 3 flats in a 6-storey building	Monitoring campaign, 2 months heating period	Simple exhaust + whole house	RH-controlled extractions + RH-controlled grills	Sections = mechanical function of RH		Surface condensation risk on windows metal frames	- 40% Of the total airflow
(Mansson, 1993) <i>Maasbree, The Netherlands</i>	1 Attached energy-efficient house	Monitoring, 2 weeks	Balanced + whole house	1) RH sensor in living room 2) RH sensor in exhaust 3) RH and mixed gas sensor in exhaust	Set-points, RH as a function of outdoor temperature, controls 3 fan speeds (35, 155, 220 m ³ .h ⁻¹)		Avg BR CO ₂ : Ref) 900 ppm 1) 1050 ppm 2) 890 ppm 3) 575–790 ppm No condensation risk	*** Fan level in % low/middle/high Ref) 73/3/24 1) 100/0/0 2) 100/0/0 3) 29/16/55
(Mansson, 1993) (Moffat et al., 1991) <i>Ottawa & Vancouver, Canada</i>	5 Energy-efficient houses	Monitoring before and after DCV installation from 189 h to 1385 h	3 Balanced, 2 simple exhaust + whole house	CO ₂ , pressure differences, temperatures, RH, absolute humidity, activity, operating air equipment	Smart ventilation strategy		Slight reduction in average CO ₂ but significant reduction in peak CO ₂ levels	- 6–21% Of total airflow - 23–34% Of fan electrical energy demand

Reference Country	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
(Nielsen, 1992) <i>Denmark</i>	A new single-family house	Monitoring for 1 month	Air supply in all the rooms, with exhausts in the bathroom and in a scullery + local regulation	RH	A damper in the inlet duct of each room regulates air volume every min, RH < 45%		RH>45% 10% Of the time No condensation CO ₂ <1200 ppm 98% of the time	Total airflow reduced from 39% compared to the Danish code
(Kesselring et al., 1993) <i>Florida, USA</i>	1 Energy-efficient home	5 Days monitoring	Balanced + whole house	One indoor CO ₂ sensor	“On-off” controlled Δt=15 min set-point at 600 ppm		CO ₂ in master bedroom 600–900 ppm	Ventilation system turned on 1/3 of time
(Nielsen and Ambrose, 1995) <i>Denmark</i>	16 Apartments	Monitoring for 3 months	Balanced + whole house + centralized + local regulation	RH air supplies and exhausts controlled by capillary hygrometers in each room	Set-points at RH=40–45%.	Results compared to a group of 16 identical apartments equipped with constant airflow ventilation	Mean RH< 43% No condensation on windows	Maximum reduction in total airflow rate: 35% For outdoor temperatures > 9°C, 0%
(Römer and van Ginkel, 2003) <i>Petten, The Netherlands</i>	1 Test low-energy house	1) Preliminary modeling (TRNYS) + 2) experimental results	Balanced + whole house + local regulation	Occupancy + RH + indoor temperature	1a) Night-time strategy 1b) occupancy strategy 2) occupancy, RH> 70% or indoor temperature > comfort		1) Not studied 2) no significant risk biological agents, temperatures >25°C often occur during the winter, low radon levels	Modeled energy savings: 1a) 15% 1b) 20% 2) No information
(Afshari and Bergsøe, 2003) <i>Denmark</i>	1 Test 1-BR apartment 74 m ² , 2-person	Monitoring for 3 days	Exhaust-only, whole house + local regulation	RH + passively controlled RH air inlets	Minimum rate fixed at 10 L.s ⁻¹ , RH=45% activate a	2-Person occupancy simulated with CO ₂ and RH emissions, a constant N ₂ O emission simulated	CO ₂ concentration, 10% in living room	Total airflow rate reduced to 20–30%

Reference Country	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
	occupancy simulated				forced rate in humid rooms	from material and furnishings	*2 in the BR Pollutant emitted by materials and furnishings, 50%	
(Pavlovas, 2004) <i>Sweden</i>	A typical Swedish apartment	Modeling (IDA Indoor Climate and Energy)	Exhaust-only, whole house + global regulation	1) CO ₂ DCV with sensors in humid rooms, 2) RH DCV with sensors in humid rooms, 3) occupancy DCV	Exhaust airflow 10 L.s ⁻¹ or 30 L.s ⁻¹	Indoor doors closed or open were also tested	CO ₂ and occupancy DCV: similar CO ₂ concentrations but increase the risk for high humidity levels RH DCV: increases CO ₂ concentrations	Annual heat demand savings: >50% (CO ₂ and RH) 20% (occupancy control)
(Jreijiry et al., 2007) <i>Athens, Greece</i> <i>Nice, Trappes, France</i> <i>Stockholm, Sweden</i>	Single-family house	Modeling (MATLAB/Simulink and Simbad)	Whole-house assisted (hybrid) natural ventilation	Toilets: occupancy kitchen and bath: RH dry rooms: 1) occupancy detection 2) CO ₂	Air inlets and grills over 8 positions. A 10-min control algorithm regulates fan speed		CO ₂ exposure in occupied dry rooms at least reduced by a factor of 2, summer thermal comfort is nearly always bettered	Heating needs reduced: 2–5% Fan electrical consumption reduced: 91–96%
(Van den Bossche et al., 2007) <i>Uccle, Belgium</i>	1 House with different airtightness levels	Modeling with CONTAM	Whole-house exhaust-only	RH-controlled exhausts in humid rooms, self-regulating trickle ventilators in dry rooms, motion sensors in kitchen and bathroom	RH sensor control [20–100%] of nominal airflow for a RH range of [30–100%]. Motion sensors activate nominal	They simulated a 4-person occupation	IAQ slightly lower for the DCV system studied. In bathroom and bedroom of an airtight house (n ₅₀ =0.6 h ⁻¹), DCV system in the range only for 67% of the time	Energy savings around 1100–1200 kWh, 27% for very airtight houses, 14% for houses with an average airtightness. The moisture buffering effect adds only a

Reference Country	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
					airflows for 20–30 min			0.75% extra energy demand
(Krus et al., 2009) 3 climates in Germany	1 Test apartment 75m ² , 3 occupants	Modeling (Wufi-Plus)	Exhaust-only, whole house + local regulation	RH + RH	RH controls opening of valves in exhaust ducts	Comparison of an exhaust-only DCV system with a balanced-heat recovery system	CO ₂ stayed lower than 1200 ppm	Not investigated
(Woloszyn et al., 2009)	1 Test room	Modeling (TRNSYS, IDA-ICE, Clim2000, HAM-Tools)	Exhaust-only, whole house + local regulation	RH controlled extractions in humid rooms	RH sensors control nominal airflow for a RH range	Gains while keeping the peak RH values at the same level	RH in the range [40–50%] 80% of the time and CO ₂ concentrations higher than 1200 ppm 33% of the time during the cold period	Mean ventilation rate reduced by 30–40% and energy savings 12–17% in the cold period
(Air H, 2010; Bernard, 2009) Paris and Lyon, France	31 New apartments	Monitoring over 2 heating seasons	Exhaust-only + whole house + local regulation	RH-controlled exhausts + RH inlets + occupancy in toilets	Sections = mechanical function of RH	Parameters measured included ventilation parameters (pressure, air inlets opening cross-sectional area, airflows through the trickle ventilators and the extraction air outlets)	CO ₂ cumulative exposure and condensation risk very low IAQ better in bedrooms (nights) than with fixed air inlets	-30% measured total average airflow - 35–50% energy savings on fan consumption - 55% total ventilation energy savings
(Nielsen and Drivsholm, 2010) Denmark	A new single-family house	Measurements with and without the DCV system	Exhaust-only + whole house + centralized regulation	Difference CO ₂ and absolute humidity between measurements in air-handling unit and outdoors	High- and low-flow rates with set-points set at a difference of 150 ppm in CO ₂ and to 2 g/kg in absolute humidity	Measurements of the fan speed throughout the week showed that the control strategy succeeds in tracing the non-occupancy schedules	No significant change in IAQ	Low ventilation rate: 37% of the time energy savings estimated at 35% on fan electricity consumption and 23% on heating needs

Reference Country	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
(Seong, 2010) <i>Seoul, South Korean</i>	A standard Korean multizone apartment	Multizone modeling CONTAM + Energy plus $\Delta t=1$ hp	Whole-house balanced DCV system	1) CO ₂ demand 2) TVOC demand Location of the sensors unknown		“On-off” control strategy, with a base airflow rate set at the reference in the Korean regulation, 0.7 h ⁻¹	1) CO ₂ <1000 ppm, TVOC in 150–800 µg.m ³ with peaks 2) CO ₂ <2200 ppm, TVOC in 400–800 µg.m ³	1) 17% 2) 26%
(Laverge et al., 2011) <i>Belgium</i>	Typical Belgian single-family house	Modeling (CONTAM)	Exhaust-only whole house + local regulation	1) RH in humid rooms 2) occupancy 3) CO ₂ in dry rooms 4) the 3 combined	1) “On-off” size grille set point RH=70%, 2) “On-off” on fan, 20 min 3) inlets reduced to 10% if CO ₂ < 1000 ppm	Results were compared to a reference exhaust-only constant flow rate ventilation. CO ₂ detection in dry rooms was found to be more robust than the other ones	CO ₂ exposure better in 2) and 3) Same exposure to the toilet tracer gas	Total mean convective heat ventilation loss in the range 25% (1 control parameter) to 60% (3 combined)
(Mortensen et al., 2011)	Single-family house	Calculation approach	Whole-house ventilation	Occupancy schedules (of 4–8 or 16 h)	Two fan speeds based on the chronic exposure equivalence calculation	Performance curve plots can define optimized points given the occupancy time, the reference rate, the high to low ratio, the emission characterization	Equivalence in 24-h chronic exposure, acceptable peak exposure	Total ventilation rate, 12% Can achieve $\geq 18\%$ if occupant emissions are dominant
(Mortensen and Nielsen, 2011)	Multi-family dwelling	Modeling study	Whole house + balanced with heat recovery + centralized		Several control strategies on air handling unit		Strategy based on the resetting of the static pressure at part load conditions	Yearly electricity consumption: –20 to 30%
(Sherman and Walker, 2011) <i>3 climates, California, USA</i>	Single-family house	a) Modeling (REGCAP) b) Field study of a prototype (RIVEC)	a) Whole house + centralized + 4 ventilation types	Control by the operation of other air devices and	A controller logic with a set of actions at each time	The theoretical background assumes a continuously occupied	Decrease of the annual average relative dose can reach 14%	a) Energy savings: –11 to 61%. Run time of the ventilation

Reference Country	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
			b) exhaust-only with economizer	with a switch-off during a 4-h peak electricity demand period	step, set primarily at 10 min; 4 periods in the day	home with a constant emission rate	Peak relative exposure no more than 11% above the target limit, even with 4- h off period	fans: -25% b) Annual energy savings estimated to 1000 kWh. Run time of the fans: -71%
(Turner and Walker, 2012) <i>16 climate zones, California, USA</i>	Single-family houses (3 geometries)	Modeling (REGCAP)	Whole house + centralized + 6 ventilation types	Same + occupancy	Controller logic was updated with 2 periods in the day depending on occupancy	Energy savings are robust across climates, house geometries and airtightness levels	Maintaining the IAQ equivalence of ASHRAE 62.2, and without acute exposures to constantly-emitted pollutants	Ventilation energy savings > 40%. Absolute energy saving 500–7000 kWh/year. Peak power reduction up to 2 kW
(Turner and Walker, 2013) <i>16 climate zones, California, USA</i>	Single-family houses (3 geometries)	Modeling (REGCAP)	Whole house + centralized + hybrid exhaust-only system	Same	If the available airflow rate in a designed passive stack insufficient, RIVEC turns on the whole-house exhaust fan	The authors show that there was a place to optimize hybrid ventilation systems with good sizing of the passive stack and smart ventilation strategies	IAQ clearly bettered	Ventilation energy savings about 25%
(Walker and Sherman, 2013) <i>Livermore and Riverside, California, USA</i>	A typical California single-family house	Modeling (REGCAP)	Whole house + centralized + 7 types of ventilation	Same. The 4-h switch-off period for peak electricity demand is the same as that for ozone peak			A reduction of 10–40% in ratios of indoor-to-outdoor ozone, while continuous exhaust ventilation systems gave ratios around 20%	

Reference Country	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
(Less et al., 2014) <i>All USA climate zones</i>	Single-family houses (2 geometries)	Modeling (REGCAP)	Whole house + centralized + exhaust-only	Outdoor temperature	4 Control strategies were studied to optimize solution	The simplest strategy with a cut-off set at an outdoor temperature of 5°C was the most efficient one across a variety of climate zones	Equivalent IAQ	For leakier than 3 ACH ₅₀ houses in severe climate, HVAC energy savings in the range 100–4000 kWh. Fan should be oversized by an average of 34%
(Szkartat and Mróz, 2014) <i>Poznan, Poland</i>	1 Passive house	Monitoring 1 year + Modeling	Whole HVC system decentralized regulation	Temperature, RH, CO ₂ sensors in every room	VAV control as a function of sensible heat balance of temp control, latent heat balance of RH control, CO ₂ balance	The issue was how to define control parameter and algorithms to deal with high internal gains in passive houses	1000 ppm was often exceeded, sometimes reached 1500 ppm or more	Not studied
(Caillou et al., 2014b) <i>Belgium</i>	1-Level house	Modeling (CONTAM)	Natural, exhaust only, balanced + whole house + regulation centralized or local	1) RH exhaust only 2) CO ₂ supply only 3) RH exhaust+ CO ₂ supply 4) RH exhaust only + central regulation 5) CO ₂ supply only + central or zonal regulation	Multiple control strategies	Study evaluating different control algorithms mainly based on the 35 DCV systems available on the Belgian market	1) ~Reference 2) better than ref 3) clearly better 4) slightly better 5) better 6) better	1) 0% 2) 26–37% 3) 38–39% 4) –21 to –28% 5) –15% to +36% 6) 4–35%

Reference Country	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
(van Holsteijn and Li, 2014) <i>The Netherlands</i>	Occupied single-family house and apartments	Experimental 1-year measurement	Natural, exhaust-only, balanced + whole house + regulation centralized or local	6) CO ₂ sensor in dry room controlling exhausts (in dry room) 13 Types of ventilation systems including 7 CO ₂ or CO ₂ +RH DCV	/	IAQ-indicator, LKI ₁₂₀₀ , Equation 1. Depending on the location of sensors, they showed poor and good performance of DCV systems	Mean annually CO ₂ exposure +11% to -70% for a single-exhaust system	MJ/m ² /year -31% to +21% for a single-exhaust system
(Hesaraki and Holmberg, 2015) <i>Sweden</i>	3-Level low-energy house	Modeling (IDA ICE 4)	Exhaust-only, whole house, centralized	Occupancy, non-occupancy periods = 8 am-6 pm Low rate used for 4,6, 8, or 10 h, starting from 8 am	Base airflow rate 60 L.s ⁻¹ is switched to 16 L.s ⁻¹ during nonoccupancy periods	For an acceptable IAQ, ventilation turned on 2 h before occupants return; reference constant airflow system delivers 60 L.s ⁻¹	Mean age of air increases resp. by 5.5, 22.2, 50, 105.5%, VOC concentration at 6 pm increases by resp. 4, 20, 65, 211%, CO ₂ stayed below 1000 ppm	20% On heating needs 30% on fan consumption, 10% on total building energy consumption
(Lubliner et al., 2016) <i>Washington and Illinois, USA</i>	2 Houses	Modeling (REGCAP and EnergyGauge USA) + Test fields	Exhaust-only, whole house, centralized	Outdoor temperature	“On-off” strategy according to a predefined set point	Investigation of a low-cost temperature-based smart ventilation control (less than \$80)	No significant impact on CO ₂ and humidity	Energy savings between 73 to 230 kWh/year

*: the reference is the constant flow rate of the required standard. The reference is also different in each country.

** : the reference case is a classic natural ventilation system

***: the reference case is a balanced ventilation system manually controlled with 3 speeds

Part 2 conclusion

Analysis of performance-based approaches that both enable and reward smart ventilation used in five countries (France, Belgium, The Netherlands, USA, Spain) reveals emission scenarios, often multizone modelling levels and indicators taken into account. This review highlights that such approaches are rarely used at the building scale, as in our purpose, but rather at the ventilation system scale, i.e. using only standard input scenarios but not data related to a given building.

It was possible to draw through this review an overview of the used methods specifying:

- the person in charge of the calculation: often the ventilation manufacturer, but can be also the specifier, the designer, or the professional involved in the EP-calculation, depending on whether the performance-based approach is applied at the building's or at the ventilation's system scale,
- the calculation method: often a multizone modelling, using conventional input data either in a deterministic or in a semi-probabilistic way, on a given period (whole year / heating period), with a given time-step (from 40s to 1h),
- the calculated IAQ performance indicators: cumulative CO₂ above a certain limit, mean CO₂ over a year (or other lengthy period), time above relative humidity thresholds, and very rarely the exposure to other pollutants of concern for occupant health.

We conclude that performance-based approaches and associated IAQ performance indicators vary from country to country and even if they have indicators in common (e.g., cumulative CO₂ above a certain level) the levels and target values are always different.

Through our meta-analysis on the performance reported in 38 studies of various residential smart ventilation systems since 1983, we learnt that demand-controlled ventilation based on CO₂ or humidity is the most established and the most studied smart system. Our review shows that there is clearly a potential for improved indoor air quality using smart ventilation strategies with significant energy savings up to 60%, with less favorable results. A very clearly identified scientific problem through this reviewing work is the lack of ventilation performance indicators, most of them being only CO₂ and humidity based indicators. Again, IAQ performance indicators vary from a study to another one, even if some indicators are more often used (e.g., average CO₂ concentration, average RH concentration, percentage of RH out of a range, cumulative CO₂ exposure above a certain level) the levels and target values are always different. As a conclusion, if residential smart ventilation systems energy performance is clearly demonstrated in the literature, new robust and common performance-based methods, using notably better IAQ performance indicators, are still needed to assess their IAQ performance.

From these both reviews, we showed the need of robust performance-based approaches for ventilation, using notably better IAQ performance assessment calculation and better IAQ indicators. Moreover, their applicability to all types of ventilation, and not only to smart ventilation is an issue of concern. Indeed, with CO₂-based DCV ventilation for instance, it is easy to obtain a good IAQ performance indicator based on CO₂ cumulative exposure over a threshold, if the switching value of the ventilation system is set just below this threshold. Consequently, the proposed method should allow to obtain a more robust IAQ assessment, based on several IAQ performance indicators using several indoor pollutants, to avoid such pitfalls.

3

Development of an original database from multizone airleakage measurements in twenty-three homes

Once we know more about performance-based approaches and used IAQ performance indicators reviewed in Part 2, we can now focus on the pollutant and airflows modelling issue. As soon as we model airflows in residential buildings, as highlighted in the Introduction and in the Part 2, the airleakage becomes an essential input parameter to consider. If the energy performance calculations are generally based on single-zone models with uniform envelope airleakage, as it is the case in France (JO, 2011), we have seen in Part 2 that multizone modelling is usually used in performance-based approaches for ventilation. Indeed, airleakage interferes with theoretical mechanical ventilation airflows and thus can affect IAQ in each room.

The issue of using more detailed data on envelope airleakage distributions become a crucial issue. However, unevenly distributed envelope airleakage is rarely investigated since it is often considered as evenly distributed in standards (CEN, 2007a; CEN, 2009) and in literature on ventilation performance (Boulanger et al., 2012b; Laverge et al., 2013; Laverge and Janssens, 2013).

In addition, taking into account internal partition wall airleakage distributions should also be considered. Indeed, leaks located on internal partition walls would directly interfere with theoretical mechanical ventilation airflows supposed to occur through doors undercuts. For instance, if we neglect them, all the fresh air coming in the bedrooms would go out through the doors to be extracted in the humid rooms. In reality, short-circuits could occur and airflows could go from a bedroom to another one through those leaks on internal partition walls.

We referred in the introduction to some experimental studies showing that envelope airleakage was not evenly distributed and that internal airleakage was unneglectable (Bossaer et al. 1998; Du et al. 2012; Guyot, Limoges, and Carrié 2012). (Bekö et al., 2010; Koffi, 2009) suggested that additional

research was needed both to get precise data on these uneven external and internal airleakage distributions, and to quantify their impacts on IAQ.

To complement results from the literature, we will organize a detailed airleakage measurement campaign on 23 homes including measurements on envelope and on internal partition walls. Results from this campaign will be analyzed and described in Part 3 through a paper published in *Building and Environment* (Guyot et al., 2016). In the second step, in Part 4, we will use those data as inputs in a multizone modelling, in order to quantify impacts on IAQ performance indicators.

Multizone Air Leakage Measurements and Interactions with Ventilation Flows in Low-Energy Homes

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ABSTRACT

Given that airtightness is recognized as an essential issue for low-energy dwellings, today it is often included in energy performance (EP) calculations, frequently through single-zone models with uniform air leakage. Because more consideration is often given to EP than to indoor air quality issues, air leakage through internal partitions is often disregarded. Therefore, additional studies are needed to check these assumptions.

In the present study air leakage through the building envelope and through internal partitions is investigated. This paper presents the methodology used in an experimental study, conducted to measure multizone air leakages, using the guarded zone pressurization technique. We developed a detailed innovative database with 456 exterior and internal partition wall air leakage measurements, taken in 23 detached houses. For each wall, the database includes general information on the building, special requirements, the building's main characteristics, measurement protocol, type of wall, measurement input data and measurement results (C_L , n , q_{50} and the reliability index developed). Then an analysis of this database is provided. The analysis reveals most important relationships. For instance, internal partition wall air leakage is not related to the envelope's airtightness level; instead, the type of building structure has greater influence. Through this study, we underline the impact on building airflows of more detailed modelling of internal and external air leakage in multizone approaches, with consequences on indoor air quality (IAQ) bedrooms where people spend most of their time. As a conclusion, we propose air leakage values and dispersion input data for multizone IAQ models.

KEY WORDS

Ventilation, air leakage, measurements, single-family dwellings, indoor air quality

I. INTRODUCTION

Adequate air change rates are necessary to ensure good indoor air quality, including a proper humidity level in buildings. On the other hand, building energy performance (EP) requires rethinking the ventilation and the air change rates, because of their impact on thermal losses. In this context, envelope airtightness treatment becomes crucial, especially for low-energy dwellings (Erhorn et al., 2008). Indeed, envelope air leakage entails thermal losses, but also modifies theoretical voluntary airflow circuits in a building. (Boulanger et al., 2012) (Laverge and Janssens, 2013) confirmed that envelope airtightness promotes better ventilation performance and indoor air quality in low-energy buildings, because the theoretical airflow circuits in buildings are better controlled.

In France, the recent thermal regulation (RT2012) generalizes low-energy dwellings and requires envelope airtightness for any new dwelling. For a single-family dwelling, the airtightness requirement is $q_{a4}=0.6 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$, (eq. (1)), that is around $n_{50}=2.3 \text{ h}^{-1}$ (eq. (2)) This EP regulation also requires an EP simulation at the design stage, based on a dynamic hourly calculation of thermal losses through the envelope, taking into account, for instance, meteorological data. The calculation checks that EP indicators are respected at the design stage with three kinds of performance requirements: 1- energy efficiency (independent of systems); 2- primary energy consumption (under approximately 50 kWh/year/m², including heating, domestic hot water, lightning, ventilation and auxiliaries) and 3- summer comfort (for buildings without air-conditioning). This is a performance-based approach.

This EP regulation does not include any new requirements on ventilation rates. The airing of dwellings comes under another 30-year-old regulation (JO, 1982), which imposes general layouts for the ventilation system and requires values for the extraction airflows in “humid” rooms, depending on the dwelling size. It uses a standardized approach.

The present paper is a part of a PhD thesis, which develops a performance-based approach for ventilation in low-energy dwellings, integrating indoor air quality and health issues. This approach implies a more precise quantification of airflows in dwellings and between rooms to prevent global and/or local situations with high pollutant or humidity levels.

Since airtightness is recognized as an essential issue for low-energy dwellings, today it is often included in regulatory EP calculations, often through single-zone models with uniform air leakage (CEN, 2007), (JO, 2011). Nevertheless, when envelope air leakage is non-uniformly distributed, IAQ impacts can be strong: if a room has substantial leakage, the other rooms can also be short-circuited and become under-ventilated. Furthermore, because more consideration is often given to EP than to indoor air-quality issues, air leakage through internal partitions is often disregarded. The limits of these assumptions have already been partially studied, either through multizone airflows measurements (Reardon et al. 1987), (Gustavsen et al., 2012), or in multizone modelling studies (Roldan et al., 1987), (Richieri et al., 2013), (Laverge et al., 2013), or in combined studies (Jokisalo et al., 2008), (Offerman, 2009), (Du et al., 2012), (Hult et al., 2012). Nevertheless, additional studies are needed to collect data in order to further check these assumptions, especially in the context of low-energy houses. Therefore, in the present study air leakage through the building envelope and through internal partitions was investigated.

Firstly, this paper presents the methodology, with the objective of measuring multizone air leakages, using the “guarded zone” pressurization technique. These measurements were used to

develop a detailed database, which includes, for each internal partition or exterior wall general information on the building, special requirements (certifications, thermal regulation), the building's main characteristics (main material, structure type, ventilation system, insulation type, number of levels, envelope airtightness), measurement protocol, type of wall, measurement input data (altitude, wind velocity, temperatures, area, volume) and measurement results (C_L , n , q_{50} , uncertainties of derived quantities and the reliability index developed).

This paper presents the analysis of the results of this innovative database, highlighting the most important relationships.

We then propose air leakage values and dispersion input data for multizone IAQ models.

The paper concludes with on-going developments concerning a numerical multizone study using these new data.

II. METHODOLOGY OF MULTIZONE AIR LEAKAGE MEASUREMENT CAMPAIGN ON 456 WALLS

1. Air leakage measurement indicators

During our campaign, we measured:

- In each house, the envelope air leakage. We used the French indicator q_{a4} [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$], eq. (1), which uses the envelope area excluding the lowest floor, converted into air change per hour at 50 Pa n_{50} [h^{-1}], eq. (2).
- In each room, the exterior wall air leakage, to obtain data on the envelope air leakage distribution on each exterior wall of the house. We used the air change rate q_{50} [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$], eq. (3) and the equivalent air leakage area ELA_4 [cm^2], eq. (4).
- In each room, the internal partition wall air leakage, to obtain data on quantification and distribution of air circulating from one room to another. We used the air change rate q_{50} [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$], eq. (3), and the equivalent air leakage area ELA_4 [cm^2], eq. (4).

$$q_{a4} = \frac{C_L \cdot (4)^n}{A_{env}} \quad (1)$$

$$n_{50} = \frac{C_L \cdot (50)^n}{V} \quad (2)$$

$$q_{50} = \frac{C_L \cdot (50)^n}{A} \quad (3)$$

$$ELA_4 = \frac{C_L}{C_D} * \sqrt{\frac{\rho_0}{2}} * \Delta P_r^{n-0.5} * \frac{1}{3.6} \quad (4)$$

where C_L is the air leakage coefficient [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{Pa}^{-n}$]; 4 is a 4-Pa reference pressure difference across the building envelope; n is the airflow exponent [-]; A_{env} is the envelope area excluding the lowest floors [m^2]; 50 is a 50-Pa reference pressure difference across the building envelope or across the measured wall; V is the building's heated volume [m^3]; A is the area of the measured wall; ρ_0 is the standard air density [$\text{kg} \cdot \text{m}^{-3}$]; C_D is the discharge coefficient [0,6]; ΔP_r is the reference pressure difference [4 Pa].

These indicators are all derived from the power-law function, eq. (5), linking the airflow through the envelope leaks [$\text{m}^3 \cdot \text{h}^{-1}$] to the pressure difference across the building envelope ΔP [Pa]:

$$Q = C_L * \Delta P^n \quad (5)$$

2. Description of the 23-house sample

Table 1 gives a description of the sample: the year the building was commissioned, whether the structure was a heavy (concrete, bricks or concrete blocks) or a light construction (wood), certification, the number of levels, the ventilation system, the floor area and the envelope airtightness value. Five types of ventilation system exist: no ventilation (4%), balanced ventilation (called “Balanced”, 39%), humidity-controlled balanced ventilation (called “Bal.DCV”, 4%), exhaust ventilation (called “Exhaust”, 13%) and humidity-controlled exhaust ventilation (called “DCV Ex”, 39%) (Figure 1).

The certification provides information on envelope airtightness. In the 2005 French low-energy certification (BBC) and in the recent French EP regulation (RT2012), envelope airtightness must be under $q_{a4}=0.6 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$. In the Passivhaus certification, it must be under $n_{50} = 0.6 \text{ h}^{-1}$. Sixty per cent of the houses in the sample fulfil the low-energy and envelope airtightness certification requirements.

Wood material (39%), wood structures (35%) and balanced ventilation systems (43%) were more numerous in this sample than in the new building stock (Figure 1). They account for only a small fraction of the new dwelling stock in France.

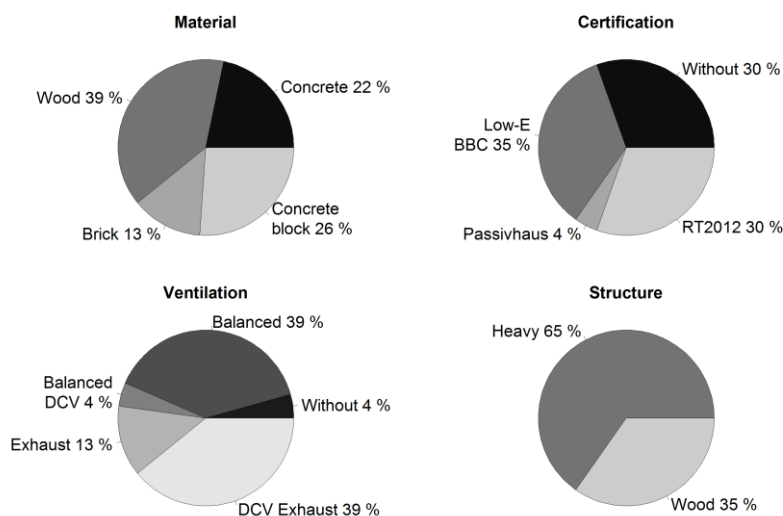


Figure 1 Overview of the 23-house sample.

Table 1. Characteristics of the 23 houses measured

House	Building year	Structure type	Certification	Number of levels	Ventilation system	Floor area (m ²)	Envelope area A _{env} (m ²)	Volume (m ³)	q _{a4} (m ³ ·h ⁻¹ ·m ⁻²)	n ₅₀ (h ⁻¹)
1	1987	Heavy	No	2	no	136.0	273.1	385.5	0.85	3.07
2	2013	Heavy	BBC	2	Balanced	161.2	260.5	400.3	0.31	1.32
3	2013	Wood	No	2	Balanced	130.9	240.3	350.0	1.10	3.55
4	2015	Heavy	RT 2012	1	DCV Ex	102.4	217.2	241.5	0.20	1.14
5	2013	Wood	BBC	2	Balanced	127.1	231.0	339.7	0.57	2.13
6	2014	Wood	RT 2012	3	DCV Ex	183.1	317.0	386.0	0.46	2.25
7	1987	Heavy	No	2	Exhaust	122.6	249.0	315.6	2.17	8.45
8	2014	Heavy	RT 2012	2	DCV Ex	114.7	192.7	291.3	0.66	2.11
9	1973	Heavy	No	1	Exhaust	111.6	239.2	290.2	1.24	5.09
10	2013	Wood	RT 2012	3	Balanced	209.6	315.2	453.0	0.80	2.90
11	2012	Heavy	No	2	DCV Ex	201.2	355.9	525.7	0.74	2.77
12	2013	Wood	RT 2012	1	Balanced	139.4	256.0	329.0	0.13	0.58
13	2014	Wood	RT2012	2	Balanced	143.4	283.9	381.2	0.29	1.11
14	2014	Heavy	RT2012	1	DCV Ex	167.5	332.0	411.0	0.47	2.08
15	2014	Heavy	BBC	2	DCV Ex	104.6	218.8	261.5	0.31	1.34
16	2013	Heavy	No	2	Bal. DCV	141.2	310.7	369.5	0.95	3.91
17	2015	Wood	RT 2012	2	DCV Ex	193.6	422.7	532.1	0.19	1.02
18	2010	Heavy	BBC	2	DCV Ex	164.0	261.0	388.0	0.33	1.28
19	2013	Heavy	No	2	DCV Ex	160.3	275.6	457.1	0.97	2.81
20	2015	Wood	Passivhaus	3	Balanced	335.9	805.3	1029.0	0.30	1.43
21	2007	Heavy	No	2	DCV Ex	137.1	211.3	312.4	1.28	4.48
22	2013	Heavy	BBC	2	Balanced	156.0	232.0	361.0	0.44	1.56
23	2013	Wood	BBC	3	Balanced	121.0	256.0	302.0	0.56	2.58

3. Measurement protocol

Multizone air leakage measurement methods in the literature. Interest in multizone air leakage measurements began in the 1980s with studies measuring air leakage with tracer gas (Roldan et al., 1987) or with depressurization techniques such as the balanced fan pressurization technique (Shaw, 1980), (Reardon et al., 1987). (Fürbringer et al., 1988) further developed the balanced fan pressurization technique with a special device and called this method the guarded zone method. This method made it possible to measure the air leakage of a wall, using two depressurization devices. The first one is used to depressurize the building envelope. The second one is used on the guarded zone in order to maintain a zero-pressure between the guarded zone and the rest of the building, and to measure airflow through the studied wall. During the first step of the method, the exterior wall air leakage of the guarded zone is measured. Then the measurement can be repeated after having opened adjacent zones, step-by-step, outdoors to balance exterior pressure. Consequently, guarded zone internal partition wall air leakage can be obtained by subtraction at each step (**Figure 2**). In the literature, air leakage multizone measurements have rarely been conducted on internal partition walls in houses (Reardon et al. 1987), but instead on walls separating dwellings in multi-family buildings (Fürbringer et al., 1988), (Herrlin and Modera, 1988), (Hult et al., 2012), or between houses and their garages (Offerman, 2009), (Emmerich et al., 2003), (Hult et al., 2012).

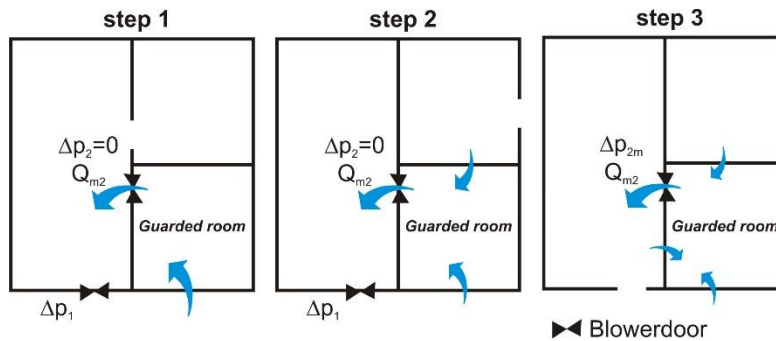


Figure 2 Illustration of the guarded zone method. Step 1: Only the external leakage is measured through device no. 2. Step 2: Additional air leakage from the first adjacent room is measured. Step 3: Additional air leakage from the second adjacent room is measured.

Air leakage accuracy in the literature. Because the airleakage is not directly measured, but extrapolated from measurable parameters, airleakage accuracy is not only a measurement accuracy problem, but also a modelisation accuracy problem (Sherman and Palmiter, 1995). Indeed, airflows are not measurable at low pressures (under 4 Pa) than the houses normally experience. This paradigm is well summarized by (Walker et al., 2013): “*Unfortunately, the more precise the blower door measurements are, the larger the extrapolation error becomes, making the most precise measurements the least accurate ones*”. (Sherman and Palmiter, 1995) suggest that airleakage error must be calculated as the square root of the sum of the squared errors from measurement and modelisation.

Estimating a multi-points airleakage measurement accuracy through the measurement uncertainty is well documented. Sources of errors during an envelope air leakage measurement have several origins, including precision and bias of the measurement devices, the impact of the user, the impact of the meteorological data and derived quantity uncertainties. The ISO guide (ISO/IEC, 2008) proposes a general method to estimate the expanded uncertainty of a measurement. (Sherman and Palmiter, 1995) proposed to consider the measurement error as the square root of the sum of the squared errors from precision, considered as the regression analysis error, and the bias. (Delmotte, 2013) and (Alfano et al., 2012) pointed out that the EN ISO 9972 proposes only a method to estimate the uncertainty on the derived quantity through a regression analysis, but that concerning the overall uncertainty, this standard just includes a general sentence “*the overall uncertainty can be estimated using the error propagation calculation*”. These both authors proposed two applications of the method described in the ISO guide (ISO/IEC, 2008) to the airleakage measurement proposed in EN ISO 9972. They describe formulations respectively for the combined standard uncertainty and the relative expanded uncertainty of the airleakage rate at 50 Pa, n_{50} . According to (Alfano et al., 2012), the relative expanded uncertainty on n_{50} ranges from 10 to 15%, and can increase up to 20-40% when measurements are no repeatable or when measurement devices are not calibrated. According to ISO guide (ISO/IEC, 2008), reproducibility (different operators, different measurement devices) and repeatability (same operator, same equipment) are indeed two influence quantities that

may affect measurement uncertainty and that can be used in the definition of the uncertainty budget. (Bracke et al., 2016) recently studied repeatability of the pressurization test on two passive houses and reported average standard deviations less than 2.7% within the same day, with an average maximum variation of 7.7%. These results are quite consistent with those of previous studies on airleakage measurement reproducibility and/or repeatability reviewed in this paper (Persily, 1982), (Kim and Shaw, 1986), (Murphy et al., 1991), (Delmotte and Laverge, 2011).

Finally, it seems also important to mention in this field, that (Delmotte, 2013) and (Sherman and Palmiter, 1995) underlined that the application of a weighted method of least-squares is generally more appropriate, than the usually used unweighted method, in the framework of building airleakage measurement. Indeed, such a method allows taking into account the fact that errors change substantially over the range of measurement.

Uncertainties related to the air leakage multizone measurement techniques are also well documented. With tracer gas techniques, uncertainties were estimated around 25% (Roldan et al., 1987). Using an especially developed device, uncertainties related to balanced fan pressurization techniques were estimated between 10% (Fürbringer et al., 1988) and 15% (Shaw, 1980). It could be reduced to 10%, taking into account errors due to a wind velocity lower than $5 \text{ m}\cdot\text{s}^{-1}$, if the base pressure in the guarded zone is kept at 50 Pa instead of 0 Pa (Herrlin and Modera, 1988). These authors showed that the wind impact is lower than the quality of the measurement protocol by itself, which might cause uncertainties around 40% when measurement is imperfect. In a more recent study (Hult et al., 2012) (Hult and Sherman, 2014), the authors were looking for the simplest measurement method (with one depressurization device) that could give the most robust and precise results concerning the air leakage of a wall located between a house and an attached garage. Using a single depressurization device, they developed a method with only 20% uncertainty. This method was based on measurement within six pressure difference ranges on the house envelope, when the garage is open to outdoor pressure and then on the garage, once the house had been closed.

Literature concerning airleakage modelisation accuracy is more limited. Nevertheless, from analysis of the power-law function, eq. (5), and from regression analysis methods (EN ISO 9972), we can identify that modelisation errors come in many forms. Firstly, we assume that the pressure across the envelope is uniform, which is very theoretical because of the wind pressures, and not physically resolved by the correction proposed in the EN ISO9972 with the baseline pressures measurements. Recent studies (Walker et al., 2014), (Carrié and Leprince, 2014) have shown that wind velocity, could have a substantial impact on envelope airtightness accuracy. On a simple model, with steady-state wind and one measurement point, (Carrié and Leprince, 2014) showed that, for wind speeds up to $10 \text{ m}\cdot\text{s}^{-1}$, modelisation errors could account for 12% on the airflow rate at a pressure point of 50 Pa and for 60% at 10 Pa. Secondly, we neglect the deviation of the flow exponent over the range of pressures (Sherman, 1992). (Sherman and Palmiter, 1995) listed other assumptions, which could add modelisation errors: the equality between the airflow through the envelope and the flow through the ventilator, the consistent character of the air density passing through the fan during the test, the extrapolation of the airflow using a power-law formulation beyond the measurement limits (for indicators at 4 Pa: ELA_4 or q_{a4}). These authors conclude that well characterized data are missing in order to determinate the size of the modelisation errors.

When using the guarded zone method, leakage airflows are not measured directly but are calculated indirectly, by a subtraction method developed in the following paragraphs. As explained by (Herrlin and Modera, 1988), we also add new modelisation errors to all classical envelope air leakage modelisation errors stemming from this method. Notably, it is assumed that the measured zero pressure between the guarded zone and adjacent zones is uniform.

Description of the selected protocol. In this study, we used the guarded zone method with two depressurization devices (Fürbringer et al., 1988), Figure 2. The guarded zone here discussed is always made up of one opening, the one where the blower door test is installed. In the first campaign conducted in 2014, two devices accommodating airflow rates ranging from 19 to 7200 m³.h⁻¹ were used. With these devices, we were not able to measure some low airflows through some very airtight walls. In the second campaign in 2015, we used two types of device: device 1 accommodated an airflow rate ranging from 19 to 7200 m³.h⁻¹ and device 2 an airflow rate ranging from 0.61 m³.h⁻¹ to 1393 m³.h⁻¹. Device 2 was used on the guarded zone, where low airflows could be measured. All these measurement devices comply with French standard annex (AFNOR, 2014). So that maximum permissible error of differential pressure measurement devices is less than 1 Pa in the range [-100 Pa, +100 Pa], that maximum permissible error of airflow measurement devices is less than the maximum between 2 m³/h and 7% times the airflow in the used range, and that corresponding certificates are less than a year old. On each room, we used the guarded zone method to determine each wall air leakage, except for the toilet where only an envelope air leakage measurement was taken. At each step, we took measurements during 30 seconds with 100 points at eight pressure ranges [$\Delta P = -10; -20; -30; -40; -50; -65; -80; -95$ Pa] measured with device 1. The highest pressure is close from 100 Pa, since the EN ISO 9972 recommends to take readings up to 100 Pa for a best measurement accuracy of calculated results, as demonstrated in the literature by (Delmotte and Laverge, 2011) and (Walker et al., 2013). Once steady state had been obtained with the two depressurization devices, we simultaneously plotted airflow at device 2 and pressure difference at device 1.

At each step, we evaluated wind velocity (Beaufort scale), temperatures (indoors, in the guarded zone, outdoors) and zero pressure differences to perform corrections according to EN ISO 9972. During tests using this method, air entering the guarded zone was mixed air between outdoor air and air in the adjacent zones, which was not exactly at the outside temperature even if windows were open. Nevertheless, we considered the outdoor temperature to perform the corrections on airflows. If large gaps were observed, we used an estimated value between outdoor and indoor temperatures. Then the time duration for one measurement (around 20 min) was low enough to consider constant temperatures during the test.

For each house, an envelope air leakage test was also performed, according to the EN ISO 9972 and GA P50-784 standards.

Meteorological conditions. The measurements were not taken during the winter to avoid high temperature differences between indoor and outdoor environments and high wind velocities. The first campaign was undertaken during spring 2014 and the second one during summer and fall 2015.

For some houses (no. 2, 3, 5, 21, 22, 23), a meteorological station was available and allowed us to check that wind velocity was low enough to not decrease measure accuracy. However, in five houses wind velocity was quite high (6 on the Beaufort scale) in 41 cases (9% of the sample). We decided to keep these measurements and to analyse them using a reliability index (developed below).

Measurement campaign. Table 2 gives an overview of the measurement campaign conditions for the 23 houses and the 456 air leakage measurements on exterior and internal partition walls. The wind exposure is characterized by 0 if the tested house is located in an urban area or strongly sheltered by obstacles in a rural area, by 1 if the tested house is located in a rural area but with some obstacles around, by 2 if the tested house is located in a rural area without any obstacle to the wind.

Table 2. Synthesis of campaign measurement conditions

House	Measurement period	Air leakage measurement devices	Maximum wind (Beaufort scale)	Outdoor median temperature (°C)	Wind exposure (-)	Number of walls for air leakage measurements
1	July 2015	type 2*	6	25	0	25
2	July 2015	type 2*	0	22	1	25
3	July 2015	type 2*	0	27	1	22
4	July 2015	type 2*	0	17	1	19
5	July 2015	type 2*	3	28	1	16
6	August 2015	type 2*	0	25	1	28
7	August 2015	type 2*	0	19	0	25
8	August 2015	type 2*	4	19	2	20
9	August 2015	type 2*	0	19	1	13
10	August 2015	type 2*	6	19	0	18
11	September 2015	type 2*	6	22	2	18
12	September 2015	type 2*	1	20	2	14
13	September 2015	type 2*	1	16	0	21
14	September 2015	type 2*	6	19	2	13
15	September 2015	type 2*	6	19	2	20
16	October 2015	type 2*	1	13	0	20
17	October 2015	type 2*	1	15	2	19
18	October 2015	type 2*	1	13	2	24
19	October 2015	type 2*	1	12	1	18
20	October 2015	type 2*	1	5	2	15
21	April 2014	type 1*	1	21	1	19
22	March 2014	type 1*	1	24	1	29
23	May 2014	type 1*	1	24	1	15

* Type 1 = two devices, 1 with airflows ranging from 19 to 7200 m³.h⁻¹, type 2 = device 1 and device 2 with airflow ranging from 0.61 to 1393 m³.h⁻¹.

4. Method for measurement analysis

Measurement data analysis. The calculation of wall air leakage from the set of measurements is described below with greater precision. For each room, at step 1 (**Figure 2**), $\{\Delta p_{m,1,k}; Q_{r,1,k}\}$ were measured and read, and then corrected according to EN ISO 9972 to obtain $\{\Delta p_{1,k}; Q_{1,k}\}$ sets, eqs. (6-7). Then the air leakage characteristics for the exterior wall $\{C_{L1}; n_1\}$ were calculated, eqs. (8-13). At step 2, we performed the same calculations, then starting from $\{C_{L2}; n_2\}$, a new set of data $\{\Delta p_{1,k}; Q_{12,k}\}$ was calculated by a subtraction, eq. (14). This set was then used to calculate air leakage characteristics for this internal partition wall $\{C_{L12}; n_{12}\}$, eq. (12&15). Finally, the airleakage rate Q_{50} of the wall was calculated using these characteristics, eq. (16).

$$x_{j,k} = \ln(\Delta p_{j,k}); \Delta p_{j,k} = \Delta p_{m,j,k} - \frac{\Delta p_{0,j,1} + \Delta p_{0,j,2}}{2} \quad (6)$$

where $\Delta p_{m,j,k}$ is the measured difference pressure at step j of the guarded zone method and at point k of the depressurization method composed of N points; $\Delta p_{0,j,1}$ and $\Delta p_{0,j,2}$ are respectively the zero-flow pressure differences measured at the beginning and at the end of the test.

$$y_{j,k} = \ln(Q_{j,k}); Q_{j,k} = Q_{r,j,k} * \left(\frac{\rho_{j,int}}{\rho_{j,out}}\right) * \sqrt{\frac{\rho_0}{\rho_{j,int}}} \quad (7)$$

where $Q_{r,j,k}$ is the read airflow on measurement device at step j of the guarded zone method and at point k of the depressurization method composed of N points; $\rho_{j,int}$ and $\rho_{j,out}$ are respectively the internal and external air densities [kg.m^{-3}] deduced from temperatures measurements at step j of the guarded zone method.

$$\bar{y}_j = \frac{1}{N} \sum_{k=1}^N y_{j,k} \quad (8)$$

$$\bar{x}_j = \frac{1}{N} \sum_{k=1}^N x_{j,k} \quad (9)$$

$$S_{xy,j} = \frac{1}{N-1} \sum_{k=1}^N (x_{j,k} - \bar{x}_j)(y_{j,k} - \bar{y}_j) \quad (10)$$

$$S_{x^2,j}^2 = \frac{1}{N-1} \sum_{k=1}^N (x_{j,k} - \bar{x}_j)^2 \quad (11)$$

$$n_j = \frac{S_{xy,j}}{S_{x^2,j}} \quad (12)$$

$$C_{L,j} = \left(\frac{\rho_{j,int}}{\rho_0}\right)^{1-n_j} * e^{\bar{y}_j - n_j * \bar{x}_j} \quad (13)$$

$$Q_{12,k} = C_{L2}(\Delta p_{1,k})^{n2} - C_{L1}(\Delta p_{1,k})^{n1} \quad (14)$$

$$C_{L12} = \left(\frac{\rho_{2,int}}{\rho_0}\right)^{1-n_{12}} * e^{\bar{y}_{12} - n_{12} * \bar{x}_{12}} \quad (15)$$

$$Q_{50,12} = C_{L,12}(50)^{n_{12}} \quad (16)$$

Airleakage accuracy and construction of a reliability index. In this study, low airflows were encountered, with direct and indirect measurements including a subtraction, eq. (14), sometimes with high wind velocities. We were also exposed to measurement and modelisation errors, on which characterization data are missing (Sherman and Palmiter, 1995). We decided to keep all the data and used a reliability index, I_R , to describe the confidence we have in every calculated wall air leakage. This index can be calculated starting from three-error estimation parameters e_i , eq. (17). I_R is 100% for high reliability measurements.

$$I_R(\%) = \frac{1}{3} \sum_1^3 e_i \quad (17)$$

- e_1 is derived from the Q_{50} measurement precision error estimation, E_1 , resulting in eqs. (7–9). We used the Annex C of EN ISO 9972, to calculate the standard uncertainty associated with a Q_{50} airleakage measurement, analysed through a linear regression, which we note ε_1 . This calculation is obviously not relevant if the measurement points do not describe a line. Since airflow was measured indirectly, using a subtraction, and modelisation associated errors are not directly calculable, we consider as acceptable for r^2 a range of [0.9;1]. Eq. (23) fulfills $E_1 = \varepsilon_1$ when $r^2 = 0.98$; $E_1 = 2\varepsilon_1$ when $r^2 = 0.9$, and proposes a linear extrapolation between these both values, determining the parameters $a = -12.5$ and $b = 13.25$.

$$\varepsilon_1 = U(Q_{50,12}) = \frac{1}{2} \left(e^{I_{y,12}(\ln(50))} - e^{-I_{y,12}(\ln(50))} \right) \quad (18)$$

$$I_{y,12} = S_{y,12}(\ln(50)) * t_{95,N-2} \quad (19)$$

where $t_{95,N-2}$ is the two-sided confidence limits for a student's t-distribution at a level of confidence of 95% and with N measurements.

$$S_{y,12}(\ln(50)) = S_{n,12} \left(\frac{N-1}{N} S_{x,12}^2 + (\ln(50) - \bar{x}_{12})^2 \right)^{1/2} \quad (20)$$

$$S_{n,12} = \frac{1}{S_{x,12}} \left(\frac{S_{y,12}^2 - n_{12} * S_{xy,12}}{N-2} \right)^{1/2} \quad (21)$$

$$E_1 = \varepsilon_1 \text{ if } r^2 > 0.98 \quad (22)$$

$$E_1 = (a r^2 + b) \varepsilon_1 \text{ if } r^2 \in [0.98; 0.9] \quad (23)$$

$$E_1 = \max(1; 2\varepsilon_1) \text{ if } r^2 < 0.9 \quad (24)$$

- e_2 can be considered as the confidence we have in the calculated n exponent. The n-value

must be between 0.5 and 1 corresponding to fully turbulent developed and laminar flows (Walker et al., 1998), in this range the value for e_2 is 100% (Table 3). (Sherman, 1992) demonstrated that the n exponent is pressure-dependent. Once again, confronted to not calculable modelisation errors, we consider as acceptable a range of [0.45; 1.05] for n , but with a value for e_2 of only 50%.

- e_3 is derived from the relative gap between the sum of all the walls Q_{50} of a zone (calculated for each wall) and the envelope air leakage zone Q_{50} (measured directly), E_3 . This gap measures notably the modelisation error resulting from the hypothesis that the zero pressure between the guarded zone and adjacent zones is uniform, which is used in all successive subtractions. In the database of 456 measurements, this gap is less than 7% for 100%.

A first database analysis allowed us to define each error estimation parameter (Table 3), e_i . For e_1 and e_3 , after having fixed the upper ($e_1=100\%$ if $E_1=5\%$ and $e_3=100\%$ if $E_3=3\%$) and lower ($e_1=10\%$ if $E_1=50\%$ and $e_3=80\%$ if $E_3=7\%$) thresholds, we proposed to linearly extrapolate for intermediate values. For e_2 , only three threshold values are proposed.

Table 3. Proposed values to calculate a reliability index I_R

$e_1(\%)$	$e_2(\%)$	$e_3(\%)$
$e_1=100$, if $E_1 < 5\%$	$e_2=100$, if $n \in [0.5 ; 1]$	$e_3=100$, if $E_3 < 3\%$
$e_1=c * E_1 + d$, if $5\% \leq E_1 \leq 50\%$ $c=-200$ and $d=110$, obtained by linear extrapolation	$e_2=50$, if $n \in [0.45 ; 1.05]$	$e_3=e * E_3 + f$, if $3\% \leq E_3 \leq 7\%$ $e=-500$ and $f=115$, obtained by linear extrapolation
$e_1=0$, else	$e_2=0$, else	$e_3=0$, else

For the data available on 59 walls, in order to further investigate global errors including modelisation errors, we also calculated the relative gap between both Q_{50} of a single wall, the first one from the first guarded zone to the adjacent zone, the second one from this adjacent zone now considered as the guarded zone. In these 59 walls, 36 walls had Q_{50} lower than $20 \text{ m}^3 \cdot \text{h}^{-1}$; the 23 other walls had Q_{50} higher than $20 \text{ m}^3 \cdot \text{h}^{-1}$. Analyzing data measured on the 36 walls with Q_{50} lower than $20 \text{ m}^3 \cdot \text{h}^{-1}$, we observed that only 16% (six partitions) had this gap lower than 20%. When analyzing the other 23 walls with Q_{50} higher than $20 \text{ m}^3 \cdot \text{h}^{-1}$, we observed as expected better results with 87% (20 partitions), which had this gap lower than 20%. We did not include these interesting results in the reliability index, because they were available for 9% of the walls of the database only.

Finally, if the number of relevant measurement points after the subtraction was less than 2 (because the others were negative), we considered $I_R=0\%$. If one point was available, we assumed an exponent $n=2/3$ in order to calculate the air leakage coefficient C_L , according to eq. (5). If no point was available, the measurement was not included in the database. This did not occur when using device 2 and rarely before.

III. RESULTS OF THE MEASUREMENT CAMPAIGN

1. Description of the database developed

For each of the 456 internal partitions or exterior walls, the database developed includes general information on the building, the building's main characteristics, measurement data, and measurement results as shown in Table 4. This database was developed starting from the French envelope airleakage database (Bailly et al., 2015), but was adapted in order to get supplementary data necessary to analyse each internal partition or exterior walls. This supplementary data is in bold in the Table 4.

Table 4. Database description

General information on building	Building's main technical characteristics	Measurement data	Measurement results for each internal partition or exterior wall
City	Certification	Wind exposition [-]	C_L [$m^3 \cdot h^{-1} \cdot Pa^{-n}$]
Region	Main material	Outdoor temperature [°C]	n [-]
Building commissioning year	Structure type	Wind velocity [Beaufort scale]	q_{50} [$m^3 \cdot h^{-1} \cdot m^{-2}$]
Number of levels	Insulation type	Devices used	ELA₄ [cm²] eq.(4)
	Ventilation system	Date	ε_1 [%]
	Heated volume [m^3]	Wall area [m²]	I_R [%]
	Floor area [m^2]	Flow direction (horizontal/vertical)	
	Loss area A_{env} [m^2]	Type of wall (internal partition/exterior)	
	Envelope air leakage q_{a4} (if already available and measured on-site) [$m^3 \cdot h^{-1} \cdot m^{-2}$]	Type of room (bedroom/bath/kitchen/toilet)	
	Type of intermediate floor (wood, concrete, no)		

2. Measurement reliability analysis

For all measurements, a reliability index, as proposed above, was calculated. Figure 3 (a) shows that measurement reliability was quite high: 73% of the data had a reliability index greater than 80%. Moreover, 63% of the data had a 100% reliability index.

Figure 3 (b) shows that the lowest reliability indexes were for low air leakage rates. We also found high reliability indexes for low air leakage rates, and in some rare cases lower indexes for higher air leakage rates. This figure shows that the fixed threshold (Table 3) also had threshold

impacts on the final calculated reliability index, with very few values within the ranges [5–30%];[35–45%];[70–90%].

Most of the measurements (79%) were taken at wind velocities lower than 1 on the Beaufort scale (Figure 4a). Higher reliability indexes were found for lower wind velocities, but the median values were quite high even for high wind velocities (Figure 4b).

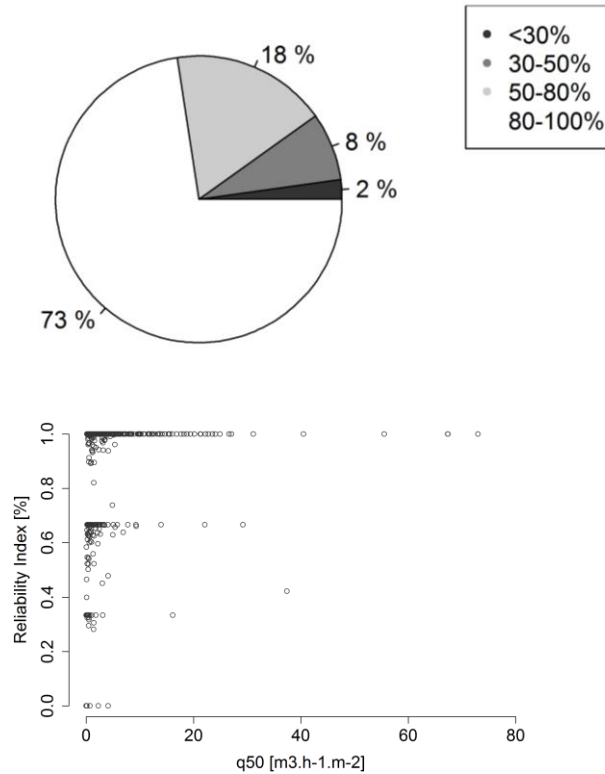


Figure 3 (a) Percentage of data in each reliability index class. (b) Reliability index as a function of the wall air leakage level.

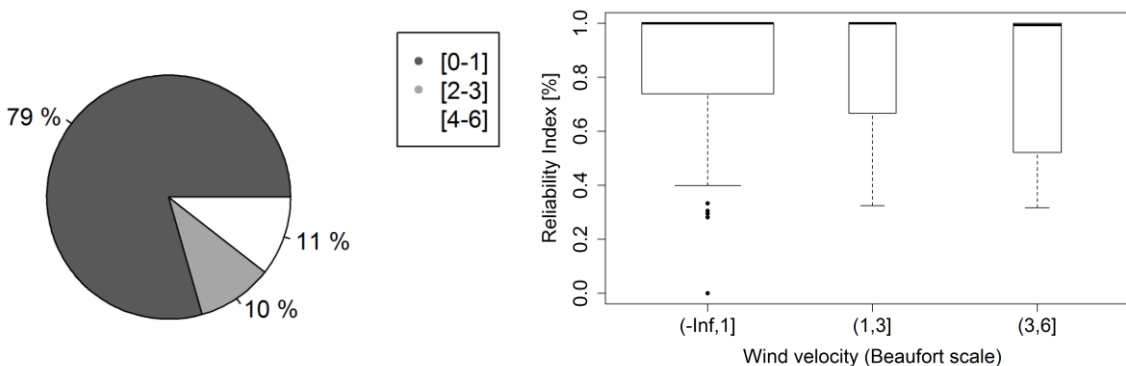
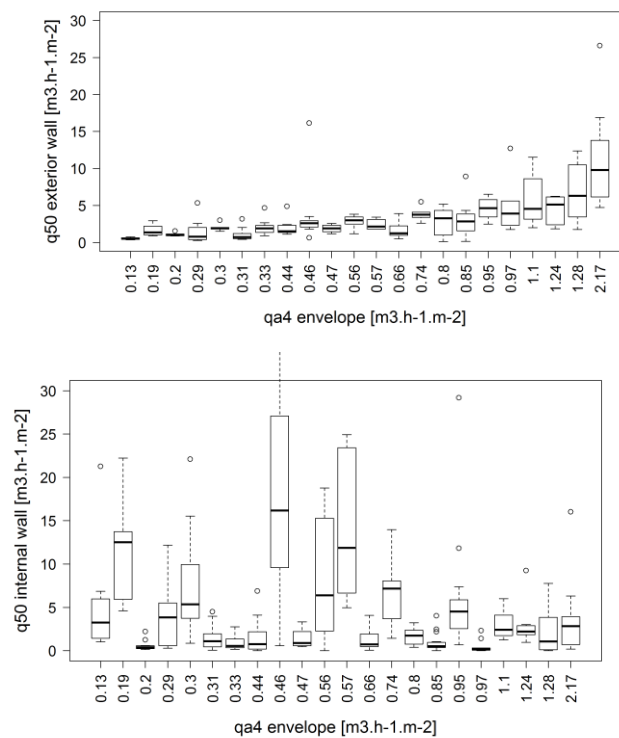


Figure 4 (a) Percentage of data in each wind velocity class (Beaufort scale). (b) Reliability index as a function of wind velocity.

3. Analysis of key factors affecting internal partition and exterior wall air leakage

Envelope airtightness level. Plotting wall air leakage as a function of envelope air leakage (q_{a4} , eq. (1)) for the 23 houses confirmed that exterior wall air leakage correlates well with envelope air leakage (Figure 5a), whereas internal partition wall air leakage was not at all related to envelope air leakage (Figure 5b). High air leakage on internal partitions can indeed be measured even if the envelope is quite airtight (houses 1, 2, 4, 5 on the graph).

Figure 5a also illustrates frequent dispersion of the values, even for airtight houses. Assuming a uniform distribution of the envelope air leakage on each exterior wall can also differ considerably from actual measurements.



On the boxplots the black line shows the median value, the rectangle delimits the 1st and the 3rd quartile. White dots are extreme values higher/lower than 1.5 times the interquartile range, not included in the boxplot.

Figure 5 Influence of envelope air leakage on exterior wall (a) and internal partition wall (b) air leakage.

Ventilation systems. Ventilation systems could impact external air leakage due to the material – number of air outlets and inlets, size, type and accessories – and due to the quality of mounting. It could be assumed that with balanced systems more attention could be given to envelope

airtightness because its quality is recognized as a condition for the efficiency of balanced ventilation.

Nevertheless, this impact is not shown by the data (Figure 6), even if the sample can be considered as quite small and any conclusions taken with caution.

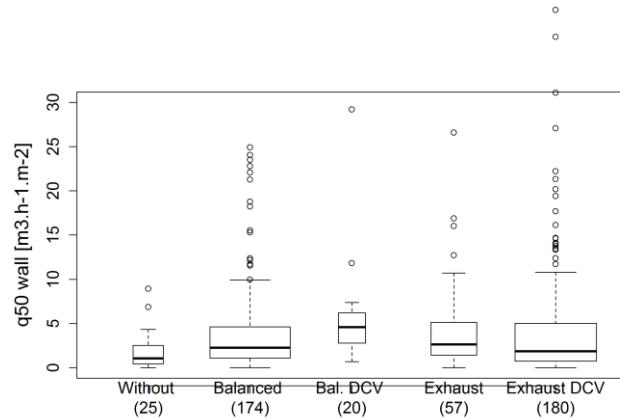


Figure 6 Impact of ventilation system on exterior wall air leakage (number of data).

Structure type: heavy vs. wood structure. We re-plotted internal partition wall air leakage as a function of envelope air leakage (q_{a4} , eq. (1)) for the 23 houses, distinguishing between heavy and wood structures (Figure 7); a strong correlation was observed. Wood-structure houses can have very airtight envelopes. However, because of a wood intermediate floor, for instance, or the lighter indoor partitions, we observed higher levels of internal air leakage than in heavy structures.

Figure 9 plots the ratio of interior partition air leakage and envelope air leakage for the two types of structure. Firstly, the median value of this ratio was nine times lower in heavy structures (1.9) than in wood structures (17.6). Moreover, there was greater dispersion of the values for wood structures, with 38.3 the interquartile range (IQR) of the ratio, than for heavy structures, with 4.0 the interquartile range (IQR) of the ratio.

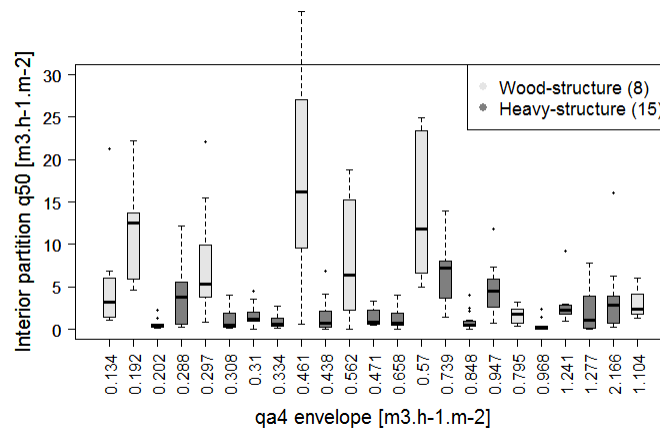


Figure 7 Interior partition air leakage as a function of envelope air leakage, depending of the type of structure.

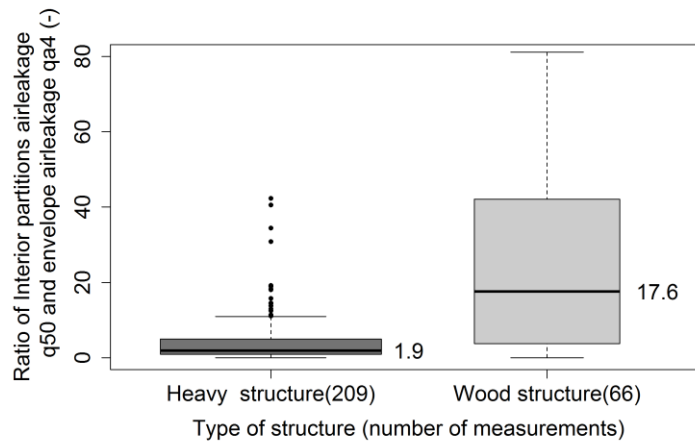


Figure 8 Impact of the type of structure on the ratio of internal partition walls air leakage and envelope air leakage.

Room type: bedroom vs bathroom. The fact that bathrooms are often built with more airtight surface materials (tiled floors, tiled walls) than bedrooms (parquet floors, no tiling) may have an impact on internal partition and exterior wall air leakage. To study this impact, we plotted in Figure 9 wall air leakage depending on the type of structure and the type of room. In this figure, the air leakage of a wall separating a bathroom from a bedroom is plotted twice (in each category). The figure shows that the type of room has no influence and confirms that the type of structure has greater influence.

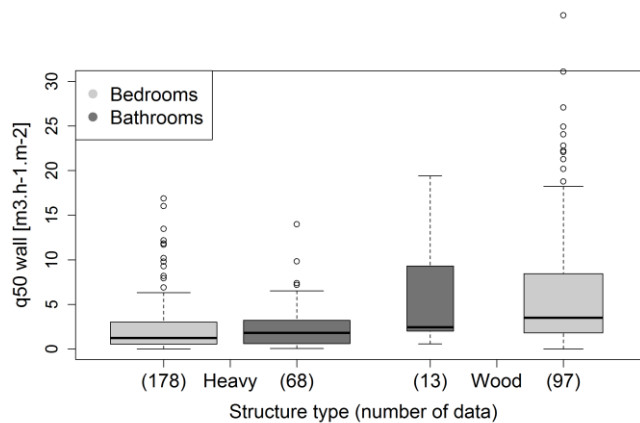


Figure 9 Influence of the type of room on exterior wall air leakage.

Wall type: exterior vs. internal partition. Figure 10 represents air leakage depending on the type of structure and the location of the wall: exterior wall (ext), internal partition wall (int), exterior and internal partition (ext&int). This category corresponds to measurements taken only on room envelopes, in the toilet for instance. Analysis of these data is less relevant because of the size of the sample (only 13 for wood and 19 for heavy structure data). Once again, considerable differences were found depending on the type of structure. Firstly concerning the median values, the exterior and internal partition wall air leakage differed by a factor of 2 for heavy structures ($q_{50}=2.3 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ for exterior vs. $q_{50}=1.2 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ for internal partition walls) and a factor of 0.5 for wood structures ($q_{50}=2.4 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ for exterior vs. $q_{50}=6.0 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ for internal partition walls). For heavy structures, internal partition walls were more airtight than exterior walls, whereas we observed the contrary for wood structures. Secondly, concerning the differences in the dispersion of the values, the values for internal partition and exterior walls were similar for heavy structures, with an IQR of $3.5 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ for exterior walls vs. $2.7 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ for internal partition walls. For wood structures, the difference in dispersion was stronger with an IQR of $1.8 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ for exterior walls vs. $12.3 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ for internal partition walls.

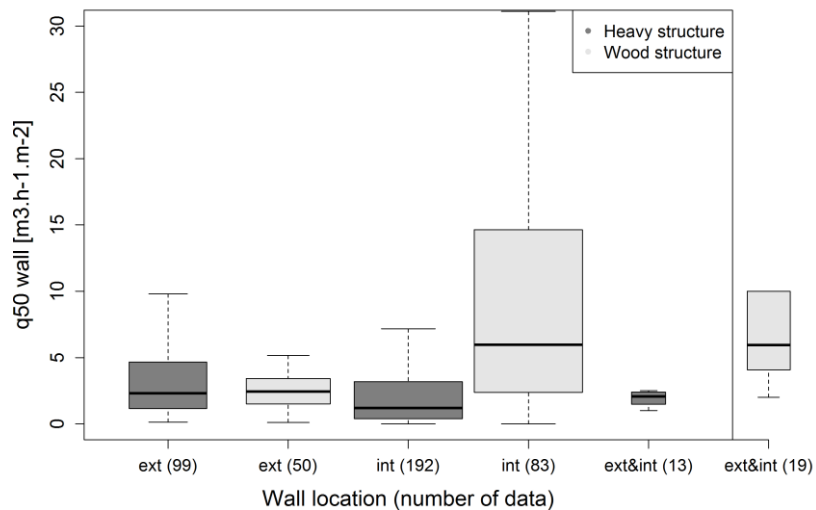


Figure 10 Influence of wall location on wall air leakage.

4. Internal air leakage significant compared to door undercuts

In dwellings, mechanical ventilation is often based on fresh air inlets in bedrooms and the living room and exhaust air outlets in humid rooms (kitchen, bathroom, toilet). When doors are closed, we commonly assume that the dwelling is aired from door undercuts. These new data on

internal partition wall air leakage allowed us to compare the size of door undercuts with the size of air leakage paths located on internal partition walls. We used eq. (4) to calculate the equivalent air leakage area ELA_4 [cm^2] for each internal partition wall. We plotted this indicator depending on the type of structure and the number of levels (Figure 11) in the house. We considered the calculated median values and multiplied this by 3 for one-level homes, assuming that we had at least three interior walls, and by 4 for two-level houses. As a result, internal partition wall air leakage accounted for 9 cm^2 (one-level structure), 24 cm^2 (two-level heavy structure) or 120 cm^2 (two-level wood structure). A door undercut is around 90 cm^2 , so that internal partition wall air leakage was fairly considerable.

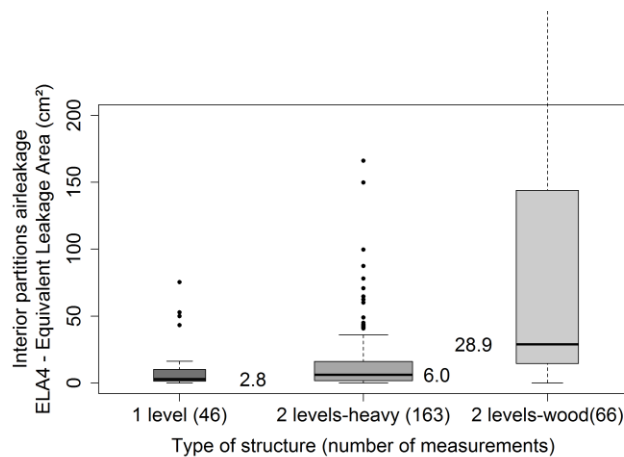


Figure 11 Internal partition wall equivalent air leakage area (cm^2) depending on the type of structure.

5. A proposal for air leakage values and dispersion input data for multizone IAQ models

Internal partition wall air leakage should be considered as well as door undercuts considering their substantial impacts on dwelling airing. With this study and these new data, we suggest input values for multizone airflow modelling to predict airflows and IAQ more precisely. According to Figure 8 and Figure 10, we suggest (Table 5) using the median values as reference values and considering a distribution of these values, according to the IQR calculated.

Concerning exterior wall air leakage data, databases exist in France (85 000 dwellings, Bailly et al., 2015) and in other countries (100 000 dwellings in the USA: Walker et al., 2013). The present study has produced new information on the dispersion of envelope air leakage. In models used in EP regulation calculation methods, we often assume that envelope air leakage is uniformly distributed in each of the dwelling's exterior walls, for instance, prorating the total air leakage according to the ratio between wall area and envelope area (CEN, 2007), (JO, 2011). This study has shown that an IQR can represent 150% of the median value for heavy structures and 75% for wood structures. We would also recommend using these IQR ratios applied to the envelope air leakage value, once converted in q_{50} .

Finally, we would recommend using these values only for single family dwellings, and for “heavy structures” defined as concrete, brick or concrete blocks structures with concrete intermediate floor, and “wood structures” defined as wood post-and-beam framing with a wood intermediate floor.

Table 5. Proposal of air leakage input data for multizone IAQ models single family dwellings

Internal partition wall air leakage reference value	Internal partition wall air leakage distribution	Exterior wall air leakage distribution
Heavy structure: $q_{50}=1.2 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ or $q_{50}/q_{a4} = 2$	Heavy structure: IQR (q_{50})= $3 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ or IQR (q_{50}/q_{a4})= 4	Heavy structure: IQR = 150% of the envelope air leakage value in q_{50}
Wood structure: $q_{50}=6 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ or $q_{50}/q_{a4} = 17.5$	Wood structure: IQR(q_{50})= $12 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ or IQR (q_{50}/q_{a4})= 38.5	Wood structure: IQR = 75% of the envelope air leakage value in q_{50}

IV. CONCLUSION AND OUTLOOK

The present paper develops a performance-based approach for ventilation in low-energy dwellings, integrating indoor air quality and health issues. The paper provides new data that could be useful for detailed modelling of internal and external air leakage, with consequences on IAQ bedrooms where people spend most of their time. This paper presents an innovative detailed database including air leakage of 456 exterior and internal partition walls measured in 23 detached houses. Each wall air leakage is described with a reliability index that we have developed, in order to describe the confidence in the airleakage measurement. This paper analyses this new database, pointing out that building structure is the most influent parameter on interior partition air leakage. This analysis also highlights that actual measurements contradict the assumption that air leakage is uniformly distributed, as often claimed in EP calculations and in IAQ multizone models used in regulations. As a conclusion of this analysis, the paper recommends values to take into account internal partition wall air leakage and to consider non-uniform distributions for air leakage in dwelling multizone IAQ models.

On-going developments concern the numerical part of this study. With these new data, we will further analyse the influence of non-uniform internal and external air leakage on airflows in single-family dwellings, with more building geometries, other ventilation systems and higher levels of internal partition air leakage. The multizone airflow model will be completed with an IAQ model, based on emissions and occupant scenarios. The final aim of this model is to evaluate the IAQ performance at the design stage of every new low energy single-family dwelling.

V. ACKNOWLEDGMENTS

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VI. NOMENCLATURE

ACR:	Air change rate per hour [h^{-1}]
A_{env} :	Building envelope area excluding the lowest floor [m^2]
Bal.DCV:	Humidity-controlled balanced ventilation
BBC:	The 2005 French low-energy certification, a first step before the RT 2012
C_L :	The air leakage coefficient [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{Pa}^{-n}$]
DCV Ex:	Exhaust ventilation
EP:	Energy-performance
IAQ:	Indoor air quality
IQR:	Interquartile range [-]
I_R :	Reliability index [%]
n :	Airflow exponent [-]
N :	Number of points of measure in a depressurization test [-]
n_{50} :	Air leakage rate at 50 Pa [h^{-1}]
Δp :	Pressure difference [Pa]
Q :	Airflow due to airleakage [$\text{m}^3 \cdot \text{h}^{-1}$]
Q_{50} :	Airleakage rate at 50 Pa [$\text{m}^3 \cdot \text{h}^{-1}$]
q_{a4} :	Building envelope air leakage rate at 4 Pa, normalized by the envelope area A_{env} [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$]
q_{50} :	Air leakage rate at 50 Pa, normalized by the surface area of the measured wall [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$]
RT 2012:	The most recent French building energy-performance regulation

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Part 3 conclusion

In this published paper presented in Part3 of this thesis, we built an innovative detailed database including air leakage of 456 exterior and internal partition walls measured in 23 detached houses, most of them being low-energy ones. Those measurements clearly contradict the assumption that envelope airleakage is uniformly distributed, as often claimed in energy performance calculations used in energy regulations. Measurement also show that internal partition air leakage was significant compared to door undercuts. Indeed, the median value, expressed in equivalent airleakage area, can reach 120 cm² for a two-level wooden structure.

As a conclusion of this analysis, the paper recommends to use uneven airleakage distributions. The paper provides airleakage values for detached houses multizone IAQ models, summarized in Table 1.

Internal partition wall air leakage reference value	Internal partition wall air leakage distribution	Exterior wall air leakage distribution
Heavy structure: $q_{50}=1.2 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ or $q_{50}/q_{a4} = 2$	Heavy structure: IQR (q_{50})= $3 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ or IQR (q_{50}/q_{a4})= 4	Heavy structure: IQR = 150% of the envelope air leakage value in q_{50}
Wood structure: $q_{50}=6 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ or $q_{50}/q_{a4} = 17.5$	Wood structure: IQR(q_{50})= $12 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ or IQR (q_{50}/q_{a4})= 38.5	Wood structure: IQR = 75% of the envelope air leakage value in q_{50}

Table 1. Proposal of air leakage input data for multizone IAQ models in detached houses.

The paper provides new data that could be useful for detailed modelling of internal and external air leakage, with consequences on IAQ bedrooms where people spend most of their time.

From this Part 3, we can conclude that in our performance-based approach, which should be a multizone approach as highlighted in Part 2, we should assume an uneven envelope airleakage distribution, combined with an uneven internal partition walls airleakage distribution. We could propose to use the input values from Table 1, depending the choice made about the structure type at the design stage of a new house. If the house would be a wooden structure house, data from line 1 could be used. If the house would be an heavy structure house, data from line 2 could be used.

4

Impact of multizone airleakage modelling on ventilation performance and indoor air quality assessment in low-energy houses

At the end of Part 3, we can consider that our measurements show that an even envelope airleakage distribution is a strong assumption, as well as ignoring internal partition wall airleakage. In this part 4, we will now quantify impacts of these assumptions on IAQ performance for a low-energy detached house.

As already mentioned, we referred in the introduction to some references (Bekö et al., 2010; Koffi, 2009) suggesting that additional research was needed both to get precise data on these uneven external and internal airleakage distributions, and to quantify their impacts on IAQ.

In this section, we will use the data provided in Part 3 as entry data in a multizone modelling in order to quantify impacts on selected IAQ performance indicators. We will use a case study of a 4 bedroom-low-energy house. This part of the work has been submitted (G. Guyot et al., 2018b).

There are also some links between Part 4 and Part 5. In the Part 4, we describe the calculated IAQ performance indicators, the used occupancy schedules and pollutant emission scenarii. The final goal is to quantify impacts of changes in the airleakage distributions on the calculated IAQ indicators. Nevertheless, we do not argue why we selected those performance indicators, those occupancy schedules and pollutant emissions scenarii. This will be done in the Part 5, throughout a review work.

Modelling the impact of multizone airleakage on ventilation performance and indoor air quality in low-energy homes

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This study examined the impacts of detailed envelope airleakage distribution and internal partition walls airleakage on the ventilation performance of a detached low-energy house. We used a multizone modelling approach based on CO₂, humidity and formaldehyde to calculate indoor air quality (IAQ) performance indicators.

We showed that formaldehyde concentrations and corresponding exposures are higher than those calculated with the selected threshold of 9 µg.m⁻³, except for the lower emission rate of 4.5 µg.h⁻¹.m⁻².

Impacts of uneven envelope airleakage distribution on selected IAQ performance indicators are generally significant whatever ventilation system is present. Impacts of internal partition wall airleakage are considerably greater with exhaust-only ventilation (39% on formaldehyde concentration) but can be high on some IAQ performance indicators (18% on humidity indicators) with balanced ventilation.

We also conclude that it is relevant to use detailed data on envelope airleakage distribution and internal partition wall airleakage to precisely assess ventilation performance on IAQ.

Keywords: indoor air quality, ventilation, house, performance, airleakage, infiltration, formaldehyde, indicator

I. Introduction

Since people spend 60–90% of their life indoors (dwellings, offices, schools, etc.), indoor air quality (IAQ) is a major factor affecting public health (Klepeis et al. 2001; Brasche and Bischof 2005; Zeghnoun, Dor, and Grégoire 2010; Jantunen et al. 2011; European Commission 2003). The current damage to public health in disability-adjusted life years (DALY) from all sources attributable to IAQ, excluding second-hand smoke and radon, is estimated in the range between the health effects of road traffic accidents (4000 μ DALY per person per year) and heart disease from all causes (11 000 μ DALY/p/yr) (Logue et al. 2011). According to the World Health Organization (WHO 2014), 99 000 deaths were attributable to indoor air pollution in 2012 in Europe.

However, building energy performance, especially in nearly-zero energy homes, requires rethinking air change rates because of their impact on thermal losses. In this context, ventilation systems are becoming smarter (Guyot, Walker, and Sherman 2018) and envelope airtightness treatment is becoming crucial (Erhorn, Erhorn-Kluttig, and Carrié 2008). As a result, airtightness parameters are now often included in energy performance (EP) calculations executed at the design stage of a building, generally through single-zone models with uniform envelope airleakage, as in France (JO 2011).

Indeed, envelope airleakage is known to lead to thermal losses, but also to modifying theoretical voluntary airflow circuits (insured by mechanical ventilation) in a building equipped with a whole-house ventilation system. Several authors have confirmed that envelope airtightness promotes better IAQ in low-energy homes, equipped with mechanical ventilation, because the theoretical airflow circuits in buildings are better controlled (Koffi 2009; Boulanger et al. 2012; Laverge and Janssens 2013). Indeed, airleakage interferes with mechanical ventilation airflows and thus can affect IAQ. Theoretically, general mechanical ventilation in French dwellings is based on outdoor air inlets in bedrooms and the living room and exhaust air outlets in “humid” rooms (kitchen, bathroom, toilets) (Figure 1a). Nevertheless, with exhaust-only ventilation systems, high airleakage on exterior walls of the humid rooms could short-circuit the bedrooms, which could become under-ventilated. When this airleakage is non-uniformly distributed, IAQ impacts can be even greater: if a room is very leaky (living room in Figure 1b), the other rooms can also be short-circuited and become under-ventilated (bedrooms in Figure 1b). Nevertheless, this impact of unevenly distributed envelope airleakage is rarely investigated since it is often considered as evenly distributed in the standards (CEN 2007a; CEN 2009) and the published literature studying ventilation performance (Boulanger et al. 2012; Laverge and Janssens 2013; Laverge, Pattyn, and Janssens 2013).

Moreover, because greater consideration is often given to energy performance than to IAQ issues, airleakage through internal partition walls between rooms is often disregarded. The rare authors considering this issue (Roldan, Allard, and Achard 1987;

Laverge and Janssens 2013; Laverge, Pattyn, and Janssens 2013) take into account evenly distributed internal partition wall airleakage.



Figure 1. (a) Theoretical ventilation airflows in a dwelling and (b) short-circuiting due to non-uniformly distributed envelope airleakage. Source: (Carrié et al. 2006).

Some experimental studies have shown, however, that envelope airleakage was not evenly distributed and that internal airleakage was considerable (Bossaer et al. 1998; Du et al. 2012; Guyot, Limoges, and Carrié 2012; Guyot et al. 2016). As a result, additional research is needed to quantify the impacts of both these assumptions on IAQ as suggested by (Koffi 2009; Bekö et al. 2010) and proposed in the present paper.

Firstly, this paper presents the methodology adopted here, describing the house studied, the modelling assumptions, the selected occupancy and pollutant emission scenarios as well as the selected performance indicators based on air change rates, CO₂, humidity and formaldehyde levels. Seven levels of details of airleakage modelling are then used to perform simulations.

The second part of the paper presents the results and their discussion. Depending on the type of ventilation, we studied the impacts of taking into account several levels of airleakage details on all the IAQ performance indicators selected.

The paper concludes with the relevance of using detailed data on envelope and internal partition wall airleakage distributions.

II. Methods

1. House studied

The present study is based on a real two-storey low-energy brick detached house equipped with a balanced ventilation system. The house has four bedrooms (called BR1, BR2, BR3, BR4), two bathrooms (Bath 1 and 2), two toilets (WC 1 and 2), a mezzanine (Mezz), a kitchen open on the living room (K+LR) and a hall, as shown on Figure 2.

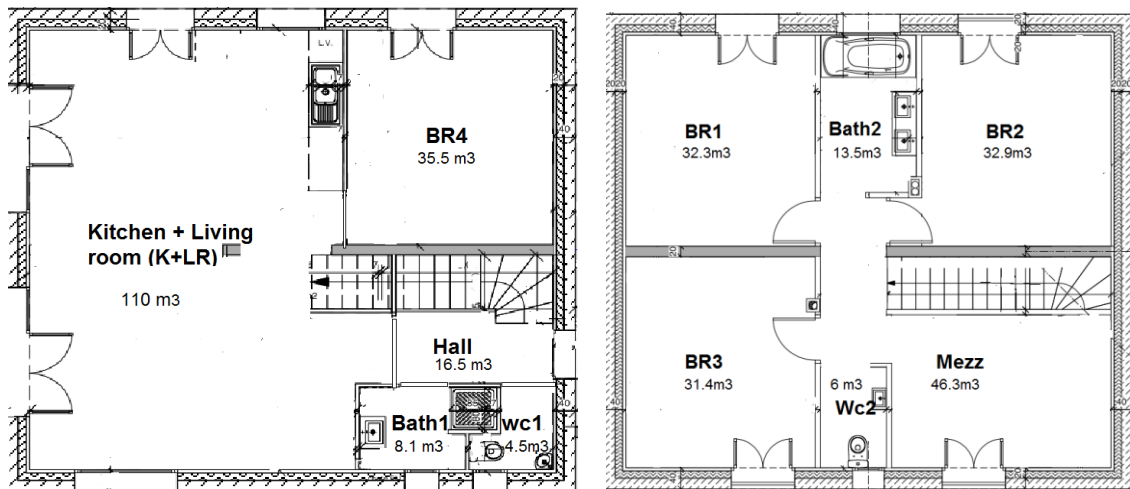


Figure 2. Plan of the house studied: (a) ground floor (b) first floor.

A measurement campaign was conducted in order to quantify and finely describe the envelope and internal partition wall airleakage (Guyot et al. 2016). Overall envelope airtightness was $n_{50}=1.5 \text{ h}^{-1}$ and internal partition walls were measured as quite airtight, with a median value of $q_{50}=0.8 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$, according to equation 1 and Equation 2, respectively.

$$n_{50} = \frac{C_L \cdot (50)^n}{V} \quad (\text{Equation 1})$$

$$q_{50} = \frac{C_L \cdot (50)^n}{A} \quad (\text{Equation 2})$$

where C_L is the airleakage coefficient [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{Pa}^{-n}$], n is the airflow exponent [-], A is the area of the measured wall [m^2], 50 is a 50-Pa reference pressure difference across the building envelope or across the wall measured and V is the building's heated volume [m^3] (337 m^3 for the house studied).

For comparison purposes, this real house was used for all simulated cases. Artificially, the ventilation system was replaced with an equivalent exhaust-only ventilation system, and the airleakage coefficient values were modified, as discussed in the following sections.

2. Modelling study

Airflows, relative humidity, CO_2 and formaldehyde concentrations were investigated using numerical modelling with CONTAM software (Walton and Emmerich 1994). The

validation of such multizone models is well documented (Lansari et al. 1996; Sextro et al. 1999; Zhao, Yoshino, and Okuyama 1998; S. Emmerich, Howard-Reed, and Nabinger 2004; S. J. Emmerich and Dols 2016; Ng et al. 2016). Moreover, several authors showed that this type of model assuming well-mixed air in every room was adapted for ventilation and IAQ modelling in houses (S. J. Emmerich 2001; Chen and Wen 2012). We used a multizone model for the dwelling, each room is one zone, which accounts for 11 zones. The mezzanine and hallway are modelled as two zones connected through and open stair case. We used a 10-min time step, with meteorological data of a typical year in Lyon (ASHRAE IWECC Weather file, 2001, Table 1).

Temperature (K)	Pressure (Pa)	Wind velocity (m.s ⁻¹)	Wind direction (°)	Humidity ratio (g/kg)
279.6	993967	3.4	193	4.9

Table 1. Average climate data parameters for the full heating period.

The calculation was performed over the heating period, from October 15th 00:00 AM to April 14th 12:00 PM, accounting for 4366 simulated hours. Indeed, air conditioning in new dwellings is rare in France and open windows ensure cooling instead. As a result, it is more relevant to calculate ventilation performance for the heating period only.

The inside temperature was assumed to be 20°C during this period. The wind at the building was calculated from the weather data using a 0.3287 modifier factor, resulting from a power law used with factors from a suburban area and the house being 8.5 m in elevation. The pressure coefficients from the EN 15242 (CEN 2007) were used, assuming no barrier, i.e. +0.5 on the upwind facades and -0.7 on the downwind facades.

Airleakage distribution

Doors were assumed to be closed, as observed in the campaign carried out by (Bernard 2009), and the door undercuts were modelled through a single 1-cm-high crack as required by the French airing regulation, with a 0.65 flow exponent and a 0.6 discharge coefficient at a 10-Pa reference pressure.

Airleakage is modelled by one path using the power-law at the centre of each external and internal partition wall of each zone.

We defined seven cases corresponding to different levels of detail in describing airleakage distributions (Table 2). Three levels of detail in modelling envelope airleakage were simulated and compared: “perfect envelope airtightness” (case a), “even external airleakage distribution” (case b) and “uneven external airleakage distribution” (case c). In cases a, b and c, the internal walls are considered airtight. Four levels of detail in

modelling internal partition wall airleakage were studied: “uneven external and internal distribution” (cases d, d2, d3, d4) are based on experimental values measured by (Guyot et al., 2016) on 23 heavy or wooden-structure houses. This previous study showed that we can obtain the same order of magnitude in the size of the path between a door undercut and internal partition wall airleakage (Guyot et al. 2016).

Figure 3 illustrates the used internal airleakage distributions for cases d, d2, d3 and d4 : median and average values and interquartile range.

Case b can be considered as a reference case used in calculating energy performance, case a as a simplified case where airflows only coming from mechanical ventilation are calculated, and the other cases as more detailed cases than the reference case.

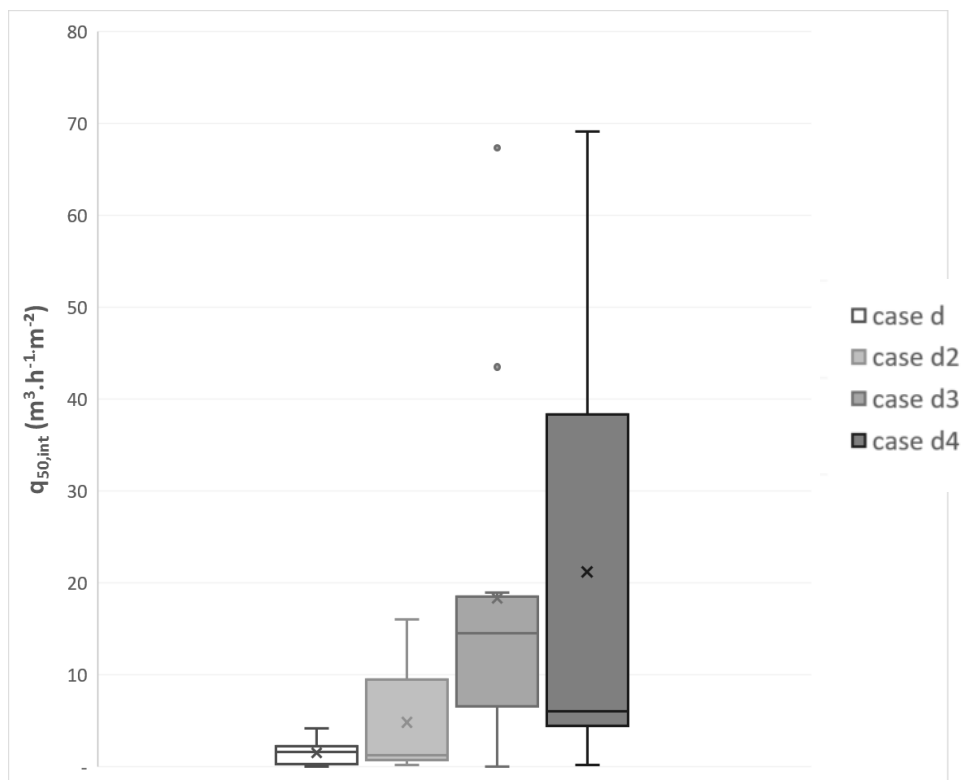


Figure 3. Internal airleakage distributions for cases d, d2, d3 and d4

Cases	Airleakage through external envelope (envelope airleakage)	Internal partition wall airleakage
Case a	Without	Without
Case b (reference)	Evenly distributed n=0.68	Without
Case c	Unevenly distributed (measured on the house)	Without
Case d (heavy structure)	Unevenly distributed (measured on the house)	Unevenly distributed (measured on the heavy structure house)
Case d2 (heavy structure)	Unevenly distributed (measured on the house)	Unevenly distributed (Theoretical distribution following input values from Guyot et al. 2016) For a heavy structure: $q_{50, \text{median}} = 1.2 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ Inter-quartile range (q_{50}) = $3 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$
Case d3 (wooden structure)	Unevenly distributed (measured on the house)	Unevenly distributed (measured on a wooden structure house)
Case d4 (wooden structure)	Unevenly distributed (measured on the house)	Unevenly distributed (Theoretical distribution following input values from Guyot et al. 2016) For a wooden structure: $q_{50, \text{median}} = 6 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ Inter-quartile range (q_{50}) = $12 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$

Table 2. The description of seven cases of airleakage distributions.

Ventilation system

The ventilation system is a whole house system assumed to provide French regulatory airflows as required by the airing regulation since 1982 (J.O. 1983). In our case study, a ventilation system for a seven-room house with two bathrooms and two toilets must provide $30 \text{ m}^3 \cdot \text{h}^{-1}$ in each bathroom, $15 \text{ m}^3 \cdot \text{h}^{-1}$ in each toilet, and $45 \text{ m}^3 \cdot \text{h}^{-1}$ in the kitchen. A high-speed ventilation must also be able to provide $135 \text{ m}^3 \cdot \text{h}^{-1}$ in the kitchen during

peak periods. As a result, the total extract airflow in the whole house is $135 \text{ m}^3 \cdot \text{h}^{-1}$ during basic mode and $225 \text{ m}^3 \cdot \text{h}^{-1}$ during peak mode. The basic mode accounts for an average dwelling air change rate of 0.4 h^{-1} .

We studied two types of constant airflow ventilation: exhaust-only and balanced ventilation. Total extracted airflows are the same in both cases. With balanced ventilation, each bedroom is equipped with a supply vent providing $19.3 \text{ m}^3 \cdot \text{h}^{-1}$, the living room with two. With exhaust-only ventilation, these seven air supply vents are replaced with self-regulating trickle vents, designed to balance the total exhaust airflow. We used the “Test data (2 points)” model proposed in CONTAM, which allows one to calculate the {C,n} parameters of a flow path using two points of a measured curve {flow, pressure}. We fitted the calculated operating curve with data from the ventilator manufacturer and obtained the power law given in (Equation 3). The calculated flow exponent is consistent with the published literature (Karava, Stathopoulos, and Athienitis 2003).

$$Q_{trickleV} = 4.79 * \Delta P^{0.53} \quad \text{(Equation 3)}$$

Moisture buffering effect

Since indoor relative humidity is one of the important outputs in this study, it must be modelled precisely. Modelling humidity transfers in dwellings should take into account the moisture buffering effect to be precise and representative (Plathner 2002; Van den Bossche et al. 2007; Steeman et al. 2009; Woloszyn, Kalamees, et al. 2009). There are several more or less accurate lumped-capacity-type methods described in the literature to simulate this effect (Woloszyn, Rode, et al. 2009), for example, the equivalent absorbing area (CCFAT 2015), the boundary layer diffusion model (Axley 1991; White 1988) used in CONTAM (Dols and Polidoro 2015) and the moisture buffering model (Duforestel and Dalicieux 1994). The last one have been shown to satisfactorily represent the joint effect of furniture and construction materials in real houses (Plathner and Woloszyn 2002); therefore it was selected for our study. Its general principle (lumped capacity) is similar to the model already implemented in CONTAM. However, the main variables and corresponding parameters are different. Consequently, preliminary simulations were needed to model Duforestel’s moisture buffer correctly using the Axley equation implemented in CONTAM. To this aim, we used the case study with high-absorbing and low-absorbing rooms from (Duforestel and Dalicieux 1994). Then, using a least-squares method, we fitted the three parameters of the Axley equation to be used in CONTAM: the film mass transfer coefficient “h”, the Henry adsorption constant “k” and “A” a surface mass (Table 3).

Parameters	High-adsorbing room	Low-adsorbing room
Film mass transfer (h)	0.0051 m.s ⁻¹	0.0066 m.s ⁻¹
Henry adsorption coefficient or the partition coefficient (k)	331.6 kg.kg ⁻¹	300 kg.kg ⁻¹
Surface mass (A)	12.3% of the room volume	2.4% of the room volume

Table 3. Parameters calculated for the boundary layer diffusion model used in CONTAM

Occupation scenarios

We used data from the French national campaign on the IAQ of dwellings from 2005 (Zeghnoun, Dor, and Grégoire 2010). This campaign was based on a representative sample of the population and included 567 dwellings and 1612 occupants. Of those occupants, 1375 provided precise information about their schedules and their occupation in the rooms (25% of the sample) so that a database of 1 386 000 10-min time steps with information on the location of the occupants was available and analysed in this study. The results show that people spend on average 67.3% of their time in homes, including 2 h 40 min spent in the kitchen, 2 h 49 min in the living room, 9 h 16 min in bedrooms, and 38 min in bathrooms. This is consistent with the results of other surveys in Europe (EXPOLIS, 56–66%) and the United States (NHAPS, 68.7%). Based on these results in the present study, we consider the following occupation scenarios for the five occupants, coupled with the ventilation schedules, presented in Table 4 and Table 5, respectively.

Occupant	In living-room + open kitchen	In bathroom	In bedroom
No. 1 and 2 (bedroom 1)	7:00–8:30 12:00–14:00 19:00–21:00 (duration, 5 h 30 min)	6:20–7:00 (bathroom no. 2)	21:00–6:20 (duration, 9 h 20 min)
No. 3 (bedroom 2)	6h20-8h30 12:00–14:00 19:00–20:20 (duration, 5 h 30 min)	20:20–21:00 (bathroom no. 2)	21h-6h20 (duration, 9 h 20 min)
No. 4 (bedroom 3)	6:20–8:30 12:00–14:00 19:00–19:40 20:20–21:00 (duration, 5 h 30 min)	19:40–20:20 (bathroom no. 2)	21:00–6:20 (duration, 9 h 20 min)
No. 5 (bedroom 4)	6:20–8:30 12:00-14:00 19:00–20:20 (duration, 5 h 30 min)	20:20–21:00 (bathroom no. 1)	21:00–6:20 (duration, 9 h 20 min)

Table 4. Occupancy schedules selected for the study.

Ventilation speed	Kitchen	Bedrooms and living room (Balanced ventilation)
Speed 1 (base)	0:00–12:00 13:00–19:00 20:00–24:00	0:00–12:00 13:00–19:00 20:00–24:00
Speed 2 (peak)	12:00–13:00 19:00–20:00	12:00–13:00 19:00–20:00

Table 5. Mechanical ventilation schedules selected for the study.

Emission scenarios: CO₂, humidity and formaldehyde

CO₂ and relative humidity in a building are related to the occupants' metabolism and activities. As a result, they are widely used to assess ventilation performance (Guyot, Walker, and Sherman 2018b). Formaldehyde is a common pollutant nearly always measured in homes (100% of dwellings in France), and it is also a nearly exclusive indoor production (up to ten times greater than outdoors) due to a substantial quantity of indoor emitting materials, furniture and products (Kirchner et al. 2006). Because of its wide range of health impacts, several studies identified formaldehyde among the pollutants of concern in dwellings (Kirchner et al. 2007; Koistinen et al. 2008; WHO 2010; Logue et al. 2011a; Borsboom et al. 2016). We therefore examined this pollutant.

CO₂ emission rates depend on the size and activity of the occupants. We assumed that the house was occupied by five adults and used the emission rates proposed by (Persily, 1997), from ASHRAE 1993: 18 L.h⁻¹ and 15 L.h⁻¹ for an occupant who is awake or asleep, respectively. These emission rates were associated with the occupation schedule (Table 4).

The moisture generation rates selected for the metabolism emission are 55/40 g.h⁻¹ (awake/asleep), again combined with the occupation schedule (Table 4). The asleep periods of moisture production occur when the occupants are in the bedrooms, whereas the awoken moisture production is effective during all the other periods. For the emissions of moisture due to activities, we selected a number of recurrent actions found in EN FD/TR 14788 (CEN 2006a) and (Pallin et al., 2011), further described in Table 6.

Formaldehyde emissions can directly be expressed as a quantity per hour for specific activities, products and building materials (Howard-Reed, Polidoro, and Dols 2003; Abadie and Blondeau 2011; Missia et al. 2012). Another issue of concern is its concentrations and correlation of emissions with temperature, relative humidity and air exchange rates (Park and Ikeda 2006; Blondel and Plaisance 2011; Liang, Lv, and Yang 2016).

This type of data brings up two types of problem: firstly, it is difficult to extrapolate emission rate behaviours from standard chamber conditions to real-use conditions, notably because of the combined effects of relative humidity and temperature on formaldehyde emissions. Secondly, it is difficult to build a robust scenario extrapolating

from the material and activities scale to the dwelling scale, as highlighted in (Boulanger et al. 2012).

Emission rates measured directly at the dwelling scale are rarely found in the literature (Hodgson et al. 2000; Sherman and Hodgson 2002; Ng et al. 2016), most particularly in low-energy dwellings considered as representative of recent French dwellings. Consequently, we propose to use a simplified method based on the mass balance equation in steady-state conditions to calculate average formaldehyde emission rates, starting from unpublished data from the (Guyot et al. 2017) measurement campaign. Based on pollutant concentrations and ventilation airflows measurements on ten occupied detached low-energy houses, we defined a low-emission class: $4.5 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, the minimum measured value; a middle-emission class, $12.0 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, the median measured value; and a high-emission class, $23.6 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, the maximum measured value. The reference area is the floor area. Then we used a continuously emitting model for formaldehyde emission.

Selected inside emission rates and outside concentrations are summarized in Table 6.

Pollutant parameter or	Outside concentration	Emission rates
CO ₂	400 ppm	Awake: 18 L.h ⁻¹ /person Asleep: 15 L.h ⁻¹ /person
Humidity	Variable, average value of 4.9 g/kg	Awake: 55 g.h ⁻¹ /person Asleep: 40 g.h ⁻¹ /person Moisture due to activities for a total of 6 kg/day: - 1 shower per person per day (for a total of five showers per day), with an emission of 1440 g.h ⁻¹ for 10 min per shower. - 3 cooking periods per day: 1512 g.h ⁻¹ for breakfast for 15 min; 2268 g.h ⁻¹ for lunch for 30 min; 2844 g.h ⁻¹ for dinner for 40 min. - 1 laundry per person per week (Monday, Tuesday, Wednesday, Saturday and Sunday): 252 g.h ⁻¹ for 2 h. - 5 laundry drying per week (same days): 136.8 g.h ⁻¹ during 11 h.
Formaldehyde	2.9 $\mu\text{g}/\text{m}^3$ (DRASS Rhône-Alpes 2007)	Low-emission class: $4.5 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ Middle-emission class: $12.0 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ High-emission class: $23.6 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$

Table 6. Overview of selected emission rates and outside concentrations in the study.

3. Performance indicators

We used indicators based on air change as well as on each of the three parameters and pollutants selected. All performance indicators were calculated over the heating period (4366 h) using the R package for the analysis of the CONTAM output data, which account for 67 airflows and 13*3 (CO₂, relative humidity, formaldehyde) concentrations for each of the 26209 time steps.

Air change performance indicators

The following indicators were used to analyse the results: average ACR for each zone and for the entire building (called envelope) ((Equation 4), as well as the time spent in the four ACR classes: $<0.3 \text{ h}^{-1}$; $[0.3\text{--}0.5] \text{ h}^{-1}$; $[0.5\text{--}1] \text{ h}^{-1}$; $>1 \text{ h}^{-1}$.

$$ACR = \frac{\sum Q_{exit}}{V_{zone}} \quad (\text{Equation 4})$$

with Q_{exit} the outgoing airflow in $\text{m}^3 \cdot \text{h}^{-1}$, V_{zone} the volume of the zone considered in m^3 , ACR in h^{-1} . Q_{exit} includes airflows through both outdoor and internal partition walls.

IAQ performance indicators using CO₂ concentration

In this study, we selected the following performance indicators related to CO₂:

- The average CO₂ concentration in each zone k.
- R: the percentage of time spent in five concentration classes [$<800 \text{ ppm}$, $800\text{--}1000 \text{ ppm}$, $1000\text{--}1400 \text{ ppm}$, $1400\text{--}2000 \text{ ppm}$, $>2000 \text{ ppm}$], defined using EN 13779 (for the first three thresholds) and the French procedure for demand-controlled ventilation (for 2000 ppm) (CEN 2007c; CCFAT 2015). We calculated the five R indices $R_{<800}$, $R_{800\text{--}1000}$, $R_{1000\text{--}1400}$, $R_{1400\text{--}2000}$, $R_{>2000}$ according to (Equation 5).

$$R_{<800,k} = \frac{\sum_i t_{<800,i}}{\sum_{tot} t_i} \quad (\text{Equation 5})$$

where $t_{<800}$ is the time step when the corresponding concentration in the zone k is lower than 800 ppm .

- The cumulative exceeding exposure above 1000 ppm and 2000 ppm , (Equation 6):

$$E_{X,k} = \sum_i C_{k >X}(t_i) * t_i \quad (\text{Equation 6})$$

with $X=1000 \text{ ppm}$ or 2000 ppm .

- The air stuffiness index for I_{ICONE} dwellings proposed in (Ribéron et al. 2016). This index is a logarithm function of the percentage of time when the measured CO_2 concentration at night is higher than 1000 ppm, f_1 , and 1700 ppm, f_2 (Equation 7). The authors propose that it should be rounded to the nearest integer.

$$I_{ICONE} = round[8.3 \log(1 + f_1 + 3f_2)] \quad (\text{Equation 7})$$

IAQ performance indicators using relative humidity

In this study, we selected the following as performance indicators related to humidity:

- Percentage of time spent with a relative humidity (RH) outside of the range [30–70%] in each room (health indicator), as proposed by (Harriman, Brundrett, and Kittler 2001) and in TR 14788 (CEN 2006b).
- Percentage of time spent with relative humidity over 70% in each room (condensation risk indicator).

IAQ performance indicators using formaldehyde

In this study, we focused on long-term exposure, because of the lack of data at the building scale on rates for short-term emissions. We decided to use the reference exposure limit value (ELV) set to the minimum value used throughout the world, i.e. 9 $\mu\text{g}\cdot\text{m}^{-3}$ for formaldehyde (USA-California) as proposed by (Cony Renaud Salis et al. 2017). We also selected the following as performance indicators related to formaldehyde:

- Average concentration in each room;
- Percentage of hours with formaldehyde concentration over the ELV in each room;
- Maximum total cumulative exposure of the five occupants: E_{\max} , (Equation 8), which will be compared to the total cumulative exposure to the ELV during the whole heating period (4366 h), $E_{ELV}=39294 \mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$:

$$E_{\max} = \max_j \left(\sum_i C_j(t_i) * t_i \right) \quad (\text{Equation 8})$$

where $C_j(t_i)$ is the exposure concentration for occupant j at the time step t_i .

III. Results

All the results are presented in comparison to case b, considered as the reference case.

1. Air change rates (ACR)

Exhaust-only ventilation

Figure 4 illustrates ACRs for the envelope and the four bedrooms (called BR1, BR2, BR3, BR4) and for the seven cases. The ratios of ACR in bedrooms as compared with the envelope ACR are given in Table 7. We can observe that the ACR of the bedrooms can be quite different from the envelope ACR of 0.43 h^{-1} by a factor in the range 0.69–1.35.

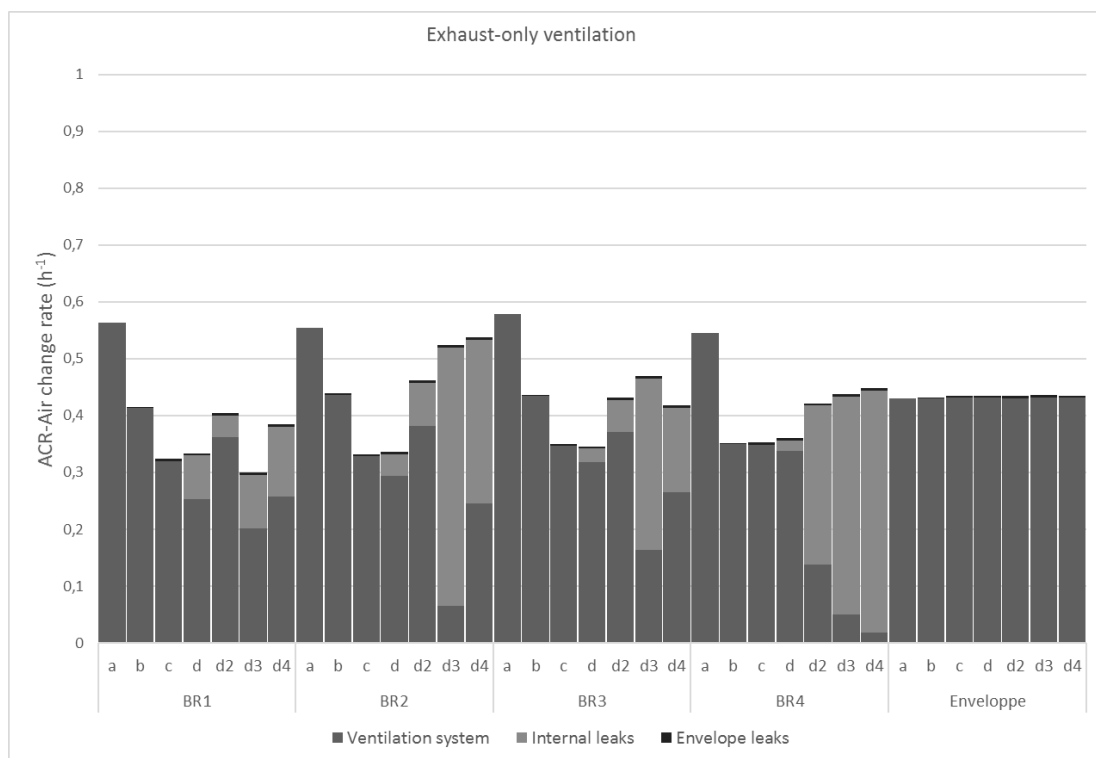


Figure 4. Average ACRs in bedrooms over the heating period. Exhaust-only ventilation. Seven airleakage cases.

cases	a	b	c	d	d2	d3	d4
BR1	1.31	0.97	0.74	0.77	0.93	0.69	0.88
BR2	1.29	1.02	0.76	0.77	1.06	1.20	1.24
BR3	1.35	1.01	0.80	0.79	0.99	1.08	0.96
BR4	1.27	0.81	0.81	0.83	0.97	1.00	1.03

Table 7. Ratio between bedroom and envelope ACRs. Exhaust-only ventilation.

The simulation results indicate that ignoring envelope airleakage accounts for a maximum 56% difference compared to bedroom ACRs (case a, BR4), even if it does not

impact the envelope ACR (0%). Taking into account uneven envelope airleakage distribution only slightly impacts the house's average ACR, with a maximum difference of +1% (case c), but this can strongly impact the bedroom ACRs with a maximum -24% difference (case c, BR2). Taking into account internal partition wall airleakage can reach an impact of 28% on bedroom ACRs for a wooden structure (BR4, case d4), even if it does not impact the envelope ACR (maximum, 1.3%, d3). In the four bedrooms, maximum air exfiltration through external and internal walls is only 0.4% of outgoing airflows in case b (BR2) and 1% in case c (BR4), but can reach as much as 24% in case d (BR1), 67% in case d2 (BR4), 96% in case d3 (BR4) and 89% in case d4 (BR4). In all the cases detailed (d, d2, d3 and d4) for at least one of the bedrooms, the proportions of these exfiltrations passing through internal partition wall airleakage exceeds 95% and could allow pollutant transfer between rooms.

Behind these average indicators, several disparities are hidden. If we look at the percentage of time spent in the four ACR classes (Figure 5), we observe that if cases c and d are close in terms of the ACR (Figure 4), time spent in BR1 with an ACR below 0.3 h^{-1} is 8% for case d versus 64% for case c. This can also be a threshold effect. In both cases the average ACR is close to the threshold value of 0.3 h^{-1} .

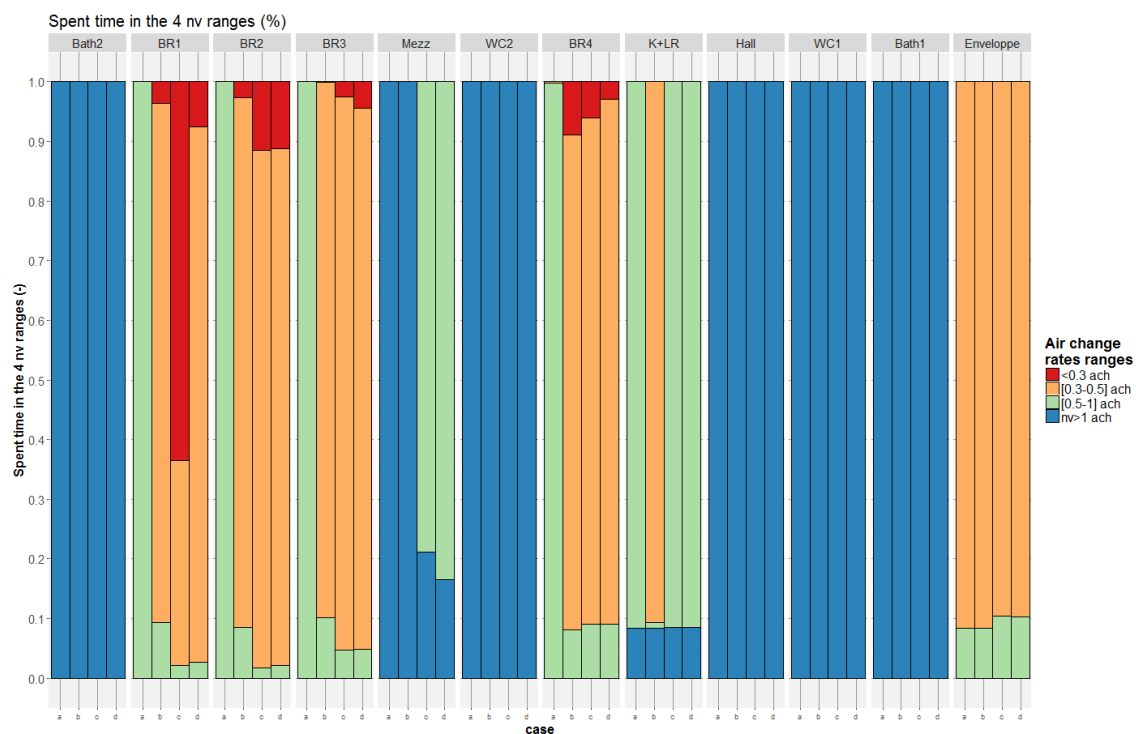


Figure 5. Time spent in the four ACR (called nv on the figure) classes. Exhaust-only ventilation. Cases a, b, c, d.

Balanced ventilation

Figure 6 illustrates ACRs for the envelope and the four bedrooms for all seven cases. The ACR ratios are given in Table 8. The bedroom ACRs are always higher than the envelope ACR of 0.43 h^{-1} by a factor in the range 1.19–1.69.

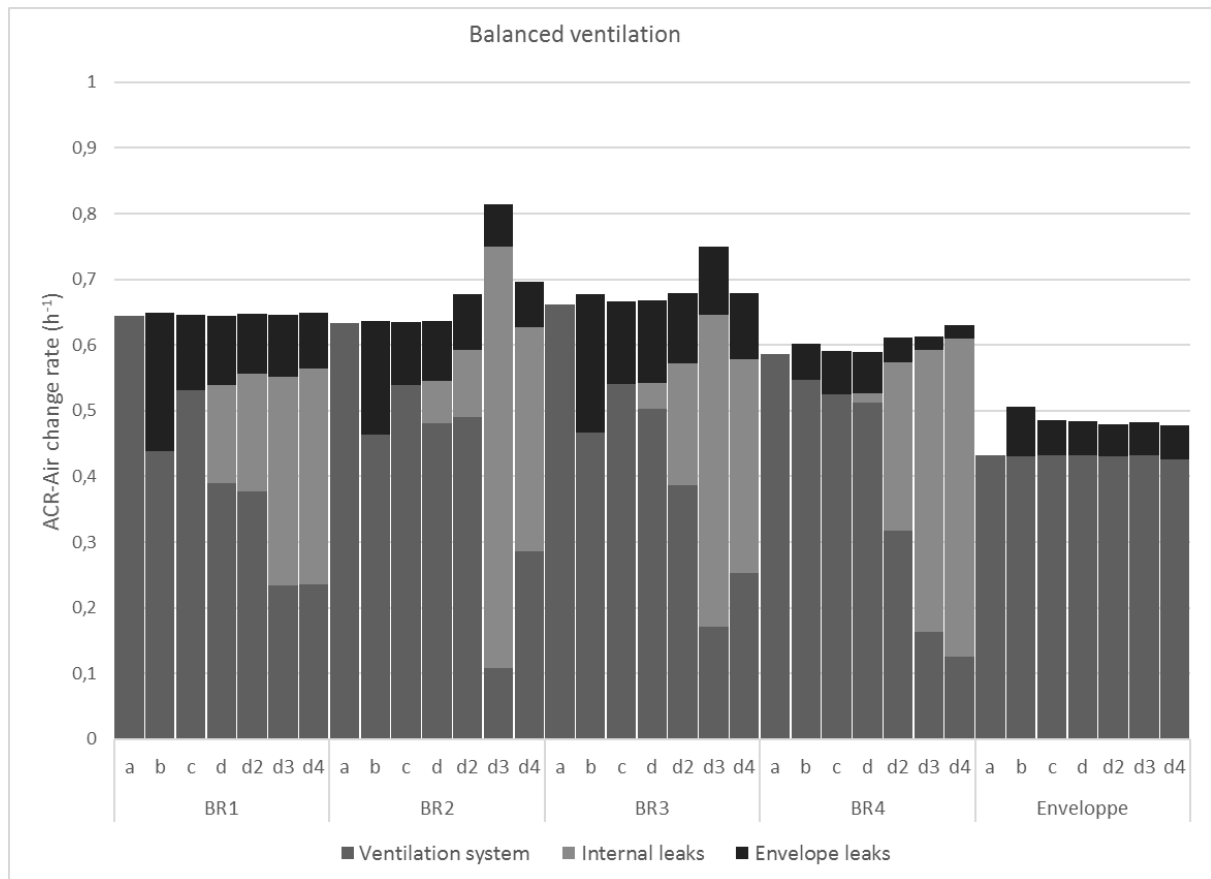


Figure 6. Average ACRs in bedrooms over the heating period; balanced ventilation; seven cases.

cases	a	b	c	d	d2	d3	d4
BR1	1.49	1.28	1.33	1.33	1.35	1.34	1.36
BR2	1.46	1.26	1.31	1.31	1.41	1.69	1.46
BR3	1.53	1.34	1.37	1.38	1.41	1.55	1.42
BR4	1.36	1.19	1.22	1.22	1.27	1.27	1.32

Table 8. Ratio between bedroom and envelope ACR. Balanced ventilation.

Ignoring envelope airleakage impacts the envelope ACR by -15% (case a). Taking into account uneven envelope airleakage and internal partition wall airleakage has nearly no impact on the envelope ACR, decreasing it by only -4% (case c) and -6% (case d4). Impacts of envelope airleakage (cases a and c) on bedroom ACRs are low (respectively, maximum -3% and -2% , BR4). Only internal partition wall airleakage significantly impacts bedroom ACRs, up to 28% for a wooden structure (case d3, BR2). For the four

bedrooms, maximum air exfiltration through internal and external walls reaches 32% of outgoing airflows in case b (BR1), 19% in case c (BR3), 31% in case d (BR1) and can reach 87% in case d3 (BR2). Only for wooden structures (cases d3 and d4), is the proportion in these exfiltrations of internal partition walls airleakage higher than 95% and could allow pollutant transfer between rooms.

4. CO₂

Exhaust-only ventilation

We plotted the average CO₂ concentrations in bedrooms for the seven airleakage cases in Figure 7, which fall within the range [741–1812 ppm], with a median value of 988 ppm. Ignoring envelope airleakage accounts for a maximum –21% difference (case a, BR4). Taking into account unevenly distributed airleakage accounts for a maximum 19% difference (case c, BR1). Taking into account internal partition wall airleakage accounts for a maximum difference of 29% (case d3, BR1).

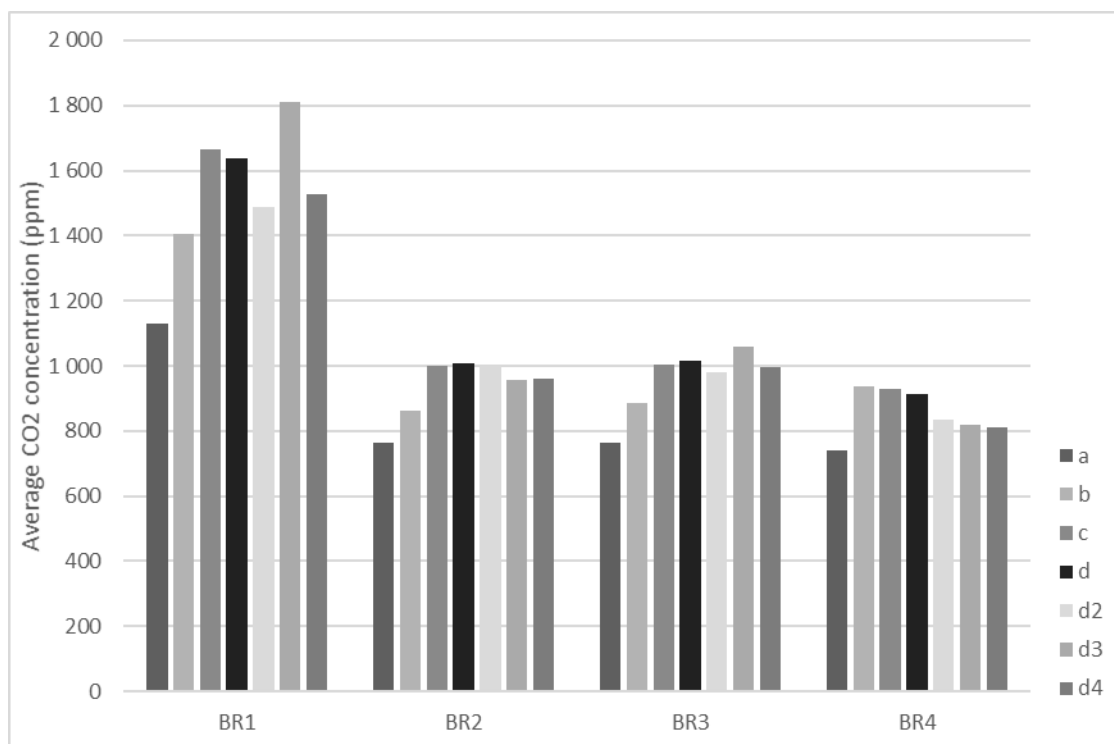


Figure 7. Average concentrations in bedrooms for the seven airleakage cases. Exhaust-only ventilation.

The CO₂ concentration significantly exceeds 2000 ppm only in BR1 due to the higher occupancy of this bedroom. Similar trends can be seen on Figure 8, when cumulative exceeding exposures over 1000 and 2000 ppm are shown. The highest values are reached in BR1: [3.8.10⁶–6.2.10⁶] ppm.h using 2000 ppm as the reference. In this

room, the exposure indicator E_{2000} difference from the reference case b is -4% for case a, 31% for case c and can reach 49% for case d3. Impacts on the bedroom exposure indicator E_{1000} are lower than for E_{2000} , but remain significant: a maximum difference of -37% for case a (BR4), 27% for case c (BR2) and 36% for case d3 (BR1).

A similar impact is also found for “spent-time” indicators shown on Figure 9. For the highest class (> 2000 ppm) in BR1, a difference of -33% for case a is observed, 17% for case c and can reach 28% for case d3.

Figure 10 shows the Icone air stuffiness index. Here, the differences between cases are lower.

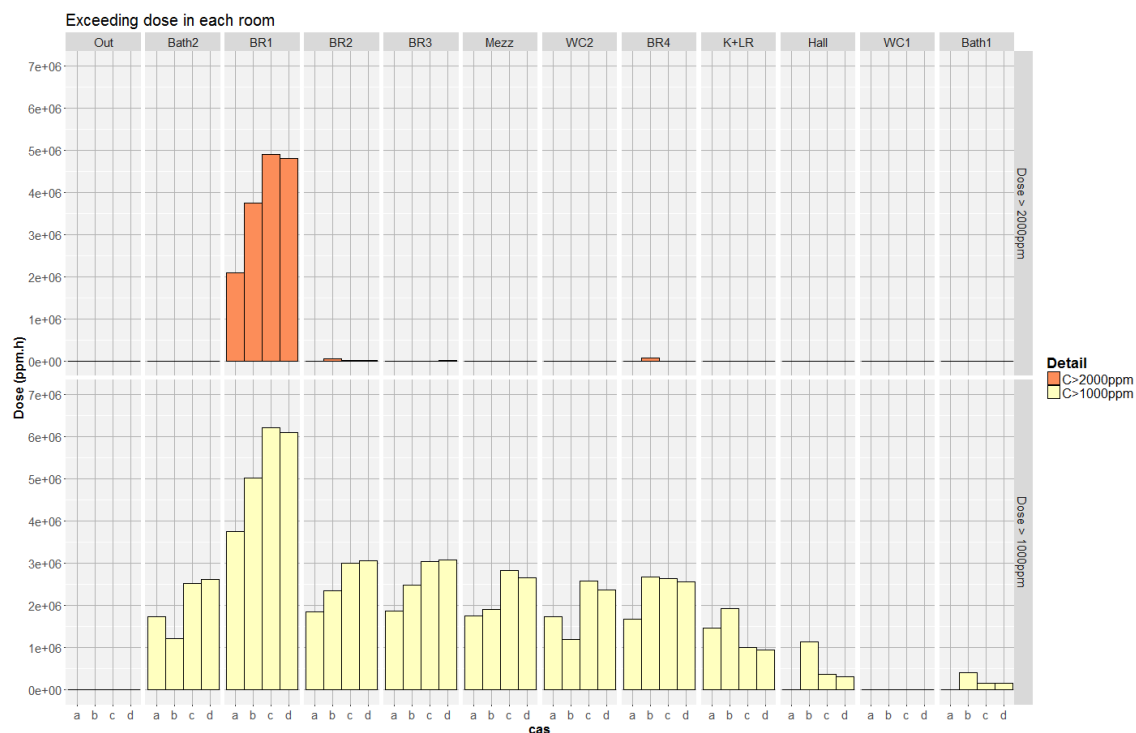


Figure 8. Cumulative exceeding exposures over 1000 and 2000 ppm. Exhaust-only ventilation. Cases a, b, c, d.

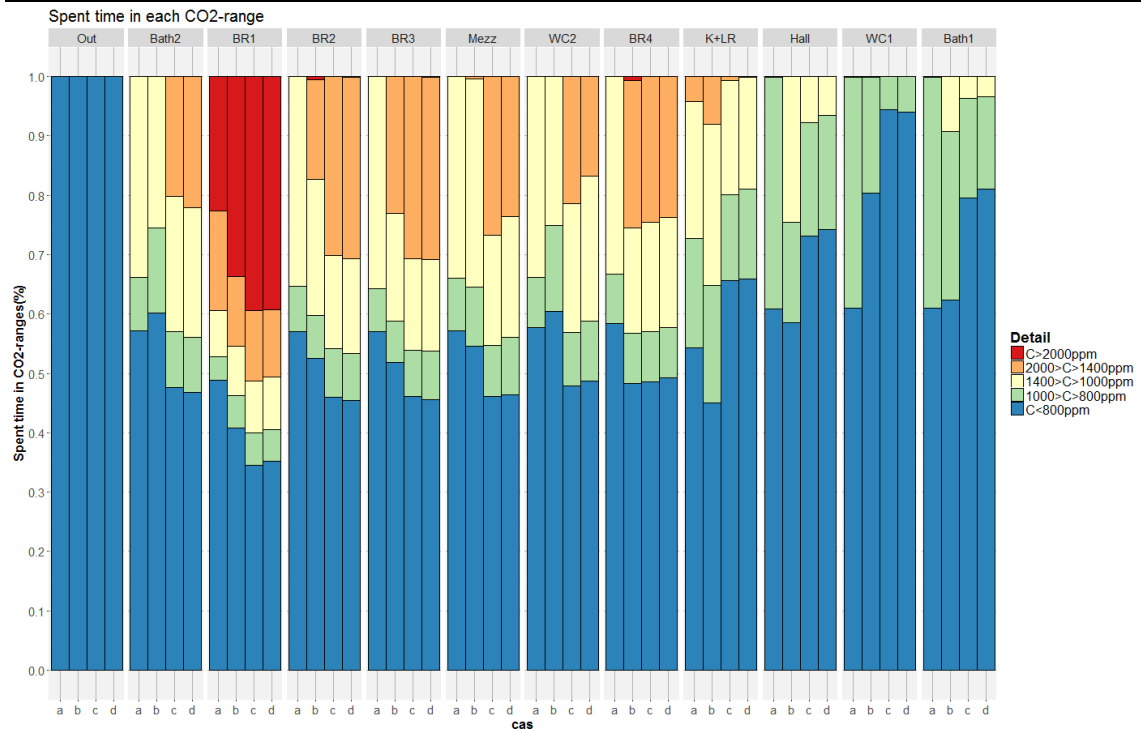


Figure 9. Time spent in each CO₂ class. Exhaust-only ventilation. Cases a, b, c, d.

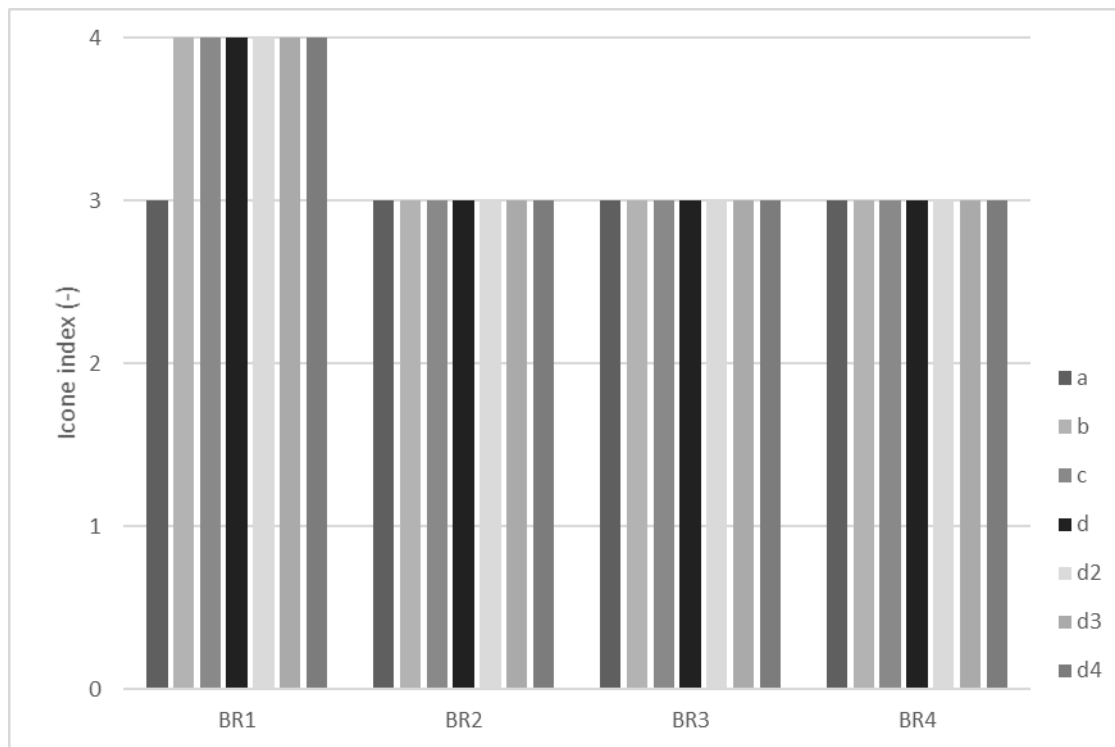


Figure 10. Icone air stiffness index. Seven airleakage cases. Exhaust-only ventilation.

Balanced ventilation

All the cases (a to d4) were also simulated with balanced ventilation. However, all ACR indicators show lower dispersion than with exhaust-only ventilation and are not shown in detail.

For all bedrooms, average CO₂ concentrations are in the range [703–1036 ppm] for the seven cases, with a median value of 717 ppm. In the seven cases, we observed no impact on average bedroom concentrations (maximum difference, 5%, BR3, d3).

The CO₂ concentration never exceeded 2000 ppm. The impacts of different simulations of airleakage on cumulative exceeding exposure over 1000 ppm are low in the bedrooms for cases b and c: maximum 4% and 3% (BR3), respectively, and moderate for cases di taking into account internal partition wall airleakage with a maximum of 15% (BR3).

We observed no difference concerning the Icone air stuffiness index.

5. Relative humidity

Exhaust-only ventilation

Figure 11 presents the percentage of time when RH was higher than 70%, while Figure 12 shows the duration outside of the [30–70%] range, for the seven airleakage cases. The first indicator is a condensation risk and is useful to study for all the rooms. The second indicator is a health indicator; therefore, the locations where occupants spent most of their time, i.e. in bedrooms, are of interest.

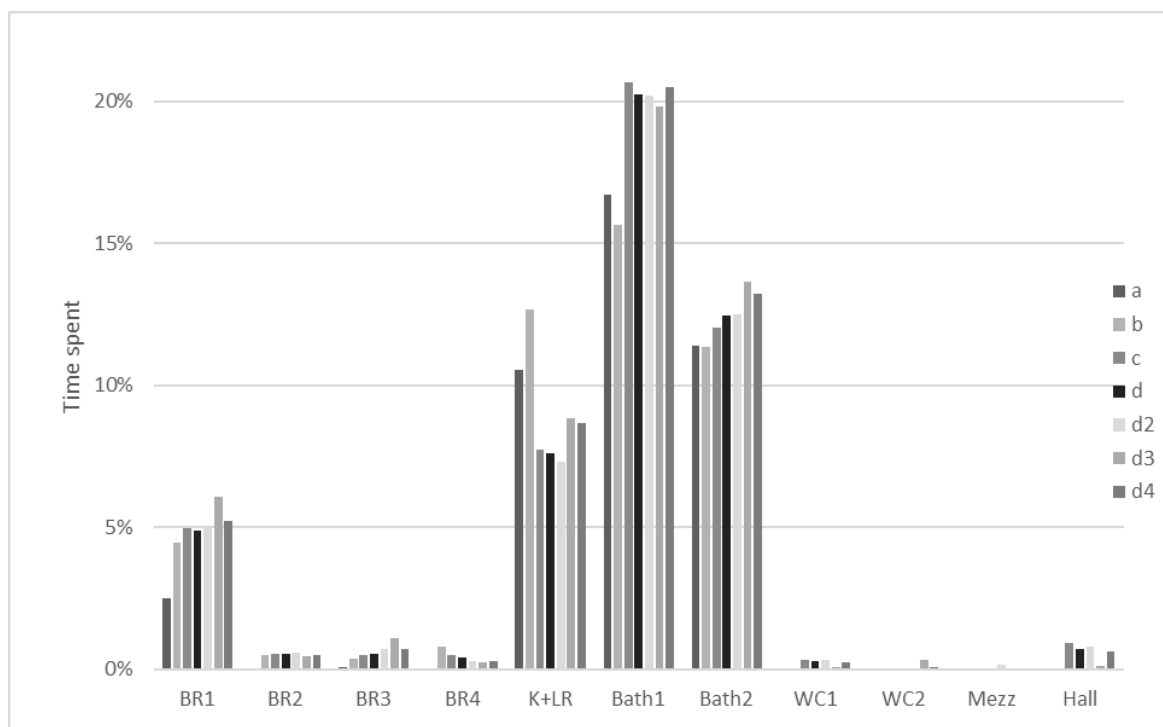


Figure 11. Percentage of time spent with RH>70% (condensation risk). Exhaust-only ventilation.

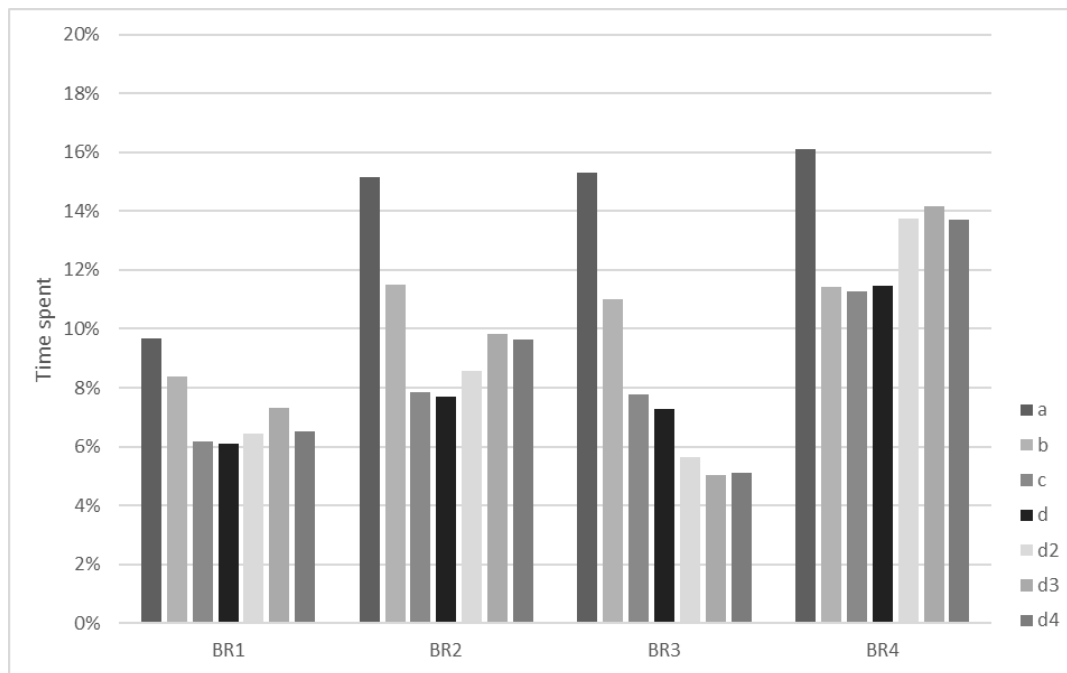


Figure 12. Percentage of time spent outside of the [30–70%] range (health risk). Exhaust-only ventilation.

With the exhaust-only ventilation system, in four rooms (Bath1 and 2, BR1 and K+LR), more than 5% of the time the RH exceeds 70%. Among these four rooms, ignoring envelope airleakage accounts for a maximum –44% difference (case a, BR1). Taking into account unevenly distributed airleakage accounts for a maximum –39% difference (case c, K+LR). Taking into account internal partition wall airleakage accounts for a maximum difference of –42% (case d2, K+LR).

Studying the time spent out of the [30–70%] range shows that for the four bedrooms (Figure 12), this indicator is in the range [5–16%]. Ignoring envelope airleakage accounts for a maximum 41% difference (case a, BR 4), taking into account unevenly distributed airleakage accounts for a maximum –32% difference (case c, BR2). Taking into account internal partition wall airleakage accounts for a maximum difference of –54% (case d3, BR3).

Balanced ventilation

When the balanced ventilation system is used, RH exceeds 70% at least 5% of the time in three rooms (Bath1 and 2 and K+LR), as shown on Figure 13. For these three rooms, ignoring envelope airleakage accounts for a maximum 11% difference (case a, K+LR). Taking into account unevenly distributed airleakage accounts for a maximum –10% difference (case c, K+LR). The impact of internal partition wall airleakage reaches a maximum difference of –18% (case d4, K+LR).

Studying the time spent outside of the [30–70%] range shows that this indicator is significantly greater in the bedrooms than with the exhaust-only ventilation. Here, as shown on Figure 14, its minimum value is 11%, whereas it was 5% with the exhaust-only ventilation. We can observe that the air is too dry in BR2, 3 and 4 and logically better in BR1 occupied by two occupants.

Once again, differences between cases are small: below 8% (case a, BR4), with one exception: ignoring envelope airleakage accounts for a 44% difference in BR1 (case a), due to a threshold effect. In case a, RH in BR1 is close to 30% for a long time.

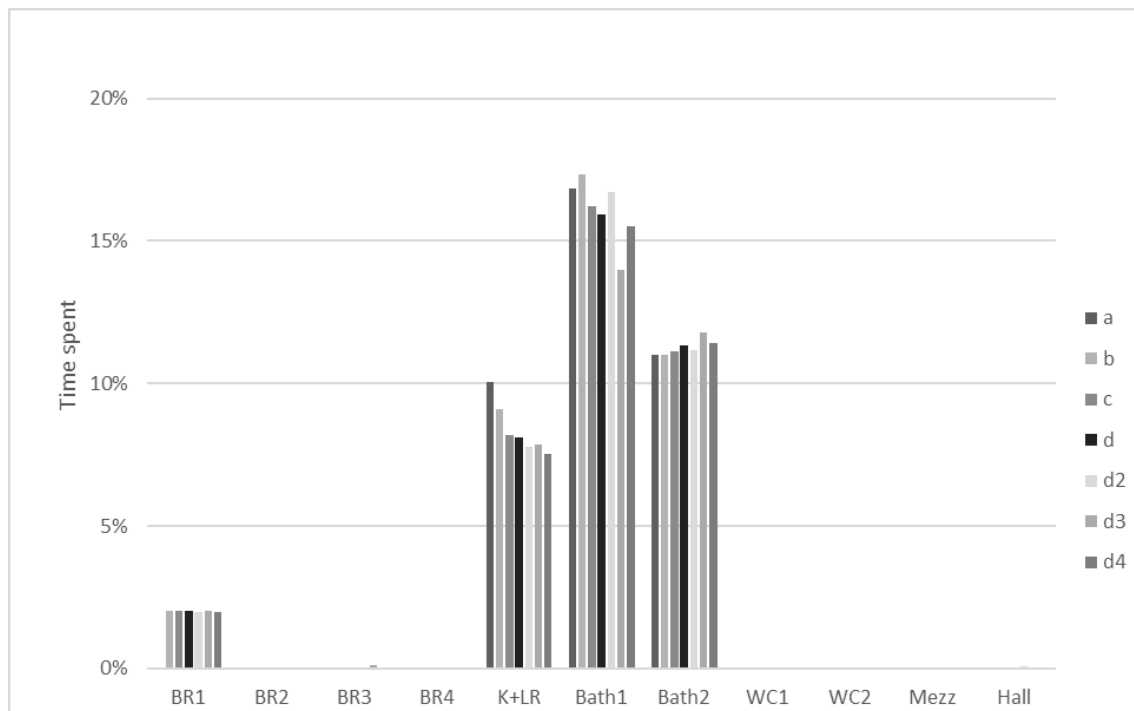


Figure 13. Percentage of time spent with RH > 70% (condensation risk). Balanced ventilation.

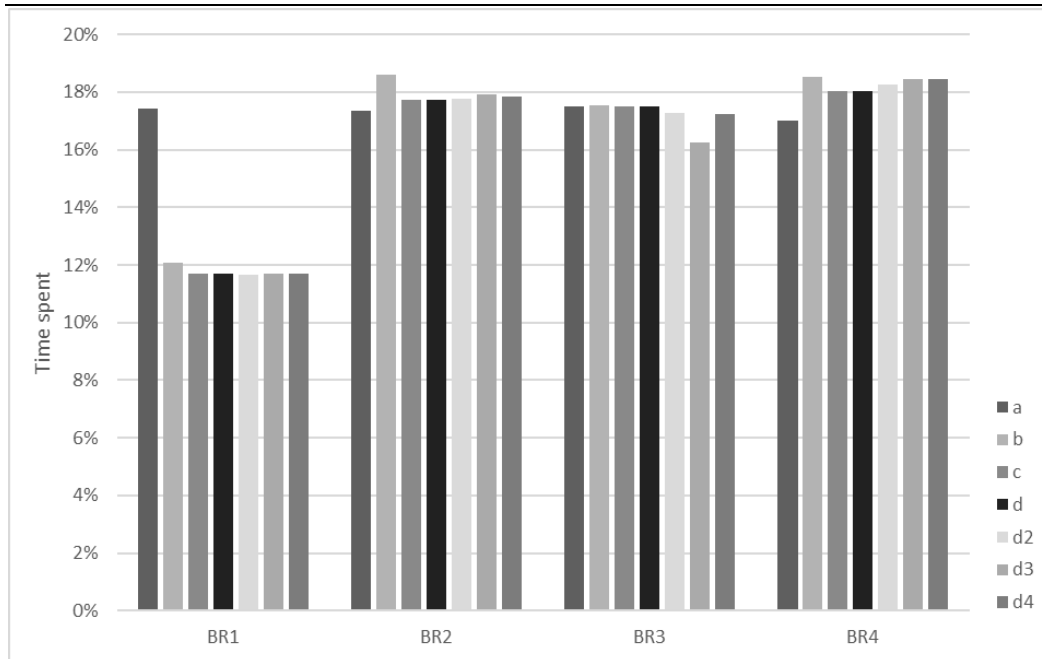


Figure 14. Percentage of time outside of the [30–70%] range (health risk). Balanced ventilation.

6. Formaldehyde

Exhaust-only ventilation

On Figure 15, we plotted the average formaldehyde concentration in each zone of the house obtained with the highest formaldehyde emission rate, for the seven airleakage cases. We also plotted the exposure ratio for the seven cases and three levels of emissions (Figure 16).

Whatever the case, with the high-emission scenario the concentration stays in the range $17.3\text{--}36.6 \mu\text{g}\cdot\text{m}^{-3}$, thus 1.9–4.1 times higher than the ELV, exceeding it more than 99.9% of the time. Ignoring envelope airleakage accounts for a maximum difference of –33% on the average concentration (case a, BR4). Taking into account unevenly distributed airleakage accounts for a maximum 27% difference (case c, BR2). Taking into account internal partition wall airleakage can reach an impact of 39% (case d3, BR1).

For the medium formaldehyde emission, average concentrations are in the range $10.2\text{--}19.9 \mu\text{g}\cdot\text{m}^{-3}$, i.e. between 1.1 and 2.2 times the ELV, exceeding it more than 99% of the time.

For the low formaldehyde emission (not shown here), average concentrations are in the range $5.6\text{--}9.25 \mu\text{g}\cdot\text{m}^{-3}$, 0.6–1.0 times the ELV. This average exceeding concentration occurs only in WC2 in the d2 case and in BR1 in the d3 case. Depending the cases studied, Bath2, WC2, BR1 and Mezz are zones with concentrations over the

ELV more than 30% of the time, even if their average concentration is below the ELV. It can be noted that only in d3, one bedroom (BR1) concentration is higher than the ELV, but 70% of the time, due to a threshold effect. For cases d, d2 and d4, the average concentration in BR1 is $8.4 \mu\text{g}\cdot\text{m}^{-3}$, with an exceeding time of 0.0, 0.2 and 4% respectively.

Studying the maximum formaldehyde exposure (Figure 16), we can first note that the exposure clearly depends on the emission level (high/medium/low). It should be added that Figure 16 shows only the case of the most exposed occupant, which differs depending on the case: occupants 1 and 2 (cases c, d3, d4), occupant 3 (cases d, d2) and occupant 5 (cases a, b).

This maximum exposure can be compared to the ELV limit exposure, and the resulting ratio is in the range [1.6–2.1] for the high emission scenario, [0.9–1.2] for the medium emission scenario, [0.5–0.6] for the low emission scenario.

Ignoring envelope airleakage always underestimates the exposure (case a), –25% for the high-emission scenario. Taking into account unevenly distributed envelope airleakage distribution slightly overestimates the exposure, –5% for the high-emission scenario. Depending on the internal partition wall airleakage distribution selected, impacts on the exposure are in the range [–9% to +0.4%].

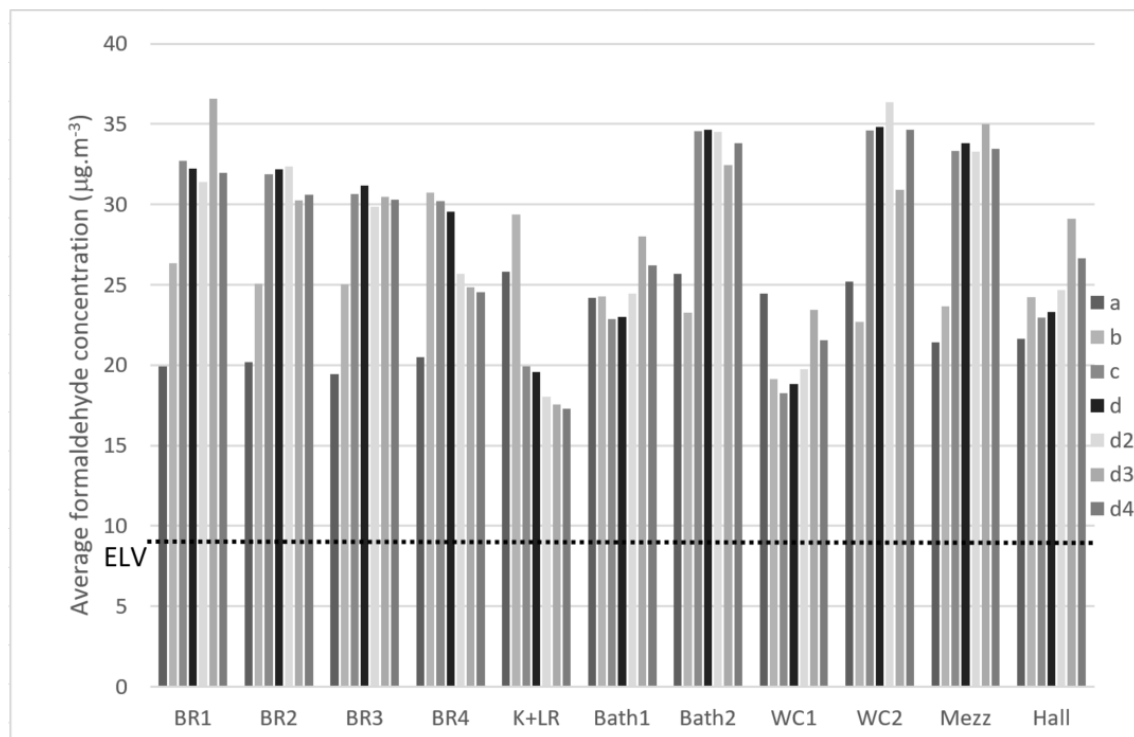


Figure 15: Impact of detailed airleakage data on average formaldehyde concentration; high-emission scenario, exhaust-only ventilation.

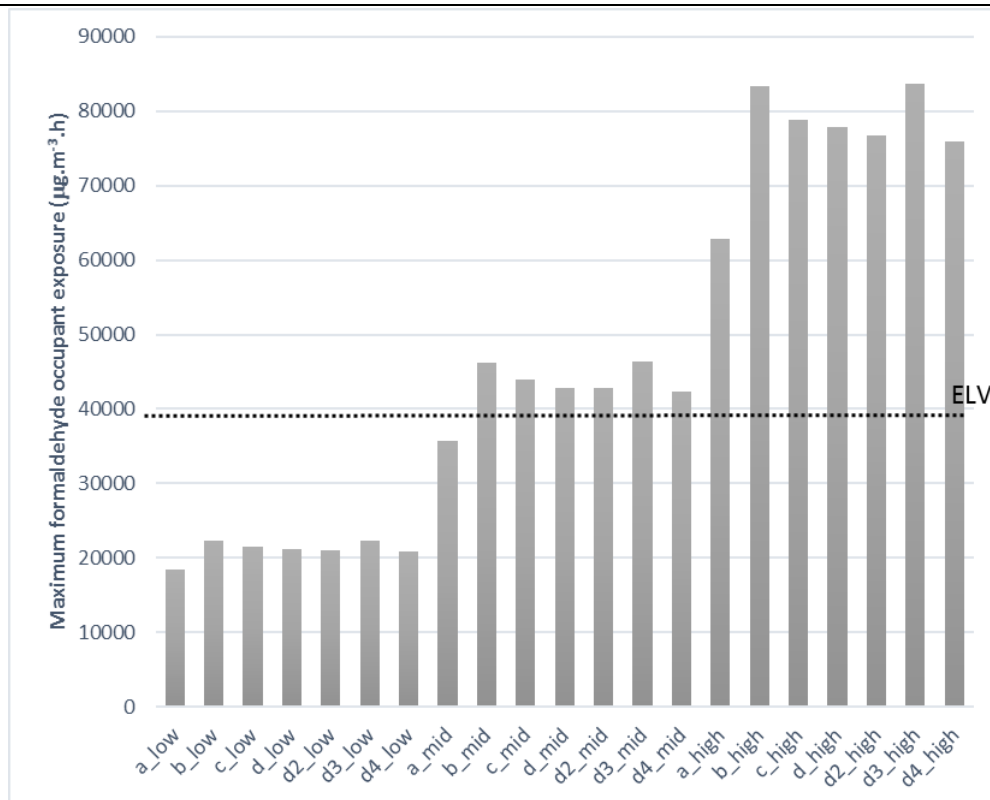


Figure 16 : Impact of airleakage distribution on maximum exposed occupant to formaldehyde; three levels of emissions, exhaust-only ventilation.

Balanced ventilation

All the cases (a to d4) were also simulated with balanced ventilation. However, all indicators show lower dispersion than with exhaust-only ventilation and are not shown in detail.

For the high-emission scenario, the concentration is in the range 17.1–26.9 µg.m⁻³, 1.9–3.0 higher than the ELV, more than 99.9% of the time. In the seven cases, we observed no impact on average bedroom concentrations (maximum difference, -1.7%, BR4, d4).

For the medium formaldehyde emission, average concentrations are in the range 10.1–15.0 µg.m⁻³, 1.1–1.7 higher than the ELV, exceeding it more than 90% of the time. For the low formaldehyde emission scenario, average concentrations are in the range 5.5–7.4 µg.m⁻³, 0.6–0.8 times the ELV. The concentration stays under the ELV in each room 100% of the time.

In the seven cases, we also obtained low impacts of airleakage cases on the ratio between maximum formaldehyde exposure and ELV limit exposure (maximum difference, 6.4%, case a). The exposure ratio is lower than with the exhaust-only

ventilation system, staying in the range [1.4–1.5] for the high-emission scenario, [0.8–0.9] for the medium-emission scenario and in the range [0.4–0.5] for the low-emission scenario.

IV. Discussion

1. Overview of the IAQ indicators calculated

Analysis of the results shows that with balanced-ventilation the bedroom ACRs are larger than the envelope ACR (0.51 h^{-1}), with dispersed values in the range [1.19–1.69]. The situation is different with exhaust-only ventilation where bedroom ACRs can be lower than the whole building's ACR (0.43 h^{-1}) in two-thirds of the cases studied, with dispersed values in the range [0.69–1.35]. These results can provide useful answers on the importance of airflows between rooms assumed in (Bekö et al. 2010; Du et al. 2012). They contradict the results from (Bornehag et al. 2005) considering that the envelope ACR and children's bedroom ACR can be considered to be close.

Analysis of the results also shows that the condensation risk is low in the secondary bedrooms and slightly higher in four other rooms (Bath1 and 2, K+LR and BR1), that have a RH higher than 70% more than 5% of the time (218 h). In the bedrooms only, this indicator is in the range [0–6%], with a median value of 0.3%, whatever the case and the ventilation system. The health risk is logically higher than the condensation risk because it includes not only the periods with RH higher than 70% but also periods with RH below 30%. For bedrooms only, this indicator is in the range [5–19%], with a median value of 12.9% (563 h), whatever the case and the ventilation system may be. Comparison of both RH indicators clearly shows that most of the time spent out of the range is due to low humidity, except for the four above-cited rooms.

For all cases and ventilation systems, average formaldehyde concentrations and corresponding exposures are higher than the selected threshold, except for the lowest emission rate. We must specify here that the French regulatory threshold is presently higher: $30 \mu\text{g}\cdot\text{m}^{-3}$ since January 2015, but should be lowered to $10 \mu\text{g}\cdot\text{m}^{-3}$ in 2023. Moreover, emission rates have been estimated here on a small sample based on only ten houses. Performing the calculation on a larger sample could lead to different emission rates and therefore different results.

2. Impact of the type of ventilation: relations between ACR and IAQ indicators

Analysis of the results shows that the envelope and bedroom ACRs are higher with balanced ventilation than with exhaust-only ventilation for the same total exhaust airflow of $135 \text{ m}\cdot\text{h}^{-1}$, +19% for the envelope ACR, and in the range [45–71%] for the bedroom ACRs in the reference case b.

As a consequence, CO₂, RH and formaldehyde concentrations are lower with balanced ventilation, which results in a better IAQ except for the RH health indicator with higher time spent below 30%.

The average CO₂ concentration in bedrooms is up to 1811 ppm with exhaust-only ventilation versus 1036 ppm with balanced ventilation (-75%). With this system, the threshold of 2000 ppm is never exceeded, whereas the cumulative exceeding concentration over 2000 ppm in BR1 can reach 6.2.10⁶ ppm.h with the exhaust-only ventilation.

We can also observe that exhaust-only ventilation provides a lower health risk regarding RH than the equivalent balanced ventilation. Indeed, low RH periods are significantly higher with balanced ventilation, with a median value of all the zones of 17.4% versus 11.8% for the exhaust-only ventilation system.

In addition, for the lowest formaldehyde emission rate, ELV is never exceeded for the balanced ventilation, whereas it is exceeded in four zones more than 30% of the time for the exhaust-only ventilation. In one room, ELV is even exceeded 70% of the time. Consequently, the maximum exposure is 1.03–1.49 higher with exhaust-only ventilation.

However, the relationship between bedroom ACRs and the IAQ indicators obtained are not so simple, and more complex links exist, as explained in the next section.

3. Impacts of airleakage distributions: overview

Table 9 and Table 10 give an overview of the calculated impacts on the IAQ indicators for the seven airleakage cases compared to the reference case b with exhaust-only and balanced ventilation. Impacts on the indicators depend strongly upon the ventilation system and the type of structure and are generally higher with exhaust-only ventilation and with a wooden structure (cases d3 and d4). We discuss here first the impacts of a detailed envelope airleakage distribution, then internal partition wall airleakage.

IAQ Indicators	Case a	Case b - ref [value]	Case c	Max (cases di)
Envelope ACR <i>case</i>	0.0%	0.43 h⁻¹	1.2%	1.3% <i>d3</i>
BR ACR <i>room (case)</i>	55.8% <i>BR4</i>	0.35–0.44 h⁻¹	-24.3% <i>BR2</i>	28.0% <i>BR4 (d4)</i>
Average BR CO ₂ concentration <i>room (case)</i>	-21.0% <i>BR4</i>	863–1405 ppm	18.4% <i>BR1</i>	29.0% <i>BR1 (d3)</i>
BR1 dose E ₂₀₀₀ <i>case</i>	-44.2%	3.8.10⁶ ppm.h	30.9%	49.2% <i>d3</i>

BR dose E_{1000} room (case)	-37.3% <i>BR4</i>	2.4–5.10⁶ ppm.h	27.2% <i>BR2</i>	36.2% <i>BR1 (d3)</i>
BR1 time spent $R_{>2000}$ case	-32.6%	34%	17.1%	27.6% <i>d3</i>
Time spent with RH>70% room (case)	-43.8% <i>BR1</i>	0.2–0.8% <i>BR1-K+LR</i>	-38.9% <i>K+LR</i>	-42.2% <i>K+LR (d2)</i>
Time spent with RH outside of 30–70% in BR room (case)	40.8% <i>BR4</i>	8.4–11.5 %	-31.7% <i>BR2</i>	-54.4% <i>BR3 (d3)</i>
Average BR HCHO concentration room (case)	-33.3% <i>BR4</i>	25.0–30.7 $\mu\text{g.m}^{-3}$	27.3% <i>BR2</i>	38.8% <i>BR1 (d3)</i>
Dose E_{max} , high emission case	-24.7%	8.3.10⁴$\mu\text{g.m}^{-3}.\text{h}$	-5.4%	-9.0% <i>d4</i>

Table 9. Overview of calculated impacts on the reference case. Exhaust-only ventilation

IAQ Indicators	Case a	Case b - ref	Case c	Max (cases di)
		[value]		
Envelope ACR <i>case</i>	-14.5%	0.51 h⁻¹	-4.0%	-5.5% <i>d4</i>
BR ACR <i>room (case)</i>	-2.5% <i>BR4</i>	0.60–0.68 h⁻¹	-1.8% <i>BR4</i>	27.8% <i>BR2 (d3)</i>
Average BR CO ₂ concentration <i>room (case)</i>	1.1% <i>BR4</i>	710–1033 ppm	0.8% <i>BR4</i>	5.2% <i>BR3 (d3)</i>
BR1 dose E ₂₀₀₀	/	0	/	/
BR dose E ₁₀₀₀ <i>room (case)</i>	3.8% <i>BR3</i>	1.5–3.3.10⁶ ppm.h	2.6% <i>BR3</i>	15.2% <i>BR3 (d3)</i>
BR1 R _{>2000}	/	0	/	/
Time spent with RH>70% <i>room (case)</i>	10.5% <i>K+LR</i>	9.1% <i>K+LR</i>	-9.9% <i>K+LR</i>	-17.5% <i>K+LR (d4)</i>
Time spent with RH out of 30–70% in BR <i>room (case)</i>	44.3% <i>BR1</i>	12.1–18.6%	-4.8% <i>BR2</i>	-7.2% <i>BR3 (d3)</i>
Average BR HCHO concentration <i>room (case)</i>	1.4% <i>BR3</i>	17.1–18.9 µg.m⁻³	1.5% <i>BR4</i>	-1.7% <i>BR4 (d4)</i>
Dose E _{max} , high emission <i>case</i>	6.4%	5.7.10⁴µg.m⁻³.h	1.8%	1.5% <i>d</i>

Table 10. Overview of calculated impacts on the reference case. Balanced ventilation.

Analysis of the results shows that a detailed envelope airleakage distribution has a low impact on the envelope ACR (maximum, 1.2%) but a larger one on the bedroom ACRs (maximum, -24.3%) with exhaust-only ventilation. In this type of system, airflows through the building envelope are driven by larger pressure differences between indoors and outdoors due to the voluntary extracted airflows and are consequently less sensitive to wind and buoyancy effects. Changing the envelope airleakage distribution can short-circuit some rooms however, as shown on Figure 1(b), significantly modifying bedroom ACRs. The contrary is observed with a balanced ventilation system, with a slightly higher impact on the envelope ACR (maximum, -4%) but a low one on the bedroom ACRs (maximum, -1.8%). In this type of system, supply and exhaust devices balance the voluntary airflows, so that impacts of wind and buoyancy effects are quite high on the building scale, but a short-circuit effect on individual rooms is limited.

Maximum impacts on the CO₂ and RH indicators and formaldehyde concentrations are strong with the exhaust-only ventilation, respectively up to 31%, 39% and 27%, respectively. With balanced ventilation, they are negligible on CO₂ indicators and formaldehyde concentrations, respectively 2.6% and 1.8%, but considerable on RH indicators, up to -10%. Impacts on maximum formaldehyde exposure are negligible whatever ventilation system is used (up to -5% only).

In conclusion, when we ignore internal partition wall airleakage, we can also observe a quite clear relationship between the impact on bedroom ACRs and the IAQ indicators, except for the impacts on RH indicators, which remain significant with balanced ventilation, mainly due to a threshold effect.

The impact of internal partition wall airleakage is low on the envelope ACR (maximum, -5.5%), but high on bedroom ACRs (up to 28% with exhaust-only and balanced ventilation). These direct airflows between rooms short-circuit theoretical mechanical ventilation airflows: exfiltration through internal partition walls can account for more than 90% of the total exfiltration in at least one bedroom whatever the ventilation system used. Nevertheless, we observe stronger maximum impacts with exhaust-only ventilation on CO₂ and RH indicators and formaldehyde concentrations, respectively up to 49%, -54% and 39%, than with balanced ventilation, respectively up to 15%, -18% and -1.7%. Impacts on maximum exposure are significantly lower for all the ventilation systems (up to -9% only).

Moreover, Table 9 and Table 10 show that the main rooms and the cases where impacts on bedroom ACRs are the highest (BR4, d4 in Table 9, and BR2, d3 in Table 10) are not the same as the rooms where impacts on IAQ indicators are the highest (BR1, d3 and K+LR, d2 in Table 9, and BR3, d3; BR4, d4 and K+LR, d4 in Table 10).

Indeed, considering internal airleakage involves short-circuits and complex air pathways through the house and between rooms. Pollutants are also diluted in some zones and concentrated in others, given that the envelope ACR remains nearly constant. As a result, impacts on evenly emitted pollutants such as formaldehyde are lower than others. Moreover, with balanced ventilation, supplying the same airflow rate in each bedroom contributes to decreasing the effects of short-circuits on concentrations.

4. Relevance of performance indicators

Conclusions on the performance indicators' relevance for ventilation performance assessment can also be addressed based on this analysis, since we showed that some indicators are not adapted to demonstrating the impacts that others are able to show, for instance the Icone index or the whole building ACR. From this analysis, we would suggest selecting at least one "constant emission" pollutant such as formaldehyde and one "variable-emission" pollutant such as humidity, which serves to estimate both health and condensation risks. We would suggest using the following indicators to be calculated over the heating period: cumulative exceeding CO₂ exposure

over 1000 ppm in the bedrooms, maximum cumulative occupant formaldehyde exposure, percentage of time with RH outside of the range [30%–70%] in the bedrooms and higher than 70% in all rooms. We often observed threshold effects: consequently, they must be carefully taken into account when choosing the indicators.

V. Conclusion and perspectives

The impacts of detailed envelope airleakage distribution and internal partition wall airleakage on the ventilation performance of a low-energy house were studied through two types of ventilation: exhaust-only and balanced ventilation. We used a multizone modelling approach performed with CO₂, humidity and formaldehyde to calculate IAQ performance indicators in each room over the heating period. We used three constant levels of formaldehyde emissions (4.5–12.0 and 23.6 µg.m⁻²).

Balanced ventilation gives better IAQ results than exhaust-only ventilation on CO₂ and formaldehyde indicators, but a worse IAQ estimated through humidity indicators. We showed that formaldehyde concentrations were rarely under the ELV, except for the lowest emission scenario with the balanced ventilation system.

Impacts of unevenly distributed envelope airleakage on selected IAQ performance indicators are generally significant for either ventilation system. The impact of internal partition wall airleakage is generally greater with exhaust-only ventilation but can be strong on some IAQ indicators (bedroom ACR, RH) with balanced ventilation as well.

We highlighted that there is no direct relation between the envelope ACR, bedroom ACRs and pollutant concentrations, because these concentrations have a complex dependence upon the air pathways through the house. Hence, to assess the performance of a ventilation system different indicators should be used: bedroom ACRs should be complemented with at least one “constant emission” pollutant such as formaldehyde and with at least one “variable emission” pollutant such as humidity (for both health and condensation risk).

The results presented herein highlight the need of multizone models for assessing ventilation and IAQ performance at the room scale, especially in bedrooms, not only at the whole building scale. They also highlight the need for using input data for envelope and internal partition wall airleakage, especially for light (wooden) structures with exhaust-only ventilation systems, to go beyond the simplifying assumption of even distribution.

Our results need to be further investigated with several house geometries, several ventilation systems, including smart ones, several envelope airleakage levels, ...

As a general perspective, to assess ventilation IAQ performance at the design stage, there is also a need for precise emission scenarios for different pollutants:

formaldehyde as well as particles, not only at the material scale but also at the room and dwelling scale.

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VII. References

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Part 4 conclusion

In this Part 4, we quantified the impacts of detailed envelope and internal partition wall airleakage distributions on the ventilation IAQ performance of a low-energy house. We studied seven airleakage cases based on seven different airleakage distributions. We assumed two types of constant-airflow ventilation: exhaust-only and balanced ventilation, both complying with the French airing regulation. We used a multizone modelling approach performed with CO₂, humidity and formaldehyde to calculate IAQ performance indicators in each room over the heating period. We used three constant levels of formaldehyde emissions (4.5–12.0 and 23.6 µg.m⁻²).

We observed that impacts on the IAQ indicators depend strongly upon the ventilation system and the type of structure and are generally higher with exhaust-only ventilation and with a wooden structure.

A detailed envelope airleakage distribution has a large impact on the bedroom ACRs (maximum, -24.3%) with exhaust-only ventilation. Maximum impacts on the CO₂ and RH indicators and formaldehyde concentrations are strong with the exhaust-only ventilation, respectively up to 31%, 39% and 27%, respectively. With balanced ventilation, they are negligible on CO₂ indicators and formaldehyde concentrations, respectively 2.6% and 1.8%, but sizable on RH indicators, up to -10%. Impacts on maximum formaldehyde exposure are negligible whatever ventilation system is used (up to -5% only).

The impact of internal partition wall airleakage is low on the envelope ACR (maximum, -5.5%), but high on bedroom ACRs (up to 28% for both exhaust-only and balanced ventilation). Stronger impacts are observed with exhaust-only ventilation on CO₂ and RH indicators and formaldehyde concentrations, respectively up to 49%, -54% and 39%, than with balanced ventilation, respectively up to 15%, -18% and -1.7%. Impacts on maximum exposure are significantly lower for all the ventilation systems (up to -9% only).

We concluded that impacts of unevenly distributed envelope airleakage on selected IAQ performance indicators are generally significant for both ventilation systems. The impact of internal partition wall airleakage is generally greater with exhaust-only ventilation but can be strong on some IAQ indicators (bedroom ACR, RH) with balanced ventilation as well.

Moreover, we highlighted that there is no direct relation between the envelope ACR, bedroom ACRs and pollutant concentrations, because these concentrations have a complex dependence upon the air pathways through the house. We observed that the main rooms and the cases where impacts on bedroom ACRs are the highest are not the same as the rooms where impacts on IAQ indicators are the highest. Indeed, considering internal airleakage involves short-circuits and complex air pathways through the house and between rooms. Pollutants are also diluted in some zones and concentrated in others, given that the envelope ACR remains nearly constant. As a result, impacts on evenly emitted pollutants such as formaldehyde are lower than others. Moreover, with balanced ventilation, supplying the same airflow rate in each bedroom contributes to decreasing the effects of short-circuits on concentrations.

Conclusions on the performance indicators' relevance for ventilation performance assessment could also be addressed based on this analysis, since we showed that some indicators are not adapted to demonstrating the impacts that others are able to show, for instance the Icone index or the whole building ACR. Hence, to assess the performance of a ventilation system different indicators should be used: bedroom ACRs should be complemented with at least one "constant emission" pollutant such as formaldehyde and with at least one "variable emission" pollutant such as humidity (for both health and condensation risk). We would suggest using the following indicators to be calculated over the heating period: cumulative exceeding CO₂ exposure over 1000 ppm in the bedrooms, maximum cumulative occupant formaldehyde exposure, percentage of time with RH outside of the range [30%–70%] in the bedrooms and higher than 70% in all rooms. We often observed threshold effects: consequently, they must be carefully taken into account when choosing the indicators.

In conclusion, with those results:

1. We confirmed the need of multizone models for assessing ventilation IAQ performance at the room scale, especially in bedrooms, not only at the whole building scale.
2. We also highlight the need for using detailed input data for envelope and internal partition wall airleakage, especially for wooden structures with exhaust-only ventilation systems, to go beyond the simplifying assumption of even distribution.
3. We were able to identify more relevant performance indicators.

5

Towards performance-based approach for ventilation – proposed methodology

As introduced, **“Performance-based” approaches** for ventilation would insure that it is designed to avoid risks for occupant’s health and building damages. Such an approach could be required at different scales:

1. At the ventilation system scale: for allowing the use of an innovative ventilation system instead of reference systems. In this case, standardized input data and scenarii should be used,
2. **At the building scale: at the design stage of a building, input data (such as airleakage, ventilation type...) from the given building should be used.**

Such approaches could also be used at different stages of the building’s construction:

1. At the design stage, as a design method;
2. **Later at the end of the design stage, during the regulatory compliance stage, to assess the design. It could be called a “design assessment method”;**
3. At initial commissioning, or later once the building is occupied, as an in-situ performance assessment method.

If we compare to the energy performance field, the design method is the detailed energy simulation performed to optimize the energy consumption of the building, the design assessment method is the regulatory energy performance calculation based on simplified assumptions and a limited number of performance indicators, complete in-situ performance assessment methods are rare but could be based on several measurements (airleakage test, wall thermal conductivity, energy consumption, ...).

Facing a lack of data about the relevant method for ventilation, we will propose in this part a performance-based approach for assessing ventilation performance at the building scale and at the end of the design stage of a residential building, as does an energy performance regulatory calculation. We propose also to be at the stage number 2 developed just above, a “design assessment method”. In order to develop such a performance-based approach, we need addressing the following topics:

1. Step 1: What are the relevant pollutants and/or parameters to use for calculating performance indicators and what indicators should be used?
2. Step 2: What are the relevant input data to use regarding the occupancy and pollutant emission scenarii?
3. Step 3: What level of detail should we use for modelling airflows and pollutants throughout the house, concerning general modelling assumptions (multizone, weather data, ...), the airleakage distributions, the moisture buffering effect?

In this Part 5 of the thesis, we will propose a method based on a literature review and on complementary analysis to answer each of these three questions, constituting an existing scientific barrier that we would like to come down.

We will complement the performance indicators from literature analyzed in Part 2 and the ones tested in Part 4, by an extensive review of literature, focusing on CO₂, humidity, PM_{2.5}, formaldehyde. We will also use the feedbacks from the Part 4 to study their relevance. We also will propose an extensive review of used pollutant emission scenarii focusing on CO₂, humidity, PM_{2.5}, formaldehyde.

After summarizing the method through an overview scheme, the proposed performance-based approach will be applied on a case study: a four bedroom-low-energy house, already modelled in the Part 4. For that, we would assume being at the design stage of this house which should comply with an assumed regulation, code or label, requiring to calculate IAQ ventilation performance indicators.

Lastly, we should conclude about the applicability of the proposed method. We will also study how the method could help at the design stage in key choices regarding their impacts on IAQ.

5.1 Proposed method

5.1.1 Step 1: Relevant IAQ indicators to be used for ventilation performance assessment

There is no consensus about the IAQ indicators to be used in a performance-based method for ventilation, as illustrated by the long list of performance indicators proposed in the EN 15665 standard “*Ventilation for buildings. Determining performance criteria for residential ventilation systems*” (CEN, 2009) and on-going works for its revision. The IEA Annex 68 “*Indoor air quality design and control in low energy residential buildings*” proposes also to define metrics and indices to evaluate the IAQ of low-energy residential buildings (Abadie and Wargocki, 2017). The EN 15665 standard gives three important definitions:

- Parameter: pollutant or marker that is used in the expression of a requirement,
- Criteria: way (method) to express the required performance, we name it “the performance indicator” in this PhD work,
- Requirement: level of required performance.

In our performance-based approach at the design stage of a residential building, the first issue to address is: what are the parameters in houses to consider in such an approach? The second one is about how to select IAQ performance indicators related to these parameters and to which requirements should they be compared? We tried to answer to these questions through a review of literature.

5.1.1.1 Parameters of concern for ventilation performance assessment

We should here define in our context what we called an indoor “pollutant” or an indoor “parameter”. According to the Oxford dictionary a “pollutant” is “*something contaminating (water, the air, etc.) with harmful or poisonous substances*”. Indoor air pollutants must also have recognized effects on occupant’s health. A “parameter” is defined as “*a numerical or other measurable factor forming one of a set that defines a system or sets the conditions of its operation*”. This definition is close from the EN 15665’s one. Indoor parameters are also measurable quantities which could be measured in an ambient zone in order to characterize this ambient zone. Indoor parameters could also include luminance, temperature, humidity, carbon dioxide, bioeffluents (organic atmospheric parameters that emanate from the bodies of humans as odors...), pollutants, airflows, air velocities, etc.

We also decided to treat in this work, firstly the indoor air pollutants of concern, then the moisture and the carbon dioxide which are not pollutants according to this definition, but are considered as parameters. Lastly, air renewal is another parameter often used in ventilation performance assessment that we will discuss here.

5.1.1.1.1 Pollutants of concern

Ventilation should not be seen as a panacea: to achieve good indoor air quality, source reduction must also be considered (Mansson et al., 1997; Sherman and Hodgson, 2002a; Wargocki, 2012; Borsboom et al., 2016). The history of combustion devices changing from open fireplaces to sealed modern

fireplaces is a good illustration of a response to the need for source reduction (Matson and Sherman, 2004). Public policies which push the development of low emitting building materials and furnishings is another example (Composite wood product airborne toxic control measure of California Environmental Protection Agency, 2011; Compulsory labeling of VOC emission of all construction products and decorative products installed indoors of French Ministry for Ecology, 2011). While source reduction is key in reducing pollutant levels, this PhD work limits its scope to ventilation system design. Ventilation should be considered a method to dilute remaining pollutants once their sources have been reduced. From this perspective, (Borsboom et al., 2016) proposes that tobacco smoke and radon should not be considered in establishing ventilation standards. Although they were clearly pointed out in a cumulative risk assessment study (WHO 2011) and in an impact assessment of chronic residential exposure (Logue, et al. 2011b), these pollutants are more impacted by home characteristics (such as the depressurization of subfloors for radon) and occupant behavior than by ventilation strategies (Borsboom et al., 2016). We can consider that carbon monoxide is, similarly, not a pollutant suitable for assessing ventilation performance as shown by the results in Emmerich, et al. (2005) in which adjusting the stove had a bigger impact than changes in air flows.

A starting point for our purpose was the AIVC technical note “TN 68: Residential Ventilation and Health” recently published by international experts of the field (Borsboom et al., 2016). They considered existing guidelines and standards, hazard assessment, cumulative risk assessment and impact assessment exposure studies, and proposed a selection of high-priority pollutants for residential ventilation standards (Table 2). **They confirmed the importance of considering particulate matter PM_{2.5}, formaldehyde and acrolein** as pointed out by (Logue et al., 2011b), Figure 4. In this paper, the authors estimated the population-averaged annual cost, in DALYs lost, of chronic air pollutant inhalation in U.S. residences. This figure gives the results in DALYs lost per year per 100,000 persons for the 12 pollutants with highest median DALY loss. DALYs lost could be calculated using three types of approaches. The intake–incidence–DALY (IND) method uses epidemiology-based Human Concentration-Response functions to quantify disease incidence rates, combined with estimates of DALY losses per disease incidence reported in the literature. If human Concentration-Response functions are not available, the intake–DALY (ID) approach calculate the health impact associated with intake of pollutants based on animal toxicity literature. The third method consists in using directly literature-reported disease incidence rates on human.

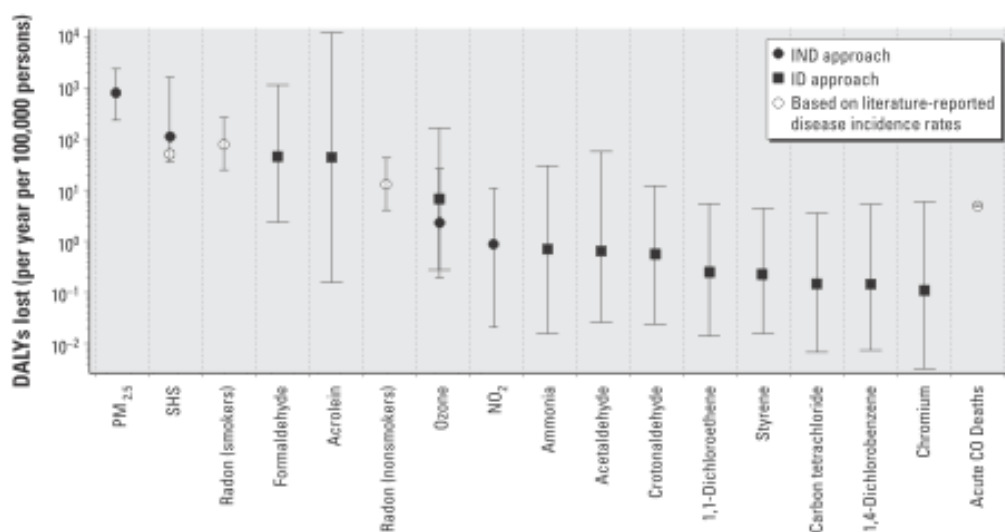


Figure 4. Estimated population-averaged annual cost, in DALYs lots, of chronic air pollutant inhalation in U.S. residences: results for the 12 pollutants with highest median DALY loss estimates. (Logue et al., 2011b)

High-priority pollutants for chronic exposure (ranked by population impact)	High-priority pollutants for acute exposure
1. Particulate matter 2. Mold and moisture 3. Formaldehyde 4. Acrolein	Acrolein, Chloroform, Carbon monoxide, Formaldehyde, NO ₂ , PM _{2.5}

Table 2: Selection of pollutants in residential ventilation standards (Borsboom et al., 2016)

PM_{2.5} are defined as particles with an aerodynamical diameter equal or inferior to 2.5 micrometer, also known as fine particles. They include also ultrafine and nanoparticles. They are emitted inside and outside because they mainly come from combustion (natural and anthropic). They can become the main contribution of the indoor pollutant concentration (He, 2004). Furthermore, because of their small dimension, these particles can penetrate more or less deeply in the airway, and may even infiltrate the blood (AFSSET, 2006). The inhalation of this particles have a large scale of effect from eyes, nose, or throat irritation to respiratory or cardio-vascular dysfunction (as myocardial infarctus or stroke) depending on the time and the intensity of exposure (AFSSET, 2010). As a result, several studies identified PM_{2.5} among the pollutants of concerns in dwellings (Kirchner and al., 2007; WHO, 2010; Logue et al., 2011a; Borsboom et al., 2016). Moreover, (Logue et al., 2011b) estimated that PM_{2.5} have an huge weight in the total health damage due to indoor air pollutants in the DALY calculation.

Formaldehyde (HCHO) is a common VOC interesting to survey in dwellings for many reasons. Firstly, this pollutant is nearly always measured in homes (100% of the French dwellings), and it's also a quasi-only inside production (until 10 times superior than the outside) due to huge quantity of indoor emitting materials, furniture and products (Kirchner and al., 2006a). It can also result from other VOC's oxidation or reaction into alkene and ozone (Uhde and Salthammer, 2007). Secondly, this substance is recognized as having a large range of health impacts, depending on the concentration and the acute and chronic exposures. Effects are known from eyes irritation to nasopharynx cancer (judging not explainable by confusion factors), and are suspected of other neurologic, reprotoxic, cancerogenic effect (AFSSET, 2007; CIRC, 2006; INERIS, 2010). As a result, several studies identified formaldehyde among the pollutant of concerns in dwellings (Kirchner and al., 2007; Koistinen et al., 2008; WHO, 2010; Logue et al., 2011a; Borsboom et al., 2016).

Acrolein comes mostly from combustion of organic matter, biocides, motor vehicle exhaust from traffic, but also from biodiesels, tobacco smoking, cooking (frying in oils) (Borsboom et al., 2016). Acrolein was pointed out by these authors, based on (Logue et al., 2011b) but not especially pointed

out in the French IAQ measurement campaign (Kirchner and al., 2006a). As a conclusion, using IAQ performance indicators based at least on the both pollutants formaldehyde and PM_{2.5} to assess ventilation performance seems worthwhile to avoid health risks. Moisture will be developed in the next section as it is not considered as a pollutant as such.

5.1.1.1.2 Humidity

Humidity is one of the prioritized pollutants of concern identified in Table 2. Nevertheless, humidity is not exactly a pollutant as such, but it's too low or too high values have both a negative effect on IAQ. Relative humidity is also more difficult to work within the context of a performance-based approach, as IAQ concerns necessitate controlling both a range with a minimal threshold to assure health and a time above a threshold to avoid a condensation risk. The high threshold value depends on climate and can be fixed at values as low as 45%, as is done in Nordic countries in order to prevent growth of house dust mites (Nielsen 1992). Moreover, from a health perspective, only a metric combining humidity, time above a limit, and temperature can adequately quantify the condensation risk.

This research also set out to answer the related question of whether relative humidity can be representative of other parameters, such as occupant-related emissions. Our literature review showed that some studies found a positive correlation and other studies found a negative one. The moisture buffering effect and the dependence of relative humidity on temperature and air moisture content reduces the relationship between moisture and occupancy. As a result, several studies (Anon, 1983; Barthez and Soupault, 1984; Sheltair scientific Ltd., 1988; Parekh and Riley, 1991) show a poor relationship between relative humidity and the occupant load in a room. (Fisk and De Almeida, 1998) confirmed that other residential pollutants are not correlated with humidity. A two-week monitoring study of a house reported by (Mansson, 1993) showed no correlation between the value given by an RH sensor and a mixed gas sensor in the living room.

In contrast, the Performance Project (Air H, 2010; Bernard, 2009) highlighted a strong correlation between CO₂ concentrations and the relative humidity levels measured in 31 apartments over the duration of more than two complete heating seasons. To quantify this correlation, the authors plotted the average degree of opening of humidity-controlled air inlets against CO₂ concentrations between 300 ppm and 2000 ppm, and observed a clear correlation between degree of inlet opening and concentration of CO₂ in bedrooms. These results confirm previous ones from 26 apartments equipped with humidity-controlled ventilation in France, Belgium, and the Netherlands (Mansson, 1993). (Moffat et al., 1991) observed in one house that CO₂ levels and relative humidity tend to track each other, but that CO₂ peaks occurred three hours later. This was confirmed by research by (Parekh and Riley, 1991). (Raatschen and Trepte, 1987) showed that, in a three-occupant living-room, air change rates necessary to remove moisture are higher than those necessary to keep CO₂ concentrations below 1000 ppm. They showed also that in an unoccupied bathroom the hourly air change rate needed to remove moisture was higher than the one needed to remove formaldehyde; the opposite was observed in the living room. In residential buildings, Raatschen and Trepte conclude that the need for ventilation in occupied rooms is dominated by moisture; in unoccupied rooms the need to ventilate for formaldehyde control is more important and must be considered when setting minimum airflows.

The correlation between absolute humidity and CO₂ might be stronger than the correlation between relative humidity and CO₂; however, it has a lag time due to sorption characteristics of the building materials and furniture in the home (Moffat et al., 1991; Savin and Jardinier, 2009).

As a conclusion, using the humidity parameter to assess ventilation performance seems worthwhile to avoid health problems and condensation risks. The fact that there is no evidence of positive correlation between humidity and other parameters of indoor air highlights the need to use humidity combined with other parameters.

5.1.1.1.3 CO₂

All analyzed performance-based approaches used in regulations and standards for smart ventilation have been using a performance indicators based on CO₂ (Gaëlle Guyot et al., 2018b), most of the analyzed literature on smart ventilation performance as well (Gaëlle Guyot et al., 2018c). However, the health impact of CO₂ is not straightforward as will be discussed in the following paragraphs. In addition, the relevance of using CO₂ for performance-based approach for ventilation will be discussed.

Several studies have shown that health effects directly attributable to CO₂ are minimal at concentrations observed in indoor environments, which are commonly in the range of 350 ppm—2000 ppm, but which have been measured at values of 6000 ppm in bedrooms during night periods (Kirchner and al., 2006b). The American Conference of Governmental Industrial Hygienists considers 5000 ppm the threshold for an 8-hour exposure in indoor environments (ACGIH 2011). The French Agency for Food, Environmental and Occupational Health Safety published results of an analysis of available CO₂ epidemiologic and toxicology studies, and of studies on CO₂'s effects on health, performance, and comfort (ANSES 2013). Results concluded that the only health threshold on which several studies converge is an exposure of 10000 ppm for 30 minutes, corresponding to a respiratory acidosis for a healthy adult with a modest amount of physical load.

The analysis does mention an experimental study (Satish, et al. 2012) of 22 human subjects that suggested an effect on psychomotricity performance above 1000 ppm attributable to CO₂ but which must still be further investigated according to the authors. The recent study of Zhang, et al. (2016) shows different results. Twenty-five human subjects were exposed for 255 minutes first to pure CO₂ (at either 1000 ppm or 3000 ppm) and then, through a decreasing of the ventilation rate, to all emissions from occupants (called bioeffluents) including CO₂, and corresponding CO₂ levels (of either 1000 ppm or 3000 ppm). No statistically significant effects were observed in the first case; the second showed an increase in reported headaches, fatigue, sleepiness, and difficulty in thinking clearly. The authors conclude that moderate concentrations of bioeffluents, but not CO₂, will affect occupants at typical indoor exposure levels. This can also be seen as a study of dose-response relationships between human bioeffluents, including CO₂, and indicators of health, wellbeing, and performance.

Other studies of specific applications such as bomb shelters, submarines (de Gids and Heijnen 2011), and high-risk industrial facilities and homes (French Ministry For Ecology 2007) have used higher threshold values for CO₂. They confirm that CO₂ is not dangerous by itself at the levels measured in residences. All these threshold values are summarized in Table 3.

Effects	CO ₂ threshold (ppm)	Comments	Source
Comfort	1000	To prevent odors from bioeffluents	(Von Pettenkofer 1858)
No effect	3000 for 255 min	Pure CO ₂	(Zhang, et al. 2016)
Increasing intensity of reported headache, fatigue, sleepiness, and difficulty in thinking clearly	3000 for 255 min	Metabolic CO ₂ + bio-effluents	(Zhang, et al. 2016)
Hygienist threshold in indoor environments	5000	For 8 hours exposure	(ACGIH 2011)
Respiratory acidosis for a healthy adult with a modest amount of physical load	10,000	For 30 minutes	Several studies reviewed in (ANSES 2013)
Bomb shelters	20,000		(de Gids and Heijnen 2011)
Submarine	30,000		(de Gids and Heijnen 2011)
Irreversible effects	50,000		(French Ministry For Ecology 2007)
Mortality level			(de Gids and Heijnen 2011)
1% lethal effects threshold	100,000		(French Ministry For Ecology 2007)
5% lethal effects threshold	200,000		(French Ministry For Ecology 2007)

Table 3: CO₂ concentrations thresholds in the literature

Nevertheless, several authors agree that CO₂ is a good indicator of occupant emissions including bio-emissions and odors (Von Pettenkofer, 1858; Cain and Berglund, 1979; Cain et al., 1983; Fanger et al., 1988; Zhang et al., 2016) as well as some VOC and particle emissions from office equipment used by occupants (Emmerich and Persily 2001; Fisk and De Almeida 1998; Mansson, et al. 1997). Von Pettenkofer (1858) proposed 1000 ppm, assuming that the outside concentration was 500 ppm, as a threshold for CO₂ level to prevent odors from bioeffluents.

Recent studies (ANSES 2013; Ramalho, et al. 2015) have demonstrated that CO₂ concentrations in homes were significantly correlated with concentrations of other pollutants such as acetaldehyde, formaldehyde, benzene, acrolein, PM_{2.5}, and PM₁₀ but that the correlations were weak (sometimes very weak). Moreover, these conclusions should also be considered carefully because CO₂ was measured every 10 minutes while other pollutant measurements were passively performed over seven days. In his review on DCV, Raatschen (1990) affirms that, according to the analyzed literature, “there is no doubt that CO₂ is the best gas to use to control a ventilation system when a building is occupied and no other large pollution sources such as smokers are present.” Ten years later, in their review on CO₂-based DCV, Emmerich and Persily (2001) highlight the limitation of using CO₂ because of its inadequacy as an overall indicator of IAQ, especially for pollutant emission from sources other than occupants such as building materials and furnishings. This is confirmed by other authors in the literature (Raatschen and Trepte 1987; Emmerich, et al. 1994; Fisk and De Almeida 1998). Nevertheless, Emmerich and Persily (2001) justify the use of CO₂ as an indicator of ventilation rate per person based on regulations or standards, because relationship between indoor CO₂ concentration and ventilation rates is well understood and described in (Persily 1997; Persily and Dols 1990).

As a conclusion on the relevance of using CO₂ as a parameter for performance-based approaches, the analyzed literature shows that even if this is not a pollutant with health effects by itself, it is at least correlated with bioeffluents which affects occupant health at CO₂-concentrations widely measured in dwellings. It seems also relevant to use it, but in addition with other parameters.

5.1.1.1.4 *Air renewal*

Air renewal is an interesting parameter because it can be easily calculated from design and data on envelope airleakage and ventilation airflows at in- and/or out-lets. It can also be measured during commissioning process and later during the building's life.

As explained in the introduction, current standards and regulations often prescribe air change rates (Brelvi and Seppänen, 2011; Dimitroulopoulou, 2012; Laverge et al., 2013) and air change rates have frequently been studied in the literature. Several authors showed that an air change rate (ACR) of 0.5 h^{-1} was the threshold to require to insure health in residential buildings (Seppänen et al., 1999; Sundell et al., 2011). (Wargocki, 2012) suggests a threshold of 0.4 h^{-1} . Two North-American studies looked for establishing an ACR thresholds based on formaldehyde emissions. (Sherman and Hodgson, 2004) proposed to set a threshold of 0.3 h^{-1} for existing houses and 0.5 h^{-1} for new ones. (Gilbert et al., 2008) showed that if we want 95% of the houses with a formaldehyde concentration below $50 \mu\text{g}\cdot\text{m}^{-3}$, ACR threshold must be 0.26 h^{-1} . This threshold would be changed to 0.34 h^{-1} for new houses with recent (< 12 months) formaldehyde sources and to 0.37 h^{-1} for dwellings with electrical heating devices.

In the literature, we also find air change rates per person (Janssen 1989). During the Healthvent project (Career et al., 2013), 48 papers have been selected and classified according the investigated health effects: asthma, allergies, respiratory symptoms, airborne infectious diseases, sick building symptoms (SBS), sick leave, productivity and performance. Authors suggest for houses to use the threshold of $7 \text{ L}/(\text{s}\cdot\text{pers})$ to avoid asthma and allergies and $8 \text{ L}/(\text{s}\cdot\text{pers})$ to avoid SBS.

The dependence of these ACR thresholds upon pollutant concentration levels is nevertheless evident.

As a result, we think interesting to use air renewal as a parameter, but again, conditionally upon the use of other parameters.

5.1.1.1.5 *Conclusion on selected parameters*

As a result, we considered as relevant to calculate indicators based on CO_2 , humidity, formaldehyde and particle matter. The use of air renewal in intermediate performance indicators is also worthwhile, to be compared to current regulations and state of the art, but also to be used in a potential measurement check at commissioning.

5.1.1.2 *IAQ ventilation performance indicators*

Once the parameters have been identified, relevant IAQ performance indicators have also to be identified. Indeed, qualifying and quantifying IAQ is a complex issue. Even with a short list of parameters, there is several ways of using measured or calculated data related to them. Performance indicators could be related to background or peak exposure, could be calculated over different time periods (whole year/heating period/ one standardized week in the winter ...). They could also be calculated per occupant or per zone, including either the whole building or specific zones, or all the zones.

5.1.1.2.1 Pollutants

Firstly, we reviewed IAQ performance indicators related to pollutants, including for our purpose formaldehyde and particle matter PM_{2.5}.

In the literature, most of the performance indicators based on pollutants come from measurement campaigns and are related to the comparison with a given threshold, set to different levels depending on guides and regulations in different countries. That's why they are called "IAQ metrics". In a recent study conducted in the IEA Annex 68 "*Indoor air quality design and control in low energy residential buildings*", (Cony Renaud Salis et al., 2017) proposed to use 3 IAQ metrics:

1. For long-term exposure: the maximal value, among the pollutants of concern, of the ratio between the mean concentration and the reference exposure limit value (ELV) set to the minimum one used through the world, i.e 9 µg/m³ for formaldehyde (Office of Environmental Health Hazard Assessment (OEHHA), 2016) and 10 µg/m³ for particle matter PM_{2.5} (WHO, 2010);
2. For short-term exposure: the maximal value, among the pollutants of concern, of the ratio between the mean concentration, over the given period of the reference acute ELV, and the reference acute exposure limit value (ELV) set to the minimum one used through the world, i.e for formaldehyde, 123 µg/m³ for formaldehyde over 1 hour (Canada) and 25 µg/m³ for particle matter PM_{2.5} over 24h (WHO);
3. The Disability-Adjusted Life Years (DALY) metric described in (Logue et al., 2011b).

In our purpose, at the design stage of a building, the issue is widely different from a measurement campaign as developed with those "IAQ metrics". The dose indicator is very interesting because it is directly related to health and dose thresholds have been proposed in literature from dose-response studies (WHO et al., 2006). It is also called "cumulative exposure" or "exposure". Some recent publications (Laverge and Janssens, 2009) propose also to use this indicator called "Occupant exposure". The dose should be calculated per person. Sometimes as shown in Part 2, it is calculated per room for simplicity reasons even if it is not physic. This indicator is rarely used in an *in situ* measurement context, as it would need to be calculated to know exactly where occupants are in the house at each time-step and to measure the concentrations in each of the rooms, also at each time-step. Nevertheless, it is one of the most relevant indicator for our purpose.

Standard EN 15665 (CEN, 2009) proposes also to use the following IAQ performance indicators depending if they are related to specific activities or a background pollution:

- For specific activities: maximal threshold, average and weighted concentration, average exceeding concentration over a threshold value, dose above a given value, decay criteria, time to obtain a percentage of the maximum value, value after a certain time,
- For background pollutants: maximal threshold, average and weighted concentration, average exceeding concentration over a threshold value, dose above a given value.

An overview of these pollutants based performance indicators is given in Table 4.

Performance indicators	Sources
3 IAQ metrics: 1. $C_{\text{long-term}}/\text{ELV}_{\text{long-term}}$ (=9 $\mu\text{g}/\text{m}^3$ for formaldehyde and 10 $\mu\text{g}/\text{m}^3$ for particle matter $\text{PM}_{2.5}$) 2. $C_{\text{short-term}}/\text{ELV}_{\text{acute}}$ (=123 $\mu\text{g}/\text{m}^3$ over 1 hour for formaldehyde and 25 $\mu\text{g}/\text{m}^3$ over 24h for particle matter $\text{PM}_{2.5}$) 3. DALY	(Cony Renaud Salis <i>et al.</i> , 2017)
Dose (also called cumulative exposure or occupant exposure)	(WHO <i>et al.</i> , 2006)
Occupant exposure	(Laverge and Janssens, 2009)
For specific activities: Maximal threshold, average and weighted concentration, average exceeding concentration over a threshold value, dose above a given value, decay criteria, time to obtain a percentage of the maximum value, value after a certain time For background pollutant: Maximal threshold, average and weighted concentration, average exceeding concentration over a threshold value, dose above a given value	EN 15665 (CEN, 2009)

Table 4 : Pollutant-based performance indicators in reviewed literature

In our work, we focused on long-term exposure, because of the lack of data at the building scale for short-term emissions, as will be discussed in section 5.1.2.5. We decided to use the reference exposure limit value (ELV) set to the minimum one used through the world, as proposed by (Cony Renaud Salis *et al.*, 2017).

We selected also as relevant performance indicators related to pollutants and calculated over the heating period including non-occupation time:

- Average concentration in living rooms and bedrooms where occupant spent most of their time;
- Percentage of hours with concentration over the ELV in those rooms;
- Maximum of the total cumulative exposure of the occupants: E_{max} , (Equation 1). It could be compared to the total cumulative exposure to the ELV,

$$E_{\text{max}} = \max_j \left(\sum_i C_j(t_i) * t_i \right)$$

(Equation 1)

Where $C_j(t_i)$ is the exposure concentration for the occupant j at the time-step t_i

5.1.1.2.2 Humidity

We also reviewed IAQ performance indicators related to humidity. Variables associated with humidity are relative humidity (RH) and absolute humidity. Relative humidity is the ratio of water vapor pressure in the air at a given temperature to the saturation water vapor pressure at the same temperature. Absolute humidity is the mass of water vapor in the air per unit mass of air. It is rarely used as a IAQ performance indicator EN 15251 (CEN, 2007b). Relative humidity is the most commonly measured and used parameter as shown in Table 5.

Performance indicators related to humidity can be divided in two categories:

1. In order to assess occupant comfort and health, indicators related to an acceptable range and a number of hours out of this range, as proposed in the standard EN 15665 (CEN, 2009). In his review, (Koffi, 2009) notices that the minimum threshold of the range varies between 20 and 40% and the maximum threshold of the range varies between 60 and 80%. Very rarely only the number when RH is lower than a threshold should be calculated. (Mansson, 2001) proposes that the number of hours with RH lower than 30% should not be higher than 800 h.
2. In order to assess the condensation risk in the building, the number of hours with humidity higher than a given threshold during a given period, set to 75% in the French regulation for DCV (CCFAT, 2015) or to 80% in the Former Belgium regulation for DCV (ATG and BCCA, 2012). In Nordic countries however, strongly different threshold could be set, 45% is proposed by (Nielsen, 1992).

Some authors as (Woloszyn et al., 2009a) propose more detailed indicators as boxplot, which are absolutely necessary and relevant for a scientific analysis. They are however less appropriate to be used in a regulatory context.

This part of literature is summarized in Table 5.

From this review, we proposed to use at least as IAQ performance indicators related to humidity:

- A health indicator: Percentage of time spent with a relative humidity out of a range, for instance [30-70%], in living rooms and bedrooms where occupant spent most of their time over the heating period, including occupancy and non-occupancy periods,
- A condensation risk indicator: Percentage of time spent with relative humidity over a threshold, for instance 70% in each room, over the heating period, including occupancy and non-occupancy periods.

Performance indicators	Thresholds	Sources
Absolute humidity	12 g/kg	EN 15251 (CEN, 2007b)
Number of hours with [RH<30%] 4-week-period with water vapor content < 7g/kg during the heating season	< 800h 0	(Mansson, 2001)
RH	Usually range: <i>[Min; Max]</i> <i>Min [20 to 40%]</i> <i>Max [60 to 80%]</i>	(Koffi, 2009)
RH	Acceptable range: <i>[30; 70%]</i>	(Harriman et al., 2001) & TR 14788 (CEN, 2006)
Number of hours with RH under or over the range, Time ratio when the value of RH is over the range during a selected period	Not given	EN 15665 - (CEN, 2009)
RH boxplot	Not given	(Woloszyn et al., 2009a)
Number of hours when RH>75% over the heating period	WC and each main room: 100 h Kitchen: 600 h Bathroom: 1000 h	French regulation for DCV (CCFAT, 2015)
Time per month while critical thermal bridges are exposed to RH> 80% from December 1st to March 1st	No absolute threshold	Former Belgium regulation for DCV (ATG and BCCA, 2012)
Number of hours with RH > 45%, (in Nordic countries)	Not given	(Nielsen, 1992)

Table 5 : Humidity-based performance indicators in reviewed literature

5.1.1.2.3 CO₂

We also reviewed IAQ performance indicators related to CO₂.

The EN 15655 (CEN, 2009) standard proposes for a background pollutant to use: the average concentration, the weighted concentration, the average exceeding concentration above a threshold value, and the dose above a threshold value. Concentrations could be compared to four classes in order to assess the IAQ level, as proposed by several European standards EN 15251 (CEN, 2007b), (FISIAQ, 1995), EN 13779 (CEN, 2007c), assuming an outdoor concentration of 400 ppm: (CO₂ lower than 750 or 800 ppm, between 750 or 800 ppm and 900 or 1000 ppm, between 900 or 1000 ppm and 1200 or 1400 ppm, and higher).

Based on this approach, (Ribéron et al., 2016) propose to use the air stuffiness index for homes ICONE. This index is a logarithm function of the percentage of time when the measured CO₂-concentration at night is higher than 1000 ppm, f_1 , and 1700 ppm, f_2 , in the main bedroom and the living room.

$$I_{ICONE} = 8.3 \log(1 + f_1 + 3f_2) \quad (\text{Equation 2})$$

Recent studies on ventilation performance (Laverge, 2013; Laverge et al., 2013) used a large set (6) of indicators: cumulative exposure over 1000 ppm [ppm.h], normalized by the heating period duration or by the exceeding period, average exceeding concentration above 1000 ppm, average concentration, percentage of time spent in 4 classes based on the 3 thresholds [400, 600, 1000 ppm] (assuming $C_{\text{outdoor}} = 0$ ppm), exposure cumulative frequency plot and standard deviation on concentrations.

Most of the reviewed performance-based approaches for ventilation studied in Part 2 (From France, Spain, The Netherlands and Belgium), but also some references as the Annex 27 IEA (Mansson, 2001, p. 27), propose to adapt the “Dose” concept initially used for pollutants and to calculate a cumulative exceeding exposure over thresholds varying between 950 ppm and 2000 ppm. They should sometimes be calculated per room or per person and the calculation period can vary (whole year, several definitions of heating period, ...).

Results are summarized in Table 6.

CO ₂ -based performance indicators	Thresholds	Sources
4 classes (assuming C _{outdoor} = 400 ppm) based on the 3 thresholds: [750 ; 900 ; 1200 ppm] [800 ; 1000 ; 1400 ppm]	Not given (relative comparison)	EN 15251 (CEN, 2007b) + (FISIAQ, 1995) EN 13779 (CEN, 2007c)
Average concentration, weighted concentration, average exceeding concentration above a threshold value, dose above a threshold value	Not given (relative comparison)	EN 15655 (background pollutant) (CEN, 2009)
The air stuffiness index for homes ICONE $I_{ICONE} = 8.3 \log(1 + f_1 + 3f_2)$	Not given (relative comparison)	Ribéron et al., 2016
<ol style="list-style-type: none"> 1. Cumulative exposure over 1000 ppm [ppm.h]: normalized by the heating period duration or by the exceeding period 2. Average exceeding concentration above 1000 ppm 3. Average concentration 4. Percentage of time spent in 4 classes based on the 3 thresholds [400, 600, 1000 ppm] (C_{outdoor}= 0), 5. Exposure cumulative frequency plot 6. Standard deviation on concentrations 	Not given (relative comparison)	(Laverge, 2013; Laverge et al., 2013)
Cumulative exposure over 1050 ppm [ppm.h]	Not given (relative comparison)	Annex 27 IEA (Mansson, 2001, p. 27)
Cumulative exposure indicator over 2000 ppm [ppm.h] in each room	400,000 ppm.h	French regulation for DCV (CCFAT, 2015)
Yearly averaged concentration in each room Yearly cumulative exposure over 1600 ppm in each room	900 ppm 500,000 ppm.h	Spanish regulation for ventilation (Spain, 2017)
Per-person cumulative exposure over 950 ppm	Not given (relative comparison)	Former Belgian regulation for DCV (ATG and BCCA, 2012)
Per-person exposure index over 1200 ppm (LKI ₁₂₀₀) $LKI_{1200} = \sum_{t=0}^T \left(\frac{C_{CO_2 > 1200}(t) - 1200}{1000} \right) * t$	30,000 ppm.h	Dutch regulation for DCV (Borsboom, 2015)

Table 6. CO₂-based performance indicators in reviewed literature

From this review, we suggest also to calculate the following indicators over the heating period including non-occupation time, in living rooms and bedrooms where occupant spent most of their time:

- The percentage of time spent in 5 classes [<800 ppm, 800-1000 ppm, 1000-1400 ppm, 1400-2000 ppm, >2000 ppm], defined using EN 13779 (for the three first thresholds) and the French procedure for DCV (for 2000 ppm) (CCFAT, 2015; CEN, 2007c). We calculated this time spent for each k-zone $R_{<800\text{ppm}}$, $R_{800-1000\text{ppm}}$, $R_{1000-1400\text{ppm}}$, $R_{1400-2000\text{ppm}}$, $R_{>2000\text{ppm}}$ according to (Equation 3) for the first class, and similarly for the remaining four.

$$R_{<800\text{ppm},k} = \frac{\sum_i t_i \text{ if } C_k(t_i) < 800\text{ppm}}{\sum_{\text{tot}} t_i} \quad (\text{Equation 3})$$

- The average CO₂-concentration and the exceeding CO₂-concentration in each k-zone, taking into account the only values above X=1000 ppm or 2000 ppm (Equation 4).

$$C_{exc,X,k} = \frac{\sum_i C_{k>X\text{ppm}}(t_i)}{\sum_{\text{tot}} i} \quad (\text{Equation 4})$$

Where $C_{k>X}(t)$ is the absolute concentration in the zone k at t time-step, if it is higher than X ppm, X = 1000 or 2000 ppm.

The cumulative exceeding exposure above X=1000 ppm or 2000 ppm (Equation 5).

$$E_{X,k} = \sum_i C_{k > X}(t_i) * t_i \quad (\text{Equation 5})$$

The air stuffiness index for homes I_{ICONE} proposed in (Ribéron et al., 2016), (Equation 2).

5.1.1.2.4 Air renewal

As reviewed in section 5.1.1.1.4, the air change rate is often used in order to assess ventilation performance or to compare prescriptive ventilation regulations.

In order to study the air renewal parameter, we suggest also to calculate average air change rate (ACR) for each zone and for the envelope of the dwelling.

$$ACR = \frac{\sum Q_{out}}{V_{zone}} \quad (\text{Equation 6})$$

with Q_{out} the outgoing airflow in $\text{m}^3 \cdot \text{h}^{-1}$, V_{zone} the volume of the zone considered in m^3 , ACR in h^{-1} . Q_{out} includes airflows through both outdoor and internal partition walls.

Regarding the different ACR threshold given in the reviewed literature in section 5.1.1.1.4, we would also suggest to study, similarly to what is proposed in standards for CO₂, the time spent in the four ACR classes (<0.3 h⁻¹; [0.3 ; 0.5] h⁻¹; [0.5 ; 1] h⁻¹; >1 h⁻¹).

5.1.1.3 Relevance of selected indicators

We selected also 12 performance indicators which could be interesting to be used in a performance-based approach for ventilation at the design stage of a building. Even some others were relevant in other purposes, as in *in situ* measurement campaigns, we think those 12 performance indicators could be the most relevant ones for our purpose.

If we compare our approach to the ones developed for energy performance, usually only 2 or 3 indicators are used, for instance: total primary energy consumption, summer comfort indicator, renewables integration indicator. We would also among these 12 performance indicators identify the most relevant ones for our purpose.

These IAQ indicators have been tested in Part 4. We showed that some indicators are less relevant, for instance the ICONE index or the whole building ACR. The ICONE index could be interested in its unrounded form, but it has only been tested in the rounded form as described as proposed by (Ribéron et al., 2016). The whole building ACR is a too rough indicator for our purpose, we need to get indicators at least at the zone scale, especially in zones where occupants are spending most of their time. We suggested selecting at least one “constant emission” pollutant such as formaldehyde, one “variable-emission” pollutant such as humidity, which serves to estimate both health and condensation risks. We suggested using at least the following 5 indicators to be calculated over the heating period:

1. Maximum cumulative exceeding CO₂ exposure (for instance: over 1000 ppm) in the bedrooms,
2. Maximum cumulative occupant formaldehyde exposure,
3. Maximum cumulative occupant PM_{2.5} exposure,
4. Maximum of the percentage of time with RH higher than 70% in all rooms (condensation risk),
5. Maximum of the percentage of time with RH outside of the range [30%–70%] in the bedrooms (health risk).

Again, even if acute exposure should also be considered, we focused on long-term exposure, because of the lack of data at the building scale for short-term emissions, as discussed in section 5.1.2.5.

We often observed threshold effects: consequently, they must be carefully taken into account when choosing the indicators.

Those performance indicators could be then compared to selected thresholds. To give an illustration of this proposal, we selected published thresholds in Table 7 and adapted them to a simulation duration of X hours. We indeed propose for CO₂, formaldehyde and particle matters to compare the calculated cumulative exposure to the threshold exposure corresponding to a constant threshold concentration (respectively 1000 ppm, 9 µg.m⁻³ and 10 µg.m⁻³) during the whole simulation. For the maximum time-spent with RH>70% in all the rooms expressed in a number of hours, we propose to compare it to the threshold of 1000 hours used in technical agreements for French demand-control ventilation (CCFAT, 2015a). In this reference 1000 hours is the threshold for time-spent with RH>75%

in bathrooms but we propose to keep this value in a conservative approach. For the maximum time-spent with RH out of 30-70% in bedrooms expressed in a number of hours, we propose to compare it to the threshold of 800 hours. Indeed, (Mansson, 2001) proposes the threshold of 900 h for time-spent with RH<30 %. We propose the value of 800 h in a conservative approach.

IAQ performance indicators	Thresholds	Reference used to calculate the indicator
Maximal cumulative exceeding CO ₂ exposure over 1000 ppm in the bedrooms (BR), E ₁₀₀₀ (ppm.h)	1000 X ppm.h	(Zhang et al., 2016) 1000 ppm with bioeffluents
Maximal cumulative occupant formaldehyde exposure E _{max} (µg.m ⁻³ .h)	9 X µg.m ⁻³ .h	(Cony Renaud Salis et al., 2017) 9 µg.m ⁻³ proposed as the ELV for formaldehyde
Maximal cumulative occupant PM _{2.5} exposure E _{max} (µg.m ⁻³ .h)	10 X µg.m ⁻³ .h	(Cony Renaud Salis et al., 2017) 10 µg.m ⁻³ proposed as the ELV for PM _{2.5}
Maximal time-spent with RH>70% in all the rooms (%)	1000/X %	(CCFAT, 2015) 1000h is the threshold for RH>75% in bathrooms. We keep this value in a conservative approach.
Maximal time-spent with RH out of 30-70% in bedrooms (BR) (%)	800/X %	(Mansson, 2001) 900 h is the threshold for RH<30 %. We select the value of 800 h in a conservative approach.

Table 7. Selected IAQ performance indicators and corresponding thresholds calculated for a X hour-simulation duration.

Results could be given with the radar approach as proposed on Figure 5. In this radar figure, we propose to plot each ratio "IAQ performance indicators / Thresholds" which must be lower than 1 for a regulatory approach, as illustrated in red on the radar. They could also be required to be lower than 80% to claim for an IAQ label, as illustrated in green on the radar. In the given case for this hypothetical house A, changes must be done on ventilation design in order to allow the ratios concerning both maximal cumulative exceeding CO₂ exposure over 1000 ppm in the bedrooms, E₁₀₀₀ and the maximal cumulative occupant PM_{2.5} exposure E_{max} to be lower than 1.

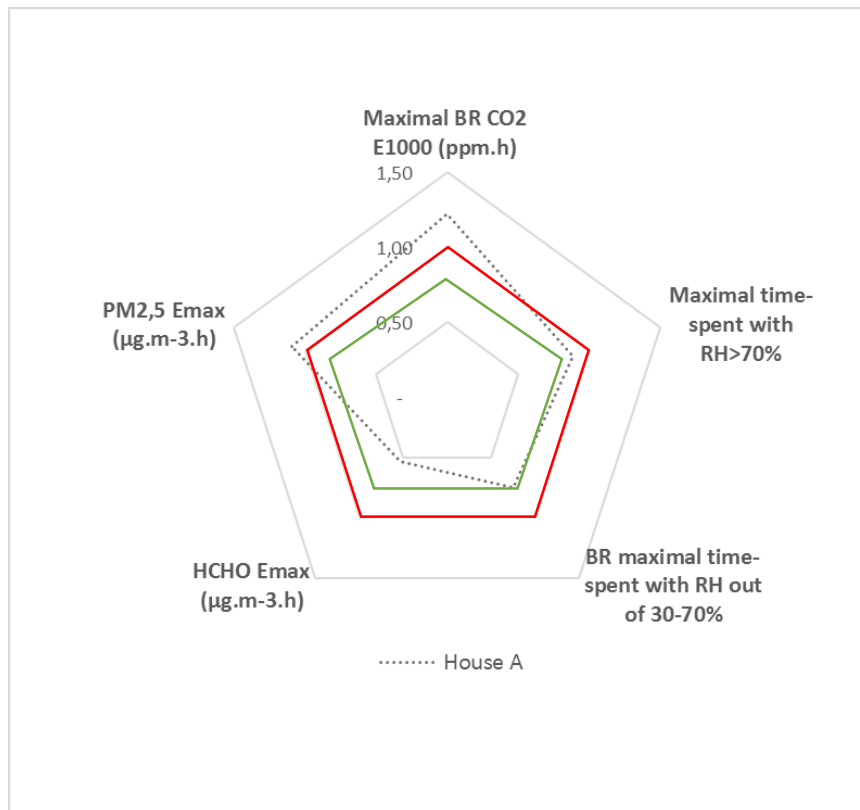


Figure 5. Calculated IAQ indicators ratios with their thresholds at the design stage of the house A. The red pentagon illustrates the required thresholds by a regulation (ratio=1). The green pentagon could illustrate the required thresholds by an IAQ label (ratio=0.8)

5.1.2 Step 2: Occupancy and emission scenarii to be used as input data

The choice of occupancy and pollutant emission scenarii is also an issue of concern in performance-based approaches as seen in Part 2. We proposed here an extensive review of occupancy and pollutant emission scenarii used in literature focusing on CO₂, humidity, PM_{2,5}, and formaldehyde.

5.1.2.1 Occupation scenarii

At the design stage of a building, it is difficult to describe the occupants: number, age, activity, schedule. So that, a standard occupancy must be assumed, taking into the size of the house, and rather worst, in order to avoid an under sizing of the ventilation airflow rates. We would suggest to define the number of occupants of a house depending the number of bedrooms, assuming two occupants in a bedroom, and one in each of the other ones.

Precisely described data for our purpose is rarely found in the literature. Energy performance (EP) calculation methods use global in/out scenarii, whereas a multizone approach requires to assume an occupancy scenario in each room of the house. (Aerts et al., 2013) proposed for EP calculations seven discrete occupancy profiles based on a time-survey on more than 3000 Belgian dwellings. They made the difference between outside, inside awake or asleep.

For our purpose, we suggest to use, if possible, more detailed data, as the ones from the French national campaign on IAQ of dwellings from 2005 (Zeghnoun et al., 2010). This campaign was based on a representative sample of the population, including 567 homes and 1612 occupants. 1375 of those

occupants have compelled precise information about their schedules and their occupation in the rooms (25% of the sample) so that a database of 1,386,000 10 minute-time-steps with precise information of location of occupants was available and analyzed in this study. The results are that people spend in average 67.3% of their time in homes. This is consistent with results of others survey in Europe (EXPOLIS, 56-66%) and in the United States (NHAPS : 68.7%).

Other interesting results are available in this study:

- The differences between week-end days and week days are light: the 3 days with the highest occupancy duration are Sunday (16.6h), Wednesday (16.5h) and Saturday (16.3h), followed by Thursday (16.1h). Friday is the less occupied day (15.7h),
- There is no statistical difference between working periods and holidays,
- Occupants are more likely at home between 12h and 14h and between 19h and 7h,
- Time spent in the homes is divided, in average, by 9h16 spent in bedrooms, 2h49 spent in living room, 2h40 spent in the kitchen and 38 minutes spent in the bathroom.

Then, from this last study, we would suggest to define occupancy scenarii for France based on:

1. A unique schedule for each day of the week all the yearlong,
2. A time spent in the house divided for each occupant by 9h20 spent in its bedroom, 2h50 spent in the living room, 2h40 spent in the kitchen (5h30 in case of open kitchen on living room) divided in three periods for breakfast, lunch and dinner, 40 minutes spent in the bathroom.
3. A ventilation high-speed in the kitchen switched-on for 1 hour twice a day at the beginning of lunch and dinner periods.

Depending the countries, habits will be different concerning meal times, school times, work times, so that occupancy schedules should be carefully adapted.

Once occupancy scenarii are selected, some pollutant and parameters emission will be correlated to those occupancy scenarii. For instance, metabolic CO₂ and humidity will be emitted only in the occupied zones, depending the activity of the occupants. Emissions due to occupants' activities will occur where and when occupants are supposed to be.

5.1.2.2 About special physiological respiratory characteristics of children

Because of the development and growth of all the organs of a child, its basic metabolism is twice the adult one. The basic metabolism is defined as the minimum energy expenditure of an organism to ensure daily functions at rest. It decreases between 6-years and 18-years from 19% to 27%, respectively for boys and girls (Knoebel, 1963).

As a result, as explained by (Déoux, 2010), even if their body surface area is lower, CO₂ and humidity emissions rates of children are so high than adults and could even be higher. The ECA guidelines for ventilation requirements in buildings (Bienfait et al., 1992) compiles data from three studies (Rasmussen et al., 1985; Pejtersen et al., 1991; Thorstensen et al., 1990), giving emission rates for adults and children, overviewed in Table 8.

	CO₂ emissions liter/(h.occupant)	Water vapour g/(h.occupant)
Sedentary adult	19	50
Low physical exercise	50	200
Medium physical exercise	100	430
High physical exercise	170	750
Children, 3-6 years	18	90
Children, 14-16 years	19	50

Table 8. Pollutant load caused by occupants. Source: (Bienfait et al., 1992)

5.1.2.3 Moisture emission rates

(Labat and Woloszyn, 2015) proposed a review of the indoor moisture sources from very simplified to more realistic ones. The simplest way of modelling is an average constant emission as proposed and analyzed by the review of nine studies of (Walker and Sherman, 2007), suggesting the average emission of 270 g.h⁻¹ to be used for a 1 year-simulation. (Labat and Woloszyn, 2015) showed also that several experimental and numerical studies preferred the use of cyclic typical schedules. Lastly, stochastic scenarii could also be used as demonstrated by (Page et al., 2008; Parys et al., 2011) in office buildings. (Labat and Woloszyn, 2015) showed on a 1 zone-experimental building how constant emission rates could result in increasing by 10 to 20% the comfort range, compared to the use of stochastic scenarii.

In a performance-based approach to be used at the design stage of a building, we also need to consider the standards and regulations treating this issue. As a result, we preferred the use of cyclic schedules (fixed schedules which are reiterated each week), differencing the metabolic emissions and the occupants activities emissions, as proposed in (British standard, 1991; Mansson, 2001; CEN, 2006; CEN, 2009; Johansson et al., 2010; CCFAT, 2015).

The human emissions are due to the metabolic function of the people as respiration, transpiration or perspiration, so they are usually given in a quantity per hour and per person. They depend on different factors as the age (Mansson, 2001), contradicted by (Bienfait et al., 1992) as seen before, or the activity level. The most frequently distinction between activity levels found in standards and regulations is asleep or awake. (Woloszyn et al., 2009a) study used a value of 2.4 kg/day in each room of water production, for a household of 3 people. Experimental studies give also worthwhile information with confidence intervals as in (Johansson et al., 2010; Pallin et al., 2011). This part of literature is summarized in Table 9.

Metabolism's emissions data	Sources
At rest: Adult: 50 g.h ⁻¹ 14-16 years: 50 g.h ⁻¹ 3-6 years: 90 g.h ⁻¹	ECA guidelines for ventilation requirements in buildings (Bienfait et al., 1992)
Awake / Asleep >15 years: 55/30 g.h ⁻¹ 10-13 years: 45/15 g.h ⁻¹ <2 years: 30/10 g.h ⁻¹	(Mansson, 2001)
Awake / Asleep 55 /38.5 g.h ⁻¹	(CCFAT, 2015) & (Riberon and Millet, 1991)
Awake / Asleep 55 / 40 g.h ⁻¹	EN 15 655 (CEN, 2009)
Active / Asleep 55 / 40 g.h ⁻¹ Recommended duration of emissions: - Living room: 4 h - Bedroom: 10 h	TR 14 788 (CEN, 2006) & (British standard, 1991)
Active / Asleep / Resting Active people= 70 ± 5 / 30 ± 2 / 50 ± 5 g.h ⁻¹	(Johansson et al., 2010; Pallin et al., 2011) Referred in (Peuportier et al., 2015)
2.4 kg/day for 3 people so 0.8 kg/day per person	(Woloszyn et al., 2009a)

Table 9 : Metabolism's moisture emission rates in reviewed literature

For our purpose, we would also suggest to use the moisture generation rates selected for the metabolism emission of 55/40 g.h⁻¹ (awake/asleep), again taking into account the occupation schedule. The "asleep" periods of moisture production take place when the occupants are in the bedrooms, whereas the "awaken" periods of moisture production are effective during all the other periods. At the design stage of a building, this is difficult to take into account the age of the occupants during the "life" of the building, so that we could assume that all occupants are adults.

The moisture is also generated by the occupant's activities and then essentially emitted in the humid rooms. Most of the time, related production is given for a precise activity with a duration per day, depending sometimes on the number of occupants. Note that two normative documents (British standard, 1991; CEN, 2006) propose the schedule approach but also the use of an average constant moisture emission rate, depending the global level of moisture production and the number of occupants. Alternative approaches based on experimental measurements are also proposed (Johansson et al., 2010; Pallin et al., 2011). This part of literature is summarized in Table 10.

Activities' emissions data	Sources
Cooking /person: 50 g during 0.5h (breakfast) - 75 g during 1h (lunch, 150 g week-end)-300 g during 1h (dinner) 300 g/shower (during 0,5 h for CCFAT) (during 6 min for EN 15665) 200 g/laundry (during 2 h) 1000 g/drying (during 20 h) With: 1 shower/(day.person) x laundry/week	(Mansson, 2001) (CCFAT, 2015) (-> x = 1 to 4 depending on the number of inhabitant) EN 15 665 (CEN, 2009) (-> x = 1)
Cooking (electric device): 2000 g/day Cooking (gas device): 3000 g/day Hand dishes washing: 400 g/day WC/shower/dishes washing: 200 g/(day.person) Laundry (hand/up opening device): 500 g/day Inside drying (naturally or with dryer without vent): 1 500 g/(day.person)	(British standard, 1991) & TR 14 788 (CEN, 2006) (called A)
Cooking: 0.6 l/s (breakfast) -1 l/s (lunch)- 1.5 l/s (dinner) during 10 min Shower: 0.5 l/s during 10 min per person Drying: 0.65 l/s during 12h	TR 14 788 (CEN, 2006) (called B)
Shower (10 min) = 250 ± 50 g Cooking meals: - Breakfast (15 ± 5 min) = 109 ± 20 g - Lunch (30 ± 2 min) = 288 ± 68 g - Dinner (40 ± 10 min) = 518 ± 152 g Dishes washing (29 ± 3 min): - Breakfast = 25 ± 3 g - Lunch = 20 ± 3 g - Diner = 240 ± 9 g Laundry drying (11 ± 2 h → 20% of the total emission during the first 2h) 1850 ± 670 g	(Johansson et al., 2010; Pallin et al., 2011) Referred in (Peuportier et al., 2015)
Moisture generation rate [kg/day] (Low /Medium/High): - 1 person: 3.5/6/9 - 2 persons: 4/8/11 - 3 persons: 4/9/12 - 4 persons: 5/10/14 - 5 person: 6/11/15	(British standard, 1991) & TR 14 788 (CEN, 2006) (called C)
Gas cooking: 350 g/day	EN 15 665 (CEN, 2009)

Table 10 : Activities moisture emission rates in reviewed literature

In order to build a scenario for our purpose, we wanted to quantify the dispersion of these values (five first lines of Table 10). We choose to compare themselves per day, assuming an occupancy of 1 or 5 people, taking into account metabolism, cooking, showering, laundry and drying. We assumed one laundry and one clothes drying per person and per week and we calculated an average weighted emission rate per day. TR 14 788 (CEN, 2006) proposes to take into account a density of vapor of 0.8 kg/m³ at 0°C and 1013.25 mbar. Lastly, we compared the results expressed as an average

emission rate in kg per day to the thresholds given in TR 14 788 – C (CEN, 2006). Results are given in Table 11 and Table 12.

	Reference	Result (kg/day)	Low 3.5 kg/day	Medium 6 kg/day	High 9 kg/day
1 occupant	TR 14 788 - A	4.1	-	X	-
	TR 14 788 - B	2.6	X	-	-
	EN 15 665	1.4	X	-	-
	CCFAT, 2015	1.6	X	-	-
	Pallin et al., 2011	2.0	X	-	-

Table 11. Comparing moisture emissions with thresholds given in TR 14 788 - C (CEN, 2006a). 1 occupant.

	Reference	Result (kg/day)	Low 6 kg/day	Medium 11 kg/day	High 15 kg/day
5 occupants	TR 14 788 - A	8.4	-	X	-
	TR 14 788 - B	7.2	-	X	-
	EN 15 665	4.9	X	-	-
	CCFAT, 2015	7.9	-	X	-
	Pallin et al., 2011	5.2	X	-	-

Table 12. Comparing moisture emissions with thresholds given in TR 14 788 - C (CEN, 2006). 5 occupants.

For the activities emissions, we decided to use the TR 14 788-A (CEN, 2006) data, because it was the most handicapping reference, according to Table 11 and Table 12. We combined them with the emission duration given by (Johansson et al., 2010; Pallin et al., 2011) because these data came from in-situ measurements, published in an IEA Annex and referred in (Peuportier et al., 2015). We obtained the following moisture generation scenario to be used:

- One shower per person per day, with an emission of 1440 g.h⁻¹ for 10 min by shower.
- Cooking periods per day: 1512 g.h⁻¹ for breakfast for 15 min; 2268 g.h⁻¹ for lunch for 30 min; 2844 g.h⁻¹ for dinner for 40 min.
- One laundry per person per week: 252 g.h⁻¹ for 2 h
- One laundry drying per person per week (same days): 136.8 g.h⁻¹ for 11 h.

This results in an average production of 6 kg/day for 5 occupants, which is rather a low emission scenario.

5.1.2.4 Carbon dioxide emission rates

CO₂ emissions rates are due to occupant metabolism and depend on size and activity of the occupants. Reviewed literature gives the same order of magnitude and generally proposes to make a difference between “asleep” and “awake”, adult and child, as summarized in the Table 13. Measured taken in

some twenty occupied apartments showed that child emissions were often underestimated in literature and were closer from the adults ones (Bernard, 2009) as explained in section 5.1.2.2.

Moreover, as for humidity, at the design stage of a building, this is difficult to take into account the age of the occupants during the “life” of the building. So that we could assume that all occupants are adults, using the emission rates proposed by (Persily, 1997): 18 L.h⁻¹ and 15 L.h⁻¹ for an “awake” or “asleep” occupant.

Emission rates	Sources
At rest: Adult: 19 L/(h.person) 14-16 years: 19 L/(h.person) 3-6 years: 18 L/(h.person)	ECA guidelines for ventilation requirements in buildings (Bienfait et al., 1992)
Awake: 16 L/(h.person) Asleep: 10 L/(h.person)	EN 15665 (CEN, 2009) + (CCFAT, 2015)
Awake/asleep: >15 year-old: 18/12 L/(h.person) 10-13 year-old: 12/8 L/(h.person) <2 year-old: 8/4 L/(h.person)	Annex 27 IEA (Mansson, 2001, p. 27)
Measured in occupied apartments: Child: 13 L/(h.person) Adult: 16 L/(h.person)	(Bernard, 2009)
Adult (office work): 18 L/(h.person) Adult (asleep): 15 L/(h.person) Child (medium exercise): 10L/(h.person)	(Persily, 1997, p. 199)

Table 13 : CO₂ metabolism’s emission rates in reviewed literature

5.1.2.5 Pollutant emission rates

Pollutant emission rates measured directly at the dwelling scale are rarely found in the literature, especially in low-energy dwellings considered as representative of the new French dwellings. We illustrate here this issue with formaldehyde and PM_{2.5}, since we identified at step 1 those both pollutants as worthwhile for our purpose.

First of all, the pollutant emission and/or concentration measurement and modelling are complex, because of physics phenomena behind (diffusion, resuspension, combined effects, ...).

For formaldehyde, several author highlighted the issue of concentrations and emissions correlation with temperature, relative humidity and air exchange rates (Park and Ikeda, 2006). Thanks to a multivariate model fitting on observation data between temperature, humidity, air change rate and outdoor concentration, (Blondel and Plaisance, 2011) considered the temperature as the more correlated variable with the formaldehyde concentration increase. The (Liang et al., 2016) study allowed, thanks to chamber tests, to propose a semi-empirical correlation law between the initial materials emittable concentration and the combined effect of humidity and temperature. Moreover, the formaldehyde emission of new houses from construction materials, such as wooden product, are known to be constant during around nine month, and start to decrease after this period (Sherman and Hodgson, 2002b), to reach a steady state emission rate after a(few) years (Park and Ikeda, 2006).

PM_{2.5} concentrations and emissions could also strongly be correlated with: outdoor conditions, intensity and type of ventilation, air leakage level, deposition and resuspension conditions (Abt et al., 2000; Lai et al., 2004; Long et al., 2000; Morawska et al., 2001). Indeed, due to their mass particles matter are deposited on surfaces by gravity and some usual actions can put these particles in resuspension. Moreover, particle matters can be formed by chemical gaseous reaction as between ozone and terpene (Rohr et al., 2003).

Moreover, indoor pollutants sources are quite different since formaldehyde is emitted by building materials, furniture, but also activities. It results in both background and peak emissions. Whereas indoor PM_{2.5} are essentially due to indoor activities, resulting mainly in peak emissions.

As a result, we found three types of data in the reviewed literature:

1. ***In situ average loads***: emission rates measured at the dwelling scale. They result from the combination of pollutant concentration and air change rate measurements in dwellings. We found few data on formaldehyde emission rates measured at the dwelling scale. We did not find any data about PM_{2.5};
2. ***In situ peak loads***: pollutant emissions due to specific activities in situ measured in homes or in experimental setups. We found such data quantifying PM_{2.5} emission rates due to activities but none data about formaldehyde;
3. ***Chamber tested loads***: Pollutant emissions due to specific activities, products and buildings materials obtained by using test chambers under standardized conditions as described for VOC in the ISO 16000-9 (International Organization for Standardization (ISO), 2006). We found more data about formaldehyde than PM_{2.5} emission rates.

We detail those results below and propose Table 14 as an overview of data on formaldehyde and PM_{2.5} emission rates found in the reviewed literature.

In situ average loads

EN 15251 standard (CEN, 2007b) proposes in an informative annex two emission rates per wall area for formaldehyde: one of 50 µg.m².h⁻¹ for low pollutant buildings (glass, steel, rock) and one of 20 µg.m².h⁻¹ for very low pollutant buildings (without tobacco). Its update pr EN 16798-1 (CEN, 2016) proposes an update of these emission rates to respectively 100 and 50 µg.m².h⁻¹, based on the results calculated for the European Reference Room as specified in CEN/TS 16516. These standards do not propose any values for PM_{2.5} emission rates.

(Hodgson et al., 2000; Sherman and Hodgson, 2002b) repeated a test three times on seven unoccupied manufactured houses and on seven unoccupied site-built houses, located in eastern and southern USA, under two different climates, hot-humid and mix-humid. The formaldehyde concentration was measured using two active samplers, inside and outside. The indoor sampler was located in the living/dining room at a height of 1.5 m above the floor. In addition, SF₆ was used as a tracer gas to measure the air change rates. The average constant emission rate was calculated from the average measured concentrations and the measured air change rate using the mass conservation equation on the whole house considered as one zone. The result was an average emission rate of 44.17 (± 36 %) µg.m⁻².h⁻¹.

(Blondel and Plaisance, 2011) performed measurements on 24 rooms of student residences equipped with five different surfaces (flooring, ceiling and walls, doors, bed and other furniture), for three construction ages. Formaldehyde concentrations were measured over 6 hours with both conventional active samplers and passive samplers. Thirteen to fifteen passive samplers were used by student room as measurements were performed in the room, in the common corridor adjacent to the room, and outside. Air change rates were measured using a CO₂ (used as tracer gas) injection method. Depending the age of the building, and the type of considered surface (flooring, ceiling and wall, door, bed, other furniture), the resulting average emissions rates were in the range [1.4; 87.3] $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$.

In situ peak loads

Several studies showed that cooking is one of the most PM_{2.5} emitting activity (Abt et al., 2000; He, 2004; Long et al., 2000; Tuckett et al., 1998). The PhD work of (Ji, 2010) corroborated this. (Ji, 2010) performed measurements in an experimental house (MARIA house of CSTB, France) to quantify occupant exposure to ultrafine particles. They directly calculated this indicator from concentration measurements using occupancy schedules, without calculating emission rates. Each source was tested three times at minimum, and the concentration was measured in three different spaces: “close”, “near” and “bedroom”, to quantify the impact of the pollutant on the whole dwelling. The results of the test allowed to class the source in four categories depending on its global impact intensity (strong, medium, limited, weak). This study highlighted that the most important sources were: cooking and extra-heating for the strong impact sources, the toaster for the medium impact sources, and the incenses, cigarettes, and candles for the limited impact sources.

(He, 2004) performed PM_{2.5} measurements on sixteen houses near Brisbane (Australia). Concentration was estimated simultaneously with a condensation particle counter and a photometer with sampling time of respectively 10 and 30 seconds during more than 48 h in the kitchen. Air change rates were measured with a tracer gas method using CO₂ during unoccupied period. The emission rate was then calculated using concentration, air change rate, volume, penetration efficiency and deposition rate. The authors published data about cooking, frying, grilling, toasting, smoking, vacuuming, and other emission rates in the range [0.07;2.78] $\text{mg}\cdot\text{min}^{-1}$.

(Olson and Burke, 2006) performed PM_{2.5} measurement on thirty-six residential homes in North Carolina (USA), during seven consecutive days for each of four seasons. Concentrations were monitored during 24 h inside and outside thanks to a filter-based monitor. The air change rate was measured with a tracer gas method, using perfluorocarbene. The air change rate was calculated thanks to a mass balance. At the same time, each occupant carried a passive sample monitor, collecting the PM_{2.5} personal data every minute, and has to fill a 15-minute time-step schedule. It allows to know occupant’s location and activities to be able to calculate emission rates of specific cooking actions (frying, grilling, toast, stovetop, burned) with an average value in the range [17;470] $\text{mg}\cdot\text{min}^{-1}$.

Chamber tested loads

(Plaisance et al., 2014) used a passive flux sampler during 6 hours to define a linear equation between the formaldehyde mass collected and the emission rate of the tested material in a test chamber, according the ISO 16000-9 standard (International Organization for Standardization (ISO), 2006). Depending the tested surface, they calculated emissions rates in the range [11.2; 682] $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$.

The (Afshari et al., 2005) study was carried out in a test chamber of 32 m³ in a research laboratory in order to characterize emissions due to activities (frying, gas stove, smoking, vacuuming, heater, radiator, scented candle, pure wax candle). PM_{2.5} concentration was measured by two different particles counters: a condensation particle counter and an optical particle counter. The concentration was continuously monitored before, during and after all the emission tests. A tracer gas decay method was used to determine the air change rate, thanks to concentration measurements made continuously during two hours with a photo-acoustic spectroscopy device. Emission rates were lastly calculated through concentration air change rates measurements and expressed in particles by minute.

To compel such chamber tested data, database have been developed. Pandora is a free access huge database for the indoor pollutant emission rates (Abadie and Blondeau, 2011), with more than eight thousand emission rates from literature classified by sources, including formaldehyde and PM_{2.5} emission rates. Other database could be found as the one developed through the EPEHCT project (Missia et al., 2012) and the NIST Database (Howard-Reed and Polidoro, 2006), including formaldehyde but no PM_{2.5} emission rates.

Emission rates	Sources <i>Type of data: In situ average loads / In situ peak loads / Chamber tested loads</i>	Pollutant (Formaldehyde/ PM_{2.5})
Low pollutant building (glass, steel, rock): 50 µg.m ⁻² .h ⁻¹ Very low pollutant building (without Tabaco) : 20 µg.m ⁻² .h ⁻¹	EN 15 251 - (CEN, 2007b) <i>In situ average loads (wall scale)</i>	Formaldehyde
Low pollutant building (stone, glass, ceramics and non-treated metal): 100 µg.m ⁻² .h ⁻¹ Very low pollutant building: 30 µg.m ⁻² .h ⁻¹	pr EN 16798-1 (CEN, 2016) <i>In situ average loads (wall scale)</i>	Formaldehyde
In µg.m ⁻² .h ⁻¹ - Average : 44.17 ± 36 % - Median: 41.72	(Sherman and Hodgson, 2002b) <i>In situ average loads (house scale)</i>	Formaldehyde
[Average ± standard deviation (min-max)] In µg.m ⁻² .h ⁻¹ H1 (built in 1998): - Flooring 2.3±1.5 (1.2-5.5) - Ceiling and wall 3.6±1.7 (1.2-6.3) - Door 4.0±2.0 (1.2-6.4) - Bed 3.3±1.8 (1.2-6.7) - Other furniture 2.8±0.9 (1.2-3.6) H2 (built in 1975 and renovated in 2003): - Flooring 1.4 ± 0.7 (1.2-2.4) - Ceiling and wall 3.2 ± 2.0 (1.2-7.1) - Door 2.6 ± 1.6 (1.2-5.5)	(Blondel and Plaisance, 2011) <i>In situ average loads (wall scale)</i>	Formaldehyde

<ul style="list-style-type: none"> - Bed 2.8 ± 1.7 (1.2-5.8) - Other furniture 3.4 ± 0.6 (2.8-4.4) <p>H3 (built in 1991):</p> <ul style="list-style-type: none"> - Flooring 5.3±3.5 (2.5-13.0) - Ceiling and wall 8.8±2.8 (4.1-12.1) - Door 7.0±4.2 (1.2-14.7) - Bed 87.3±37.5 (21.3-131.3) - Other furniture 2.9±1.9 (1.2-7.0) 		
<p>[median ± standard deviation] in mg.min⁻¹</p> <ul style="list-style-type: none"> - Cooking: 0.11 ± 0.99 - Frying: 2.68 ± 2.18 - Grilling: 2.78 ± 17.8 - Toasting; 0.11 ± 0.37 - Smoking: 0.99 ± 0.81 - Vacuuming: 0.07 ± 0.04 - ... 	<p>(He, 2004) <i>In situ peak loads</i></p>	<p>PM_{2.5}</p>
<p>[mean; median ± standard deviation] in mg.min⁻¹</p> <ul style="list-style-type: none"> - Frying: 60; 33 ± 92 - Grilling: 173; 155 ± 92 - Toasted: 51; 45 ± 27 - Stovetop: 17; 6.9 ± 35 - Burned: 470; 231 ± 530 	<p>(Olson and Burke, 2006) <i>In situ peak loads</i></p>	<p>PM_{2.5}</p>
<p>In µg.m⁻².h⁻¹</p> <ul style="list-style-type: none"> - Fiberboard Medium 1: 92.5 - Fiberboard Medium 2: 135.5 - Fiberboard Medium 3: 133.3 - Sealing plaster: 43.4 - Finishing plaster: 682 - OSB: 11.2 - Chipboard: 244.4 	<p>(Plaisance et al., 2014) <i>Chamber tested loads</i></p>	<p>Formaldehyde</p>

$\text{In } 10^{11} \cdot \text{part. min}^{-1}$ <ul style="list-style-type: none"> - Frying: 8.27 - Gas stove: 1.30 - Smoking: 3.76 - Vacuuming: 0.38 - Heater: 3.89 - Radiator: 8.84 - Scented candle: 0.88 - Pure wax candle: 3.65 	<p>(Afshari et al., 2005) <i>Chamber tested loads</i></p>	<p>PM_{2.5}</p>
<p>More than 8 000 emission rates from consumer products and building materials</p>	<p>Pandora Database (CNRS & LaSIE, 2014) EPEHCT project (Missia et al., 2012) NIST Database (Howard-Reed and Polidoro, 2006) <i>Chamber tested loads</i></p>	<p>Formaldehyde + PM_{2.5}</p>

Table 14 : Overview of formaldehyde and PM_{2.5} emission rates found in reviewed literature.

Conclusion

As a result, few of those data are fully useful for performance-based approach for ventilation. We found either few or no data on average loads in situ measured at the dwelling scale, and especially in low-energy dwellings considered as representative of the new French dwellings. We found more data about in situ peak loads on PM_{2.5} for usual activities and about chamber tested emissions of products and buildings materials.

Consequently, the problem with the available data is of two kinds:

1. Firstly, it is difficult to extrapolate emission rates behaviors from test chamber conditions to in situ conditions, notably because the complex physic phenomena (combined effects, resuspension, etc...).
2. Secondly, it is difficult to build robust scenarii from the materials, products and activities scale to the dwelling scale, as highlighted in (Boulanger et al., 2012a).

We accordingly propose in the following section to use a simplified calculation method and to apply it on unpublished data gathered on French low-energy homes to calculate in situ average loads at the dwelling scale.

5.1.2.6 Calculating pollutant emission rates at the building scale: Formaldehyde

As argued above, we propose to use a simplified method to calculate average emission rates and we apply it to unpublished data from the (Guyot et al., 2017a) measurements campaign. During this campaign, we carried out on 21 recent French low-energy houses: a visual survey, a measurement of airflow or pressure at each of the air-vents, a measurement of ventilation duct airleakage, and acoustics measurement. Then, we selected 10 dwellings to carry out an indoor air quality winter campaign. During 7 days, 16 VOC, 8 aldehydes, NO₂, CO (if there is a source of combustion in the

dwelling), PM_{2.5}, CO₂, temperature and relative humidity were measured in the living room and in the main bedroom. VOC and NO₂ were also measured outdoor. Aldehydes were measured using passive (diffusive) samplers. Particle matters were measured using an active air sampling on a filter with a pump. Inhabitant habits and building influence were studied through a complementary questionnaire survey. CO₂, temperature and relative humidity were measured with a time-step of 10 minutes.

This simplified method uses the mass balance equation applied on a house considered as one zone to obtain an average pollutant emission rate.

$$V \cdot \frac{dC}{dt} = C_{out} \cdot Q + g - C(t) \cdot Q$$

(Equation 7)

With C(t) the inside concentration [$\mu\text{g}\cdot\text{m}^{-3}$], C_{out} the outside concentration [$\mu\text{g}\cdot\text{m}^{-3}$], V the volume of the house, Q the total ventilation volume airflow [$\text{m}^3\cdot\text{h}^{-1}$] and g the emission rate [$\mu\text{g}\cdot\text{h}^{-1}$].

Assuming steady state over the measurement period ($\frac{dC}{dt} \approx 0$), since often only the average measured concentration is available, notably because of the use of passive methods, the emission rate can be approached by :

$$g = Q \cdot (C_{average} - C_{out})$$

(Equation 8)

In the (Guyot et al., 2017a) campaign, both pollutants concentrations and ventilation airflows measurements were performed on ten low-energy houses. Data were globally analyzed and published but without the key information to be able to calculate pollutant emission rates for each house. Indeed, air change rates and average concentrations were not published for each house, but only globally analyzed. We also use here unpublished data from this campaign.

For the house total ventilation airflow calculation, we used, when they are both available, the two used airflows for basic conditions and peak conditions (Q_{basic} and Q_{peak}) weighted by their duration of use. We assumed that the peak airflow is used one hour per day, corresponding to thirty minutes for both the lunch and the dinner.

In eight houses equipped with a balanced ventilation system (numbered n°1-5;7;9-10 in Table 15), airflows measurements were taken at each air supply and at each air exhaust of each house. For the air flow values (Q_{basic} and Q_{peak}), we decided to select the highest value between the total supplied and extracted airflows. Indeed, infiltrations would balance both airflows. As a result, we used (Equation 9).

$$\begin{cases} Q = \frac{23}{24} \cdot Q_{basic} + \frac{1}{24} \cdot Q_{peak} \\ Q_{basic} = \max\{Q_{basic,supplied}; Q_{basic,extracted}\} \\ Q_{peak} = \max\{Q_{pointe,supplied}; Q_{peak,extracted}\} \end{cases}$$

(Equation 9)

For the two houses equipped with humidity controlled ventilation (numbered n° 6 and 8 in Table 15), pressure measurements were taken at each air exhaust of each house. The total airflow was estimated using the average airflow proposed in the corresponding technical agreement, called “Avis technique” (CCFAT, 2015), also described in (Guyot et al., 2018c). These airflows depend on the used ventilation system and the size of the house, especially the number of dry and humid rooms. This average airflow was then corrected in order to take into account the gap between the in-situ measured pressure difference (P_i) at each of the exhaust devices and the theoretical minimum pressure of the range (P_{min}). This correction factor (δQ) was calculated according to (Equation 10), using the measured pressures (P_i) at the N exhaust devices.

$$\delta Q = \left(\frac{\sum_{i=1}^N P_i}{N * P_{min}} \right)^{0.5} - 1$$

(Equation 10)

All tested houses comply with the envelope airtightness requirement in the French EP regulation: the indicator q_{a4} [$m^3 \cdot h^{-1} \cdot m^{-2}$] must be under $0.6 m^3 \cdot h^{-1} \cdot m^{-2}$ (Equation 11). We decided to neglect in the total airflow the part due to infiltrations through the building envelope, except the part already used to balance the flow as explained in (Equation 9).

$$q_{a4} = \frac{C_L * (4)^n}{A_{env}}$$

(Equation 11)

where C_L is the air leakage coefficient [$m^3 \cdot h^{-1} \cdot Pa^{-n}$]; 4 is a 4-Pa reference pressure difference across the building envelope; n is the airflow exponent [-]; A_{env} is the envelope area excluding the lowest floors [m^2].

In this campaign, the $PM_{2,5}$ concentrations were measured using an active sampler, composed of a pre-weighted filter and a pump, in the living room between 5 PM to 8 AM in the week, and during the whole days of the week-end. The concentrations were available in two houses only, indeed they remain lower than the measurement device threshold in the eight other houses. As a result, we decided to not apply the method to $PM_{2,5}$, because of the limited size of the remaining sample.

Formaldehyde concentrations were measured over a week during the winter period, using passive (diffusive) samplers by reaction with 2-4 DNPH, liquid chromatography and UV detection, according to the standard ISO 16000-4 (ISO, 2011). Since measures were taken in the living room and the main bedroom, we used also the average of both values.

The outside concentration of formaldehyde was not measured during this campaign. In France, the outdoor formaldehyde concentration is commonly very low compared to the indoor one (ANSES, 2017). We assumed an outdoor constant value of $2.9 \mu g \cdot m^{-3}$, measured in a study on nursery schools in the same region as the IAQ campaign (DRASS Rhône-Alpes, 2007). We noted that this value is above the median value of formaldehyde outdoor concentration of $1.9 \mu g \cdot m^{-3}$ measured during an extended IAQ campaign on French dwellings in 2005 (Kirchner and al., 2006a).

The input data for calculation and the calculated formaldehyde emission rates per floor area square meter are given for each house in Table 15.

Based on these measurements, we propose to define three classes of formaldehyde emissions to be used as input data for IAQ modelling as in Part 4 of this thesis, and for ventilation performance-based approaches at the design stage of low-energy houses:

1. The low-emission class: $4.5 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, defined by the minimal calculated value;
2. The medium-emission class: $12.0 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, defined by the median calculated value;
3. The high-emission class: $23.6 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, defined by the maximal calculated value.

Of course, the sample used here is rather small and the results need further validation. Therefore, we hope this method could be used in future publication and works.

House	Floor area [m ²]	Volume [m ³]	Q [m ³ .h ⁻¹]	C [μg.m ⁻³]	Constant emission rate g [μg.h ⁻¹ .m ⁻²]
1	174	452	110.3	22.9	12.7
2	121	302	73.7	31.1	17.2
3	168	437	308.4	9.0	11.3
4	161	419	209.8	10.3	9.7
5	176	456	286.0	17.4	23.6
6	67	174	40.6	17.9	9.1
7	150	375	60.7	24.1	8.6
8	151	378	79.8	35.9	17.4
9	112	314	40.1	15.4	4.5
10	80	209	150.0	11.9	16.8

Table 15 : Calculated formaldehyde emission rates from the (Guyot et al., 2017a) campaign.

5.1.2.7 Conclusion on available input scenarii

We highlighted in this review that:

- A lot of relevant data on CO₂ and humidity emissions due to metabolism and activities are available in the literature and we selected the ones which could be used in a performance-based approach at the design stage.
- We can find some relevant data on occupancy schedules, even if most of them are not precise enough to give information about occupancy in each room of the house. For France, we proposed occupancy schedules to be used in a performance-based approach at the design stage.
- There is a lack of exploitable data to model PM_{2.5} and formaldehyde average and peak emissions at the dwelling scale. Therefore, we propose new input data on formaldehyde average loads based on measurements on occupied houses. Available data on PM_{2.5} were not workable.
- As a result, even if a performance-based approach should include PM_{2.5} and acute exposure, at this step of the work, we must also give up the original idea to take into account PM_{2.5} and acute exposure in our proposed performance-based approach.

Table 22 gives an overview of these selected emission scenarii to be used in a performance-based approach at the design stage of a building.

For formaldehyde emission rates, we would suggest to adapt them to the used materials and corresponding IAQ labelling as the one required in France since 2012 (French Ministry for Ecology, 2011). For instance, it is possible to decide at the design stage of a new building:

- If only A-class IAQ labelled materials are used and there is an awareness of occupants, low-emission formaldehyde class can be used in the IAQ calculation. Indeed, in order to secure a low emission rate, it is necessary to increase occupant's awareness and to help them to become "low-emitting" occupants, throughout their activities and their furniture. Tools have been developed for occupants in this aim (Déoux et al., 2016).
- If no information is given, or only D-class IAQ labelling materials are used, high-emission formaldehyde class must be used.
- In other cases, medium-emission formaldehyde class can be used.

Parameter or pollutant	Emission rates
CO ₂	Asleep: 15 L.h ⁻¹ /person Awake: 18 L.h ⁻¹ /person
Humidity	Asleep: 40 g.h ⁻¹ /person Awake: 55 g.h ⁻¹ /person Moisture due to activities: - 1 shower per person per day (for a total of five showers per day), with an emission of 1440 g.h ⁻¹ for 10 min per shower. - 3 cooking periods per day: 1512 g.h ⁻¹ for breakfast for 15 min; 2268 g.h ⁻¹ for lunch for 30 min; 2844 g.h ⁻¹ for dinner for 40 min. - 1 laundry per person per week (Monday, Tuesday, Wednesday, Saturday and Sunday): 252 g.h ⁻¹ for 2 h. - 1 laundry drying per person per week (same days): 136.8 g.h ⁻¹ during 11 h.
Formaldehyde	Low-emission class: 4.5 µg.h ⁻¹ .m ⁻² Medium-emission class: 12.0 µg.h ⁻¹ .m ⁻² High-emission class: 23.6 µg.h ⁻¹ .m ⁻² (per m ² of floor area)

Table 16. Selected emission scenarii to be used in a performance-based approach at the design stage of a building.

5.1.3 Step 3: Modelling at the design stage

5.1.3.1 The need of a multizone approach

Envelope airtightness is often included in regulatory energy performance (EP) calculations, frequently through single-zone models with even airleakage distribution. Because more consideration is often given to energy performance than to indoor air quality issues, multizone approaches for ventilation are usually disregarded. Nevertheless, ventilation in new homes in Middle and North-Europe, is very often based on a whole-house ventilation strategy, where fresh air enters the dry rooms, and moves to the humid rooms to be exhausted there (Kolokotroni, 2008; Sowa, 2008; Wouters et al., 2008; Dimitroulopoulou, 2012). In such a strategy, a multi-zone approach in the design and the performance evaluation is more applicable than a single-zone one, as pointed out by (Laverge, et al. 2011). In existing performance-based for residential smart ventilation reviewed in Chapter 2, multizone modellings are always used except in the USA (ASHRAE 62.2 standard). We detail here why a multizone approach is needed.

5.1.3.1.1 Field studies: disparity in pollutants or CO₂ concentrations in the different rooms of a house

The literature shows how CO₂, humidity, and/or pollutant concentrations can vary from room to room. Measured concentrations are influenced by many parameters, including differences in emission and ventilation rates, presence of a DCV strategy, presence of an air recirculating system, and also the position of the indoor doors (Rudd and Lstiburek, 2000; Björling et al., 2007; Sherman, 2008; Sherman and Walker, 2008). To evaluate differences between well-mixed and zonal approaches, we used the metric proposed by Hodgson, et al. (2004): **the absolute average fractional difference**, defined as the difference between two values (one in a room, one in another room) divided by the average of the two. Reviewed studies apply to VOC, CO₂ and radon measurements in houses.

Hodgson, et al. (2004) measured 22 volatile organic compounds (VOC) concentrations during one year in a new manufactured house. Depending on the particular VOC, the absolute average fractional difference between living room and master bedroom was in the range of 1%-48%, with a standard deviation in the range 5%-58%. Authors observed a statistically significant difference between the two rooms for phenol, toluene, styrene, m/p-xylene, and 1,2,4-trimethylbenzene through 2-tailed Student's t test with $p > 0.95$. (Alessi and Sollaris, 2011) also measured the concentration of several VOC with passive samplers throughout a week in all 12 rooms of two two-story laboratory passive houses, the INCAS houses, equipped with a balanced ventilation system. They observed strong differences in some pollutants, such as benzene, between the kitchen and living room on one side and the bedrooms on the other side. Other pollutants such as toluene and formaldehyde were more evenly distributed among the rooms.

Difference on CO₂ concentrations are widely observed, this is absolutely consistent with the difference in emissions depending the occupancy of a house. (Nielsen and Drivsholm, 2010) monitored CO₂ concentrations for a week in all the rooms of an existing house equipped with a constant airflow ventilation system. The absolute average fractional differences between living room and master bedroom can be calculated in the range of 29%-56%, with a median value of 44% and a mean value of 42%. The absolute average fractional differences between the master bedroom and the boy's room can be calculated in the range of 67%-79%, with a median value of 67% and a mean value of 70%. (van Holsteijn and Li, 2014) monitored the ventilation and IAQ of all individual rooms in 62 homes every

five minutes for a whole year. They calculated the CO₂-exceeding exposure per room, for each type of ventilation system. The absolute average fractional differences between living room (or open kitchen) and master bedroom can be calculated in the range 1%-171%, with a median value of 97% and a mean value of 91%. The absolute average fractional differences between the two bedrooms can be calculated in the range 42%-192%, with a median value of 151% and a mean value of 142%. Such difference between rooms on CO₂ were observed by (Eklund et al., 2015) who studied ventilation effectiveness by monitoring 29 houses with five types of ventilation systems in Washington State, and by Guyot, et al. (2016) who monitored IAQ in 10 new energy-efficient houses during a winter week, two of which were equipped with a humidity-based DCV system. (Ribéron et al., 2016) calculated an air stuffiness index in the main bedroom and the living room of 10 homes based on measurements during two weeks. They showed that only 60% of the homes could be considered as uniform.

(Derbez et al., 2014) monitored the IAQ in seven new energy-efficient houses before and during the first year of occupancy. The absolute average fractional differences in the measured radon concentrations between living room and master bedroom can be calculated in the range 20%-100%, with a median and a mean value of 50%.

5.1.3.1.2 Differences between single-zone and multi-zone modelling in residential buildings

Modelling studies comparing single-zone and multizone modelling approaches confirm those experimental observations and highlight errors coming from single-zone modelling in an IAQ approach.

(D'Ottavio and Dietz, 1985) studied the gaps resulting from the use of a single-zone ventilation model on a ranch house with a basement. They demonstrated that, with a single-zone model, differences on peak concentration could be $\pm 35\%$, depending on the definition of the zone perimeter, with a variable emission source such as a gas stove compared to a two-zone model. With a constant emission source, differences are in a larger range (-19%; +60%). They also demonstrated that these differences do not depend linearly on differences in the air exchange rate, so that they conclude that an accurate air change rate measurement combined with a zone model should be considered only as a first approximation.

(Roldan et al., 1987) also demonstrated that errors coming from single-zone modelling were unneglectable when studying dynamic thermal simulation.

(Du et al., 2012) characterized air change rates and interzonal airflows in 126 residences and evaluated their effects on IAQ. Then, a two-zone model (the bedroom and the rest of the house) calibrated with the field study was conducted for the IAQ study. Air change rate measurements were made using the constant multi-zone injection method, using two tracer gases, over a week, in different seasons. ACR was $0.73 \pm 0.76 \text{ h}^{-1}$ (median value = 0.57 h^{-1} ; n=263) in the living room, and higher in the bedrooms: $1.66 \pm 1.5 \text{ h}^{-1}$ (median value = 1.23 h^{-1} ; n=263). They showed that $26 \pm 20\%$ of the air entering the living room comes from the bedrooms, $50 \pm 18\%$ from the rest of the house, with slight variations over the seasons. In the IAQ modeling study, they considered either a PM_{2.5} source in living room or in the bedroom. They also showed strong differences between the average PM concentrations in the living room and in the bedroom. Concentrations in the bedroom are 43%-47% lower than those in the living room. For strong sources in the bedroom, the concentrations are 65 to 74% higher than those in the

living room. A sensitivity analysis using the two-zone model demonstrated that the key factors influencing pollutant concentrations are the emission source strength and location, the air change rates, and the inter-zonal air flows. They concluded that single-zone models should apply only in the case of uniform emission sources for tight homes, with closed bedroom doors and no central forced air system.

As a result, our review of literature based on measurement campaigns and on studies comparing single-zone and multi-zone modelling shows that for assessing ventilation performance in a house, it seems necessary to use at least multizone approaches where one room is modelled as one zone. Multi-zone IAQ modeling approaches are provided by software such as CONTAM or COMIS which have been validated through controlled experiments using tracer gas injections of (Lansari, et al. 1996; Sextro, et al. 1999; Zhao, et al. 1998, 1998).

5.1.3.2 General assumptions and models

In order to assess ventilation performance at the design stage of a building, general assumptions have to be made and described concerning the physical model, the building modelling and the boundary conditions.

1. The physical model and its resolution:

- a. For a multizone approach, pressure codes seem to be the more relevant level of model to use, for instance existing softwares as COMIS, CONTAM, ... The validation of such multizone models is well documented (Lansari et al., 1996; Sextro et al., 1999; Zhao et al., 1998). Moreover, several authors showed that this type of model assuming well-mixed air in every room was adapted for ventilation and IAQ modelling in houses (Emmerich, 2001; Chen and Wen, 2012; Laverge et al., 2013). Each room of the dwelling is modelled as a zone.
- b. Stack effect should be taken into account. Isothermal assumption can be done indoor during the heating period. Stack effect between indoor and outdoor should be considered.
- c. Moisture buffering effect should be modelled when modelling humidity transfers in dwellings as pointed out by (Plathner, 2002; Steeman et al., 2009; Van den Bossche et al., 2007; Woloszyn et al., 2009a). There are several more or less accurate lumped-capacity-type methods described in the literature to simulate this effect (Woloszyn et al., 2009b), for example, the equivalent absorbing area (CCFAT, 2015), the boundary layer diffusion model (Axley, 1991; White, 1988) used in CONTAM (Dols and Polidoro, 2015) and the moisture buffering model (Duforestel and Dalicieux, 1994). The latter have been shown to satisfactorily represent the joint effect of furniture and construction materials in real houses (Plathner and Woloszyn, 2002). Therefore it should be used as a reference.
- d. The calculation period should be adapted to the climate and habits of the country / region. In France where air conditioning is rare in new residential buildings and open windows ensure cooling instead, the heating period is the more relevant calculation period to use. In other countries where air conditioning is widely used, the whole year would be more relevant to be used.

- e. The calculation time-step should be maximum 10 minutes, in order to fit to moisture production scenario and evolution.
- 2. The building modelling:**
- a. Building geometry, number and geometry of modelled zones should be precisely described.
 - b. The location of internal doors and associated models should also be given. They should be assumed to be closed, as observed in the campaign carried out by (Bernard 2009). This would give a conservative assessment.
 - c. Envelope and internal partition walls airleakage distributions should be used and described. We highlighted in Part 4 of this thesis that impacts of uneven envelope airleakage distributions on IAQ are significant, as well as impacts of internal partition walls airleakage. We propose to use input values from the measurement campaign on 23 detached houses presented in Part 3 of this thesis.
 - d. The ventilation system should be described with associated physical laws. Incoming air (air supplies if balanced ventilation, trickle vents if exhaust-only ventilation) and outgoing air (exhaust devices) in each room should at least be described with associated airflows. Ducts and ventilators could also be modelled in a more detailed approach.
- 3. The boundary conditions:**
- a. The outdoor concentrations should be as representative as possible of the outdoor concentrations around the design building, with a time-step as close as possible to the calculation time-step,
 - b. The weather data should include at least wind speed and direction, atmospheric pressure and should be as representative as possible of the weather data around the design building, with a time-step as close as possible to the calculation time-step. Weather data of a typical year are worthwhile data to be used (ASHRAE IWEC Weather file, 2001).
 - c. The wind model used to calculate wind speed at the building starting from weather data should be given. The used pressure coefficients on facades as well.

Other assumptions must also be described concerning the airleakage distributions and the doors, the ventilation systems and the moisture buffering model and are discussed in dedicated sections.

5.2 Overview scheme of the proposed method

We updated the scheme proposed in the introduction with the proposed topics developed in this section 5.1. *Proposed Method*.

This is important to divide the inputs in two categories:

1. The ones which correspond to “standard” data, as discussed in section 5.1.2. They are called “Standard conditions and scenarii”,
2. The ones which are data from a given building due to design choices on this building. They are necessary input data regarding the modelling requirements. They are called “Building design data”.

The “Inputs” part of the scheme has been developed according the section 5.1.2 for “Standard conditions and scenarii” and the section 5.1.3 for “Building design data”, the “Modelling” part of the scheme has been developed according the section 5.1.3, and the “Ouputs” part of the scheme has been developed according to section 5.1.1.



Building design data

- Geometry data for each of the room (multizone approach)
- Envelope airleakage value
- Type of structure: heavy/wooden (regarding the impact of envelope and internal partitions wall airleakage distributions)
- Ventilation system (exhaust-only, balanced, ...) and associated airflows at each of the air inlets and outlets
- Doors (location, size and undercut)
- IAQ labelling of material and products => level of emission (high/middle/low)

Standard conditions and scenarios

1-Standard boundary conditions (as representative as possible):

- Weather : wind speed and direction, temperature, atmospheric pressure, relative humidity,
- Pollutants concentration profiles

2-Standard occupancy scenario

- Number of occupants = f(number of bedrooms), only adults
- At each time-step, how many occupants in each room + activities, for France (see):
- A unique schedule,
- Time spent for each occupant: 9h20 in its bedroom, 2h50 in the living room, 2h40 in the kitchen in 3 periods for breakfast, lunch and dinner, 40 minutes in the bathroom.
- A ventilation high-speed in the kitchen switched-on for 1 hour twice a day.

3-Standard pollutant emissions scenario

- At least: CO₂, humidity, formaldehyde, PM_{2.5}
- See Table 14.

Physical model

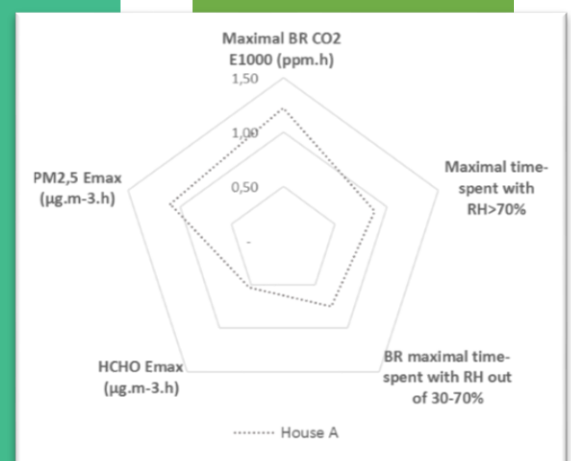
- Need of multizone (CONTAM, COMIS, ...)
- stack effect model and assumptions,
- wind model and pressure coefficients c_p distribution,
- moisture buffering effect model and assumptions,
- calculation period adapted to the climate and habits of the country,
- time-step > 10 minutes,

Buildings model

- Closed doors,
- Uneven distributions of envelope and internal partition walls airleakage with data proposed in Part 3,
- Models used for airflow calculation at each of the ventilation components,
- Ducts and ventilators could also be modelled in a more detailed approach.

IAQ performance indicators

- At least 5 indicators: see Table 6 with associated thresholds
- 1. Maximum cumulative exceeding CO₂ exposure (for instance: over 1000 ppm) in the bedrooms,
- 2. Maximum cumulative occupant formaldehyde exposure,
- 3. Maximum cumulative occupant PM_{2.5} exposure,
- 4. Maximum of the percentage of time with RH higher than 70% in all rooms (condensation risk),
- 5. Maximum of the percentage of time with RH outside of the range [30%–70%] in the bedrooms (health risk).



- Rooms ACR also usefull as intermediate metrics

Figure 6. Overview scheme illustrating the proposed performance-based approach for ventilation.

5.3 Application and results on a case study

5.3.1 Description of the case study

We assume here applying a performance-based approach at the design stage of a house which must comply with a hypothetical regulation, code or label, requiring to calculate IAQ ventilation performance indicators based on given occupancy and pollutant scenarii.

We applied the proposed methodology to a 2 stories-low-energy brick house, located near Chambéry, France. This house has four bedrooms (called BR1, BR2, BR3, BR4), two bathrooms (Bath 1 and 2), two toilets (WC 1 and 2), a mezzanine (Mezz), a kitchen open on the living room (K+LR) and a hall, as shown on Figure 7. Its whole volume is 337 m³ and the total floor area is 135 m².

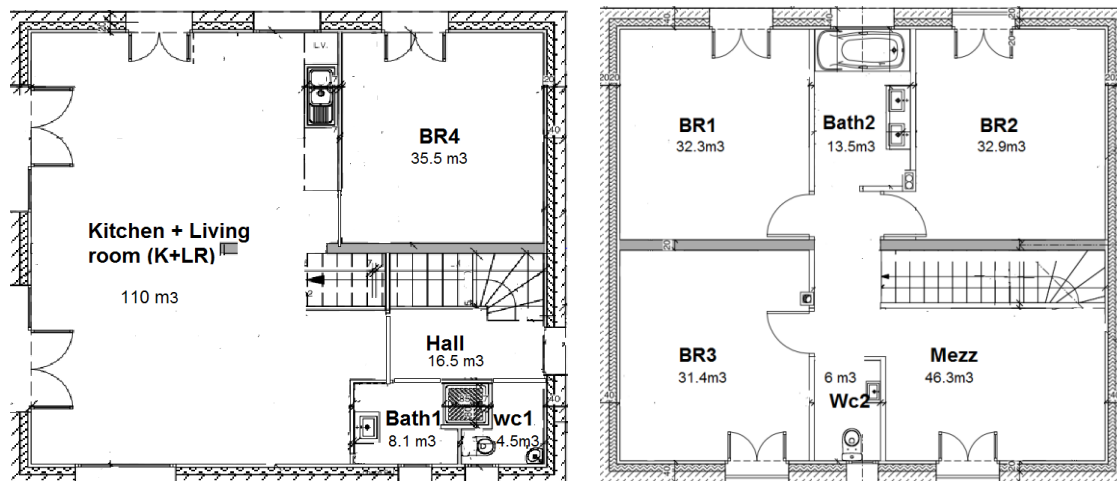


Figure 7. Plan of the house studied: (a) ground floor (b) first floor.

The hypothetical regulation, code or label requires a calculation performed over the heating period, defines from October 15th 00:00 AM to April 14th 12:00 PM, accounting for 4366 simulated hours. Indeed, air conditioning in new dwellings is rare in France and open windows ensure cooling instead. As a result, it is more relevant to calculate ventilation performance for the heating period only.

Airflows, relative humidity, CO₂ and formaldehyde concentrations were investigated using numerical modelling with CONTAM software (Walton and Emmerich, 1994). This software is utterly useful to describe finely uneven airleakage distributions.

We used a multizone model for the dwelling, modelling each room as one zone, with a 10-min time step.

We used weather data of a typical year in Lyon (ASHRAE IWEC Weather file, 2001). An overview of assumptions on average climate parameters is given in Table 17. The inside temperature was assumed to be 20°C during this period. The wind at the building was calculated from the weather data using a 0.3287 modifier factor, resulting from a power law used with factors from a suburban area and the

house being 8.5 m in elevation. The pressure coefficients from the EN 15242 (CEN 2007) were used, assuming no barrier, i.e. +0.5 on the upwind facades and -0.7 on the downwind facades.

Outside concentrations for the three studied pollutants are assumed to be constant for CO₂ and formaldehyde and variable for humidity, as proposed in Table 18. According to the Haut Conseil de la Santé Publique (the French Health Council), a value of 2.9 µg.m⁻³ was selected, extracted from a French study on the nursery school in the same region than the house (DRASS Rhône-Alpes, 2007). This value is above the median value of formaldehyde outdoor concentration, of 1.9 µg.m⁻³ from (Kirchner and al., 2006).

Other assumptions must also be described concerning the airleakage distributions and the doors, the ventilation systems and the moisture buffering model and are discussed in dedicated sections.

Temperature (K)	Pressure (Pa)	Wind velocity (m.s ⁻¹)	Wind direction (°)	Humidity ratio (g/kg)
279.6	993967	3.4	193	4.9

Table 17. Average climate data parameters for the full heating period.

CO ₂ (ppm)	Humidity (g/kg)	Formaldehyde (µg.m ⁻³)
400	Variable, average value of 4.9	2.9

Table 18. Outdoor concentrations for the three studied pollutants.

5.3.2 Step 1: Assumed IAQ ventilation performance requirements

We assume that the hypothetical regulation, code or label, requires to calculate the four key performance indicators identified as relevant in section 5.1.1.3, with thresholds given in Table 7:

1. Maximum cumulative exceeding CO₂ exposure (for instance: over 1000 ppm) in the bedrooms,
2. Maximum cumulative occupant formaldehyde exposure,
3. Maximum of the percentage of time with RH higher than 70% in all rooms (condensation risk),
4. Maximum of the percentage of time with RH outside of the range [30%–70%] in the bedrooms (health risk).

As discussed in section 5.1.2.7, facing a lack of data, it is not possible at the moment to apply the performance-based approach using PM_{2.5} and acute exposure.

As proposed in Table 7, Table 19 gives the required thresholds calculated with a simulation duration of 4366 hours, corresponding to the heating period from October 15th 00:00 to April 14th 24:00.

IAQ performance indicators	Thresholds
Maximal cumulative exceeding CO ₂ exposure over 1000 ppm in the bedrooms, E ₁₀₀₀ (ppm.h)	4.4.10 ⁶ ppm.h
Maximal cumulative occupant formaldehyde exposure E _{max} (μg.m ⁻³ .h)	9 x 4366 h = 3.9 10 ⁴ μg.m ⁻³ .h
Maximum time-spent with RH>70% in all the rooms (%)	1000 / 4366 = 23 %
Maximal time-spent with RH out of 30-70% in BR (%)	800 / 4366 = 18 %

Table 19. Required four IAQ performance indicators and corresponding thresholds calculated for a 4366 hour-simulation duration.

5.3.3 Step 2: Assumed standard occupation and pollutant emission scenarii

Standard occupation and pollutant emission scenarii are also supposed to be described in the hypothetical regulation, code or label, requiring to calculate IAQ ventilation performance indicators.

Regarding the study of (Zeghnoun et al., 2010) analyzed in section 5.1.2.1, we could assume that the required occupation scenarii for this 4 BR-house will be based on 5 occupants as described in Table 20, coupled with the following ventilation schedules described in Table 21 :

1. There is a unique schedule for each occupant and each day of the week all the yearlong,
2. The time spent in the house is divided for each occupant by 9h20 spent in its bedroom, 5h30 spent in the open kitchen divided in three periods for breakfast (from 6:20 to 8:30 depending the occupant), lunch (from 12:00 to 14:00) and dinner (from 19:00 to 21:00 depending the occupant), 40 minutes spent by each occupant in one of the both bathrooms.
3. A ventilation high-speed in the kitchen switched-on for 1 hour twice a day at the beginning of lunch (12:00) and dinner (19:00) periods.

Occupant	In open kitchen	In bathroom	In bedroom
N°1 and 2 (bedroom 1)	7:00-8:30 12:00-14:00 19:00-21:00 (5h30-duration)	6:20-7:00 (bathroom n°2)	21:00-6:20 (9h20 duration)
N°3 (bedroom 2)	6:20-8:30 12:00-14:00 19:00-20:20 (5h30-duration)	20:20-21:00 (bathroom n°2)	21:00-6:20 (9h20 duration)
N°4 (bedroom 3)	6:20-8:30 12:00-14:00 19:00-19:40 20:20-21:00 (5h30-duration)	19:40-20:20 (bathroom n°2)	21:00-6:20 (9h20 duration)
N°5 (bedroom 4)	6:20-8:30 12:00-14:00 19:00-20:20 (5h30-duration)	20:20-21:00 (bathroom n°1)	21:00-6:20 (9h20 duration)

Table 20. Standard occupancy schedules for a 4 BR-house

Ventilation speed	Kitchen (and bedrooms and living room if balanced ventilation)
Speed 1 (basic)	13:00-19:00 20:00-12:00
Speed 2 (peak)	12:00-13:00 19:00-20:00

Table 21. Standard mechanical ventilation schedules

Regarding our review of pollutant emission scenarii presented in section 5.1.2 and overviewed in Table 16, we could assume that the hypothetical regulation describes the following emission scenarii to be used in the case study IAQ performance-based calculation :

- Carbon dioxide is emitted by occupants when they are in bedrooms at the “asleep” rate (15 L.h⁻¹) and when they are in other rooms at the “awake” rate (18 L.h⁻¹). The occupation schedules are the ones described in Table 20.
- Humidity is emitted by occupants when they are in bedrooms at the “asleep” rate (40 g.h⁻¹) and when they are in other rooms at the “awake” rate (55 g.h⁻¹). Again, the occupation schedules are the ones described in Table 20.
- Humidity is also produced by human activities. Each occupant takes a shower a day starting when he is supposed to go in the bathroom according to the occupancy schedule (Table 20), with an emission of 1440 g.h⁻¹ for 10 min per shower. They are three cooking periods per day of 1512 g.h⁻¹ for the breakfast for 15 min starting at 6:20, of 2268 g.h⁻¹ for the lunch for 30 min starting at 12:00, of 2844 g.h⁻¹ for the dinner for 40 min starting at 19:00. Lastly, they are five laundries and dryings per week (on Monday, Tuesday, Wednesday, Saturday and Sunday) emitting respectively 252 g.h⁻¹ for 2 h and 136.8 g.h⁻¹ for 11 h, both in bathroom 1.
- Formaldehyde is continuously emitted in every room proportionally to its floor area. At the design stage, three classes could be assumed depending the used materials and

corresponding IAQ labelling. If only A-class IAQ labelled (French Ministry for Ecology, 2011) materials are used and there is an awareness of occupants (guides, interview, ...), low-emission formaldehyde class can be used. If no information is given, or only D-class IAQ labelling materials are used, high-emission formaldehyde class must be used. In other cases, medium-emission formaldehyde class can be used.

Table 22 gives an overview of these standard emission scenarii described in the hypothetical regulation. For the 4 BR-house case study.

Pollutant	Emission rates	Room and schedule
CO ₂	Asleep: 15 L.h ⁻¹ /person Awake: 18 L.h ⁻¹ /person	In occupied* bedrooms In other occupied* rooms
Humidity	Asleep: 40 g.h ⁻¹ /person Awake: 55 g.h ⁻¹ /person Moisture due to activities for a total of 6 kg/day: - 1 shower per person per day (for a total of five showers per day), with an emission of 1440 g.h ⁻¹ for 10 min per shower. - 3 cooking periods per day: 1512 g.h ⁻¹ for breakfast for 15 min; 2268 g.h ⁻¹ for lunch for 30 min; 2844 g.h ⁻¹ for dinner for 40 min. - 5 laundries per week (Monday, Tuesday, Wednesday, Saturday and Sunday): 252 g.h ⁻¹ for 2 h. - 5 laundry drying per week (same days): 136.8 g.h ⁻¹ for 11 h.	In occupied* bedrooms In other occupied* rooms Starting at: 20:00 in Bath1 and 6:20, 7:00, 19:40, 20:20 in Bath2 6:20, 12:00 and 19:00 in the kitchen 19:00 in Bath1 21:00 in Bath1
Formaldehyde	Low-emission class: 4.5 µg.h ⁻¹ .m ⁻² Medium-emission class: 12.0 µg.h ⁻¹ .m ⁻² High-emission class: 23.6 µg.h ⁻¹ .m ⁻²	Continuously in all rooms, per m ² floor area.

Table 22. Standard emission rates for the 4 BR-house case study. *:Occupied periods defined according to Table 20

5.3.4 Step 3: Modelling

More details about airleakage distributions, door undercuts and ventilation airflows are given in the appendix 9.2.

5.3.4.1 Envelope and internal partition walls airleakage distributions

As proposed in section 5.1.3.2, we assume the hypothetical regulation would require to use input values from the measurement campaign on 23 detached houses presented in Part 3 of this thesis.

At the design stage, this performance-based study could also help to quantify IAQ impact of design choices as the type of structure, between wood structure or heavy structure, so that we selected 2 cases of internal partition walls airleakage distributions described in Table 23.

For the envelope airleakage distribution, we used data measured on the studied house, which was included in the sample studied in Part 3, (Guyot et al. 2016). Envelope airtightness was $n_{50}=1.5 \text{ h}^{-1}$, according to (Equation 12), and was unevenly distributed.

$$n_{50} = \frac{C_L * 50^n}{V}$$

(Equation 12)

where C_L is the airleakage coefficient [$\text{m}^3 \cdot \text{h}^{-1} \cdot \text{Pa}^{-n}$], n is the airflow exponent [-], 50 is a 50-Pa reference pressure difference across the building envelope and V is the building's heated volume [m^3] (337 m^3 for the house studied).

Cases	Envelope airleakage	Internal partition walls airleakage
Case d2	Uneven distribution ($n_{50}=1.5 \text{ h}^{-1}$)	Uneven theoretical distribution For a heavy structure: $q_{50, \text{median}} = 1.2 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ Inter quartile range (q_{50}) $= 3 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$
Case d4		Uneven theoretical distribution For a wood structure: $q_{50, \text{median}} = 6 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ Inter quartile range (q_{50}) $= 12 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$

Table 23. Description of studied airleakage distributions, from Part 3 (Guyot et al., 2016)

5.3.4.2 Internal doors

As proposed in section 5.1.3.2, we assume the hypothetical regulation would require internal doors to be closed in the simulation, as observed in the campaign carried out by (Bernard 2009). The door undercuts were modelled through a single crack of 1-cm height, as required by the French airing regulation, with a 0.65 flow exponent and a 0.6 discharge coefficient at a 10-Pa reference pressure.

5.3.4.3 Modelling the ventilation system and its out and inlets

At the design stage, this performance-based study should also allow to quantify IAQ impact of the type of ventilation system.

In this case study, we study two types of constant airflow ventilation: exhaust-only and balanced ventilation. Total extracted airflows are the same in both cases. Both systems can be considered as “reference” systems since they comply directly with the French airing regulation.

The French airing regulation requires extract airflows in humid rooms, depending the number of main rooms (a large living room accounts for two rooms), toilets and bathrooms. In our case study, a ventilation system for a seven-room house with two bathrooms and two toilets must provide $30 \text{ m}^3 \cdot \text{h}^{-1}$ in each bathroom, $15 \text{ m}^3 \cdot \text{h}^{-1}$ in each toilet, and $45 \text{ m}^3 \cdot \text{h}^{-1}$ in the kitchen. A high-speed ventilation must also be able to provide $135 \text{ m}^3 \cdot \text{h}^{-1}$ in the kitchen during peak periods. As a result, the total extract airflow in the whole house is $135 \text{ m}^3 \cdot \text{h}^{-1}$ during basic mode and $225 \text{ m}^3 \cdot \text{h}^{-1}$ during peak mode. The basic mode accounts for an average dwelling air change rate of 0.4 h^{-1} .

With balanced ventilation, each bedroom and the mezzanine is equipped with a supply vent providing $19.3 \text{ m}^3 \cdot \text{h}^{-1}$, the living room with two. It balances the total extracted airflow in the basic mode.

With exhaust-only ventilation, these seven air supply vents are replaced with self-regulating trickle vents, with a $22 \text{ m}^3 \cdot \text{h}^{-1}$ module to balance the total exhaust airflow in the basic mode. They are self-regulated in order to “cut” effects of strong wind which could led to a pressure difference over 20 Pa. We used the « Test data (2 points) » model proposed in CONTAM which allows one to calculate the {C,n} parameters of a flow path using two points of measured curve {flow, pressure}, (Equation 13 and (Equation 14), (Dols and Polidoro, 2015).

$$n = \frac{\ln(q1) - \ln(q2)}{\ln(dP1) - \ln(dP2)}$$

(Equation 13)

$$C = \frac{Q1}{dP1^n} = \frac{Q2}{dP2^n}$$

(Equation 14)

with $q1$ and $q2$ ($\text{kg} \cdot \text{h}^{-1}$) the mass flow rates corresponding to the volume flow rates $Q1$ and $Q2$ ($\text{m}^3 \cdot \text{h}^{-1}$), $dP1$ and $dP2$ the pressure differences corresponding to flow rates $Q1$ and $Q2$ read on the response curve published by the manufacturer ALDES (Figure 8).

We fitted the calculated operating curve with data from the ventilator manufacturer using the two points $\{10 \text{ m}^3 \cdot \text{h}^{-1}; 4 \text{ Pa}\}$ and $\{23.5 \text{ m}^3 \cdot \text{h}^{-1}; 20 \text{ Pa}\}$. We obtained the power law described in (Equation 15). The calculated flow exponent is consistent with the published literature (Karava et al., 2003).

$$Q_{trickleV} = 4.79 * \Delta P^{0.53}$$

(Equation 15)

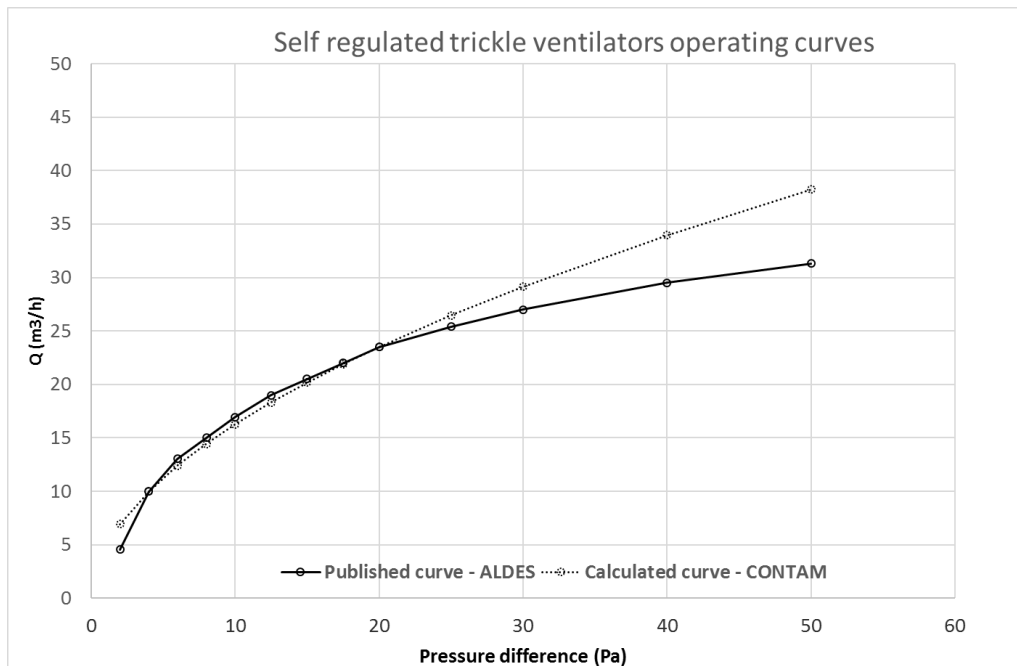


Figure 8. Operating curves for the selected trickle ventilator. Case study.

5.3.4.4 Modelling the moisture buffering effect

As proposed in section 5.1.3.2, we assume the hypothetical regulation would require the use of the moisture buffering model (Duforestel and Dalicieux, 1994).

Its general principle (lumped capacity) is similar to the model already implemented in CONTAM. However, the main variables and corresponding parameters are different. Consequently, preliminary simulations were needed to model Duforestel’s moisture buffer correctly using the Axley equation implemented in CONTAM. To this aim, we recreated a case study with high-absorbing and low-absorbing rooms and emissions lasting 10 h. We used the points obtained by the analytical solution of the Duforestel model using the parameters from (Duforestel and Dalicieux, 1994). Then, using a least-squares method, we fitted the three parameters of the Axley equation to be used in CONTAM: the film mass transfer coefficient “h”, the Henry adsorption constant “k” and “A” a surface mass (Table 24). Further developments are given in the appendix 9.1.

Parameters	High-adsorbing room	Low-adsorbing room
Film mass transfer (h)	0.0051 m.s ⁻¹	0.0066 m.s ⁻¹
Henry adsorption coefficient or the partition coefficient (k)	331.6 kg.kg ⁻¹	300 kg.kg ⁻¹
Surface mass (A)	12.3% of the room volume	2.4% of the room volume

Table 24. Parameters calculated for the boundary layer diffusion model used in CONTAM

5.3.5 Results

5.3.5.1 IAQ radar obtained on the case study

We firstly consider that the owner wants a house in wooden structure, equipped with a constant-airflow exhaust-only ventilation, and doesn't want to report IAQ labelling of the used materials and products.

As a result, we are in case d4 (wooden structure) and should use the high-class formaldehyde emission rate of $23.6 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$.

The four required IAQ performance indicators were calculated and given in Table 25. We again normalized them by the thresholds values given in Table 19 and used the radar approach in Figure 9. We can note here that the radar approach is more relevant with more than 4 entries, which should be the case in the medium term, with the acute and $\text{PM}_{2.5}$ performance indicators.

Structure type	Ventilation type	Maximal CO_2 dose E_{1000} (ppm.h) <i>(obtained in BR1)</i>	Maximal time-spent with $\text{RH}>70\%$ <i>(obtained in Bath1)</i>	BR maximal time-spent with RH out of 30-70% <i>(obtained in BR 4)</i>	HCHO E_{max} ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}$)
Case d2 (heavy structure)	Exhaust-only ventilation	$5.5\text{E}+06$	20.5%	14.2%	$2.1\text{E}+04$

Table 25. IAQ performance indicators for our case study.

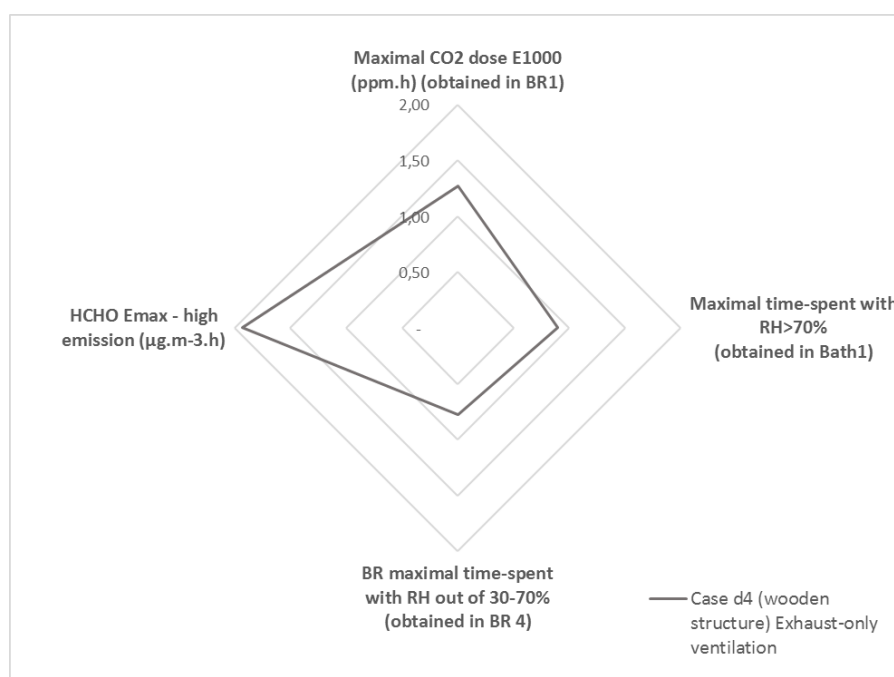


Figure 9. IAQ performance indicators for our case study. With the radar approach.

The maximal CO_2 cumulative exposure is obtained in BR1, occupied by two persons, the maximum time-spent with RH higher than 70% is obtained in Bath1, where laundry and drying take place, the

maximum time-spent in bedrooms with RH out of the selected range is always obtained in BR4. The formaldehyde cumulative exposure is not related to a room but to an occupant.

In this case, two IAQ performance requirements are not fulfilled because ratios with thresholds values are higher than 1: 1.3 for the maximal CO₂ dose E_{1000} (ppm.h) and 1.9 for the maximal occupant exposure HCHO E_{max} ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}$).

Changes must be done on this house in order to comply with this hypothetical regulation, code or label. It will be discussed in the two next sections. The first one will treat the choice of key parameters as type of structure regarding its impact on airleakage distributions, type of ventilation system, level of pollutant emissions. The second one, will treat the design of the ventilation (distribution of components, airflow rates).

5.3.5.2 How the method should help in key design choices

As in our case study, design changes must be done on the house in order to comply with this hypothetical regulation, code or label, we will here illustrate how the method can help in key design choices: type of structure regarding its impact on airleakage distributions, type of ventilation system, level of pollutant emissions.

We also studied, according to former descriptions in above sections, different variants on these three parameters:

- airleakage distributions: representative of a wood-structure (case d4) or a heavy structure (case d2),
- type of ventilation system: balanced or exhaust-only ventilation,
- level of formaldehyde emissions: high-class, medium-class or low-class emission rate.

We calculated the four IAQ performance indicators for all these variants and plotted them in Figure 10 with the radar approach once they have been normalized by selected thresholds from Table 19. For a better readability of the graph, we plotted three times the formaldehyde performance indicator for the three emission classes (high, medium, low)

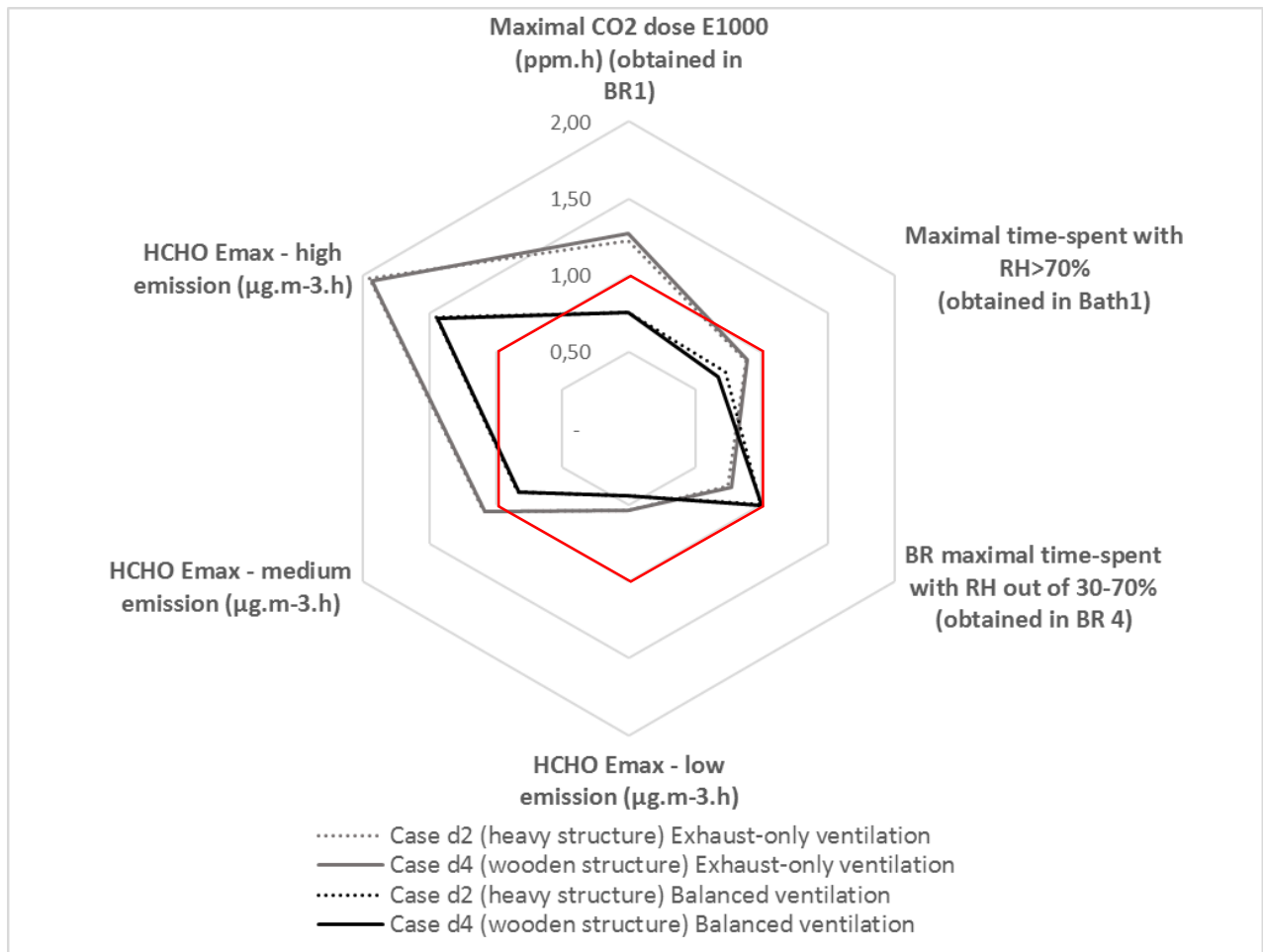


Figure 10. Calculated IAQ performance indicators ratios with their thresholds. Impacts of ventilation system, internal partition wall airleakage distribution and formaldehyde emission class.

Regardless ventilation type and building structure, the maximal CO₂ cumulative exposure is always obtained in BR1, occupied by two persons, the maximum time-spent with RH higher than 70% is always obtained in Bath1, the maximum time-spent in bedrooms with RH out of the selected range is always obtained in BR4.

Figure 10 illustrates that in order to get all the plotted ratios lower than 1, we can make the following choices on those three key issues:

- **Type of structure regarding its impact on airleakage distributions.** The maximum difference is obtained on the condensation risk indicator with balanced ventilation. With a wooden structure the ratio is 0.68 against 0.73 with a heavy structure, resulting in a 7% difference only. This design choice will have a negligible impact on selected IAQ performance indicators in this case. A wooden structure tends to slightly improve the IAQ with an exhaust-only ventilation and slightly degrade it with a balanced ventilation;
- **Type of ventilation system.** In this case, the black curves (balanced ventilation) are in the red hexagon (ratio lower than 1), except with the formaldehyde high-emission class, whereas the grey curves (exhaust-only ventilation) are out of the red hexagon for the maximal CO₂ dose (ratios of 1.22 and 1.27) and for the formaldehyde medium-emission class (ratios of 1.08 and 1.09). The BR maximal time-spent with RH out of the 30-70% range is however poorer, even

lower than 1, with balanced ventilation (ratios of 1.00 and 1.01) than with exhaust-only ventilation (ratios of 0.73 and 0.68). As a result, selecting a balanced ventilation system instead of an exhaust-only ventilation, would allow to fulfill all the IAQ requirements including the CO₂ requirement;

- **Level of formaldehyde emissions.** In this case, Figure 10 shows that formaldehyde exposure ratios are higher than 1.44 with both types of ventilation for the highest-class emission. At the design stage of this house, it would be critical to require the use of building materials with A- or B-class IAQ labels (French Ministry for Ecology, 2011). Moreover, in order to secure a medium emission rate, it could be suitable to increase occupant's awareness and to help them to become "low-emitting" occupants, throughout their activities and their furniture. Tools have been developed for occupants in this aim (Déoux et al., 2016). If the designer does not accept to decrease pollutant emissions using these proposed methods, the regulation / code / label using this performance-based approach could require to increase ventilation airflow rates, resulting in an EP penalty.

5.3.5.3 How the method can be used to design the ventilation system

As in our case study, design changes must be done on the house in order to comply with this hypothetical regulation, code or label, we will here illustrate how the method can allow the design of the ventilation (distribution of components, airflow rates) to fulfill IAQ requirements.

Indeed, using a multizone IAQ performance-based approach shows that with a same total exhaust airflow in a house, different IAQ levels can be obtained, depending upon the precise location of the air inlets and the air outlets, or the distribution of the extract airflows. Proposed multizone simulations can also be used for adjusting air inlet distribution in different rooms.

5.3.5.3.1 Adjusting air inlets distribution

We illustrate the impact of the air inlets distribution in the house on the IAQ performance, modelling the house equipped with an exhaust-only ventilation system providing the same total regulatory air exhaust airflow, with the same total module of trickle ventilators, but with a different distribution. In the initial simulation, we modelled seven self-regulating trickle vents providing the airflow Q_{trickleV} modelled using the law described in (Equation 15). One was located in each bedroom and in the mezzanine, two in the living room.

Variant n°1 (initial simulation):

- BR 1,2,3,4 and mezzanine: $5 \times Q_{\text{trickleV}}$,
- Living room: $2 \times Q_{\text{trickleV}}$.

In Variant n°2, we assume a new distribution:

- BR 1: $1 \times 5/3 Q_{\text{trickleV}}$,
- BR 2,3,4: $3 \times 4/3 Q_{\text{trickleV}}$,
- Living room and mezzanine: $3 \times 0.44 Q_{\text{trickleV}}$.

The sum of the coefficients is seven, i.e the same than in the initial simulation.

In this way, we wanted to improve IAQ for the same exhausted airflows, providing more air in all the bedrooms, and even more in the one occupied by two persons (BR1), to decrease both CO₂ and formaldehyde based exposure performance indicators.

The comparison of both variants is shown in Figure 11. Again, the maximal CO₂ cumulative exposure is always obtained in BR1, the maximum time-spent with RH higher than 70% (condensation risk indicator) is always obtained in Bath1, the maximum time-spent in bedrooms with RH out of the selected range (RH health indicator) is always obtained in BR4.

We succeed to improve both formaldehyde and CO₂ based IAQ performance indicators, maintaining them under their thresholds. We also slightly decreased the RH in the bedrooms but the RH health indicator (RH in the 30-70% range) ratio stays lower than 1. As ACR in humid rooms is dominated by exhausted airflows, as shown in Table 27, it was nevertheless not possible to improve the condensation risk indicator (RH>70%) in bathrooms. It could be done in future, combining a modification of air inlets distribution, with an additional modification of air outlets distribution.

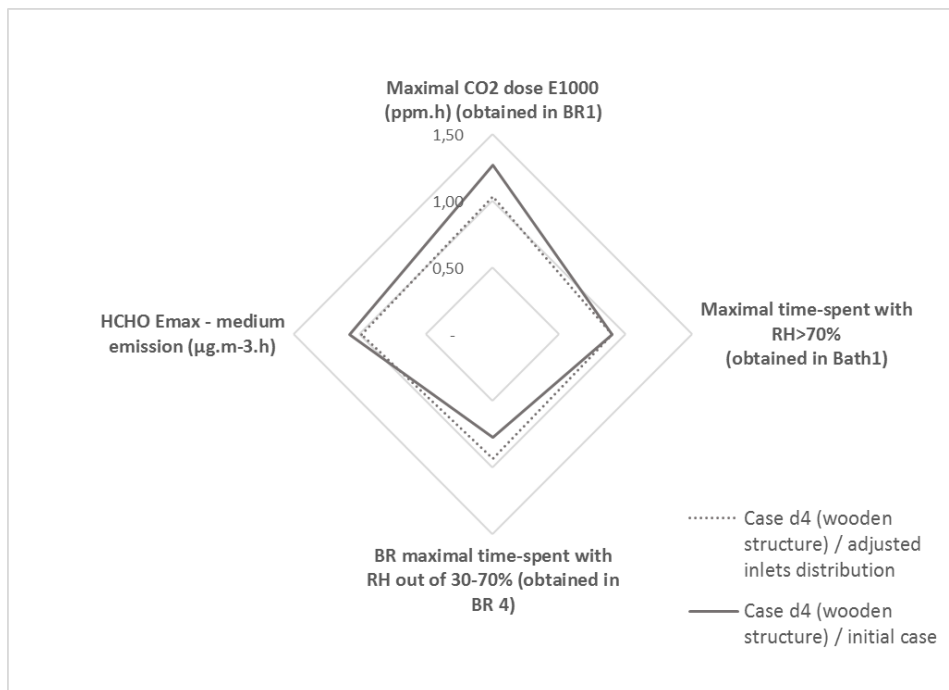


Figure 11. IAQ performance radar obtained while adjusting air inlets distribution.

5.3.5.3.2 *Setting each of the ventilation airflows*

So far, we used the IAQ performance-based method, considering ventilation airflows set according to a prescriptive regulation requiring for this study case house a total extract airflow of 135 m³.h⁻¹ during basic mode and of 225 m³.h⁻¹ during peak mode.

We could also consider a performance-based approach taken to its logical conclusion. The hypothetical regulation/ code/ standard would not set ventilation airflows but only IAQ performance indicators. Rooms ACR and/or airflows at in- and out-lets would also be intermediate performance indicators which could be easier measured in-situ if a control at commissioning would be required. The analysis tools developed during this PhD thesis are not yet optimized for this purpose but is ready to become it as a perspective.

5.4 Complementary discussion

5.4.1 *Quantifying the benefits of a multi-zone approach*

Based on a literature review, we proposed in section 5.1.3.1 that such a performance-based approach should be based on a multizone simulation. To quantify the impact of this assumption, we used the metric proposed by Hodgson, et al. (2004) as described in the section 5.1.3.1.1: **the average fractional difference (called FD)**. It is defined as the difference between two values (one in a room, one in another room) divided by the average of the two. FD takes a value of 0% for two equal values, 67% if one is the double of the other one, and is 50% if one of the both values is zero. The advantage of this method is to quantify the non-uniformities between rooms obtained in a multizone simulation, without additional assumptions due to the use of a new single-zone simulation.

We performed the calculation on several performance indicators, including ACR, CO₂ cumulative exposure exceeding 1000 ppm and average concentration, time-spent with RH higher than 70% (condensation risk indicator), time-spent with RH out of the range 30-70%, average formaldehyde concentration.

We calculated the average fractional difference between the living-room and the main bedroom (called FD1), and between the main bedroom and other bedrooms (called FD2,i). We used the maximal one (called FD2) and identified the bedroom in which it was obtained in Table 26. Results are given in Table 26. We used for formaldehyde the high-class emission rate. Formaldehyde occupant exposure is not on Table 26 since this is not a per room-calculated indicator.

			ACR	Average CO ₂ Concentration	CO ₂ dose E ₁₀₀₀	Time-spent with RH>70%	Time-spent out of 30-70%	Average BR HCHO Concentration (high-class emission)
case d2-heavy	Exhaust-only	FD1	15%	-18%	-36%	10%	20%	-12%
case d2-heavy	Exhaust-only	FD2	3%	-14%	-21%	-45%	18%	-6%
			<i>BR2</i>	<i>BR4</i>	<i>BR4</i>	<i>BR4</i>	<i>BR4</i>	<i>BR3</i>
case d4-wooden	Exhaust-only	FD1	15%	-19%	-37%	12%	20%	-9%
case d4-wooden	Exhaust-only	FD2	8%	-15%	-23%	-45%	18%	-5%
			<i>BR2</i>	<i>BR4</i>	<i>BR4</i>	<i>BR4</i>	<i>BR4</i>	<i>BR3</i>
case d2-heavy	Balanced	FD1	1%	-6%	-23%	30%	1%	5%
case d2-heavy	Balanced	FD2	1%	-9%	-19%	-50%	11%	6%
			<i>BR3</i>	<i>BR4</i>	<i>BR4</i>	<i>BR4</i>	<i>BR4</i>	<i>BR4</i>
case d4-wooden	Balanced	FD1	1%	-5%	-23%	29%	1%	6%
case d4-wooden	Balanced	FD2	4%	-10%	-19%	-50%	11%	7%
		<i>bedroom</i>	<i>BR3</i>	<i>BR4</i>	<i>BR4</i>	<i>BR4</i>	<i>BR4</i>	<i>BR4</i>

Table 26. Average fractional difference between the main bedroom and the living room (FD1) and between the main bedroom and another bedroom (FD2), with exhaust-only and balanced ventilation, for several performance indicators.

Table 26 shows that:

- FD are rather low on the ACR (maximum 15%) and are lower with balanced ventilation system (4%),
- Even if FD are low on ACR, they can be high (maximum 50%) on IAQ performance indicators,
- FD1 between the living room and the main bedroom can be higher than FD2 between two bedrooms (for instance: CO₂-cumulative exposure) for but the contrary is also observed, depending the type of ventilation and the observed IAQ indicator (for instance: condensation risk indicator),
- FD are higher on the CO₂-cumulative exposure (maximum -37%) than on the average concentration (-19%), It confirms that this latest performance indicator can also be considered as less relevant than the ones identified in section 5.1.1.3,
- FD are also rather low on average formaldehyde concentration (maximum -12%). It confirms that this latest performance indicator can also be considered as less relevant than the ones identified in section 5.1.1.3.

We can also notice, comparing cases d2 and d4 calculated FD, that changing the internal partition wall airleakage has a low impact on quantified non-uniformities between rooms.

As a result, we confirm with this analysis that a performance-based approach for ventilation in residential buildings should use a multizone approach able to model those IAQ disparities between rooms.

5.4.2 *About the non IAQ equivalence of “reference” systems*

Part 2 of this thesis showed that in the field of performance-based approach used for residential smart ventilation, there are two possibilities of assessing the ventilation performance:

- Either the indicators can be compared to absolute given thresholds, as in France, the Netherlands and Spain. We propose this approach in this work.
- Or they can be compared to obtained values with “reference” ventilation systems, to be sure they are at least “IAQ equivalent”, i.e, they give at least the same IAQ level, as in the ASHRAE 62.2 standard (USA) and Belgium.

“Reference” ventilation systems are usually defined as the widely used ventilation systems, or the ventilation systems directly providing the constant airflows required by the regulation. There is rarely only one reference system. As reviewed in the Part 2 of this thesis, the Belgium regulation for demand control ventilation is based on the comparison to three reference systems: A=natural ventilation, C=exhaust-only ventilation, D=balanced ventilation. In France, the three reference ventilation systems for houses would be the balanced ventilation and the exhaust-only ventilation system, providing directly the constant airflows of the airing regulation (even if they are rarely installed in new dwellings), and the humidity based ventilation system “Hygro B” (having published “Avis technique” agreements and widely installed in new dwellings).

We also analyzed in this section how the studied ventilation systems were - or not- equivalent in this case study, from an ACR and an IAQ point-of-view.

From an ACR point-of-view, we give in Table 27 the ACR for the envelope, the bedrooms and the Bath1, as this bathroom has been pointed out as being the one with higher condensation risk.

On the one hand, impact of envelope airtightness is larger with the balanced ventilation system, involving an envelope ACR of 0.48 h^{-1} , i.e 10% higher than with the exhaust-only ventilation system.

On the other hand, depending the ventilation system, bedrooms ACR are strongly different, with a gap between 45% (BR4) to 69% (BR1). Humid rooms are not impacted as their ACR is controlled by the exhausting devices.

We can conclude that the both reference ventilation systems are not equivalent from an ACR point-of-view.

Structure type	Ventilation type	Envelope ACR (h ⁻¹)	BR1 ACR (h ⁻¹)	BR2 ACR (h ⁻¹)	BR3 ACR (h ⁻¹)	BR4 ACR (h ⁻¹)	Bath1 ACR (h ⁻¹)
case d2-heavy	Exhaust-only	0.44	0.40	0.46	0.43	0.42	3.74
case d4-wooden	Exhaust-only	0.44	0.38	0.54	0.42	0.45	3.74
case d2-heavy	Balanced	0.48	0.65	0.68	0.68	0.61	3.74
case d4-wooden	Balanced	0.48	0.65	0.70	0.68	0.63	3.74

Table 27. Envelope and rooms ACR for cases d2 and d4, with balanced or exhaust-only ventilation.

From an IAQ point-of-view, we highlighted in Part 4, that pollutants concentrations are not only correlated with rooms ACR. Indeed, these detailed pathways throughout the internal partition wall airleakage result in entering air coming from different polluted connected rooms. As a result, pollutant concentrations are different in every room, even if sometimes ACR are close. So that, the non-equivalence of the reference from an ACR point-of-view would no necessary results in a non-equivalence from an IAQ point-of-view, at least not on the same magnitude.

The radar Figure 10 revealed that the both studied ventilation systems don't result in two identical radars, and none of the vertex neither. The relative gaps are 68% on the maximal CO₂ dose indicator (BR1), 32% on the condensation risk indicator (Bath 1), 30% on the RH health indicator and 26% on the formaldehyde dose. We can conclude that, even if they provide the same total extracted ventilation airflow of 135 m³.h⁻¹, with the same extracted airflow in each wet room, two reference ventilation systems are not equivalent from an IAQ point-of-view neither.

We highlight here a key issue for performance-based approaches, and notably for those taken at the ventilation system scale. In this context, we should compare an innovative system, for instance a smart ventilation system, to the reference systems. As they are not equivalent, a relevant solution would be to compare the performance indicators obtained with this innovative system, to the ones obtained with all the reference systems. The innovative system should be at least as IAQ-performant than the worst of the reference systems.

5.5 Part 5 conclusion

In this last part of the PhD thesis, we proposed a performance-based approach to be used at the design stage of a given residential building, during the regulatory compliance stage. It could be called a design assessment method.

We described and proposed the method with three steps. In the first step, we identified from a literature review five relevant IAQ performance indicators to be used as output data of such an approach:

- the maximum cumulative exceeding CO₂ exposure over 1000 ppm in the bedrooms,
- the maximum cumulative occupant formaldehyde exposure,
- the maximum cumulative occupant PM_{2.5} exposure,
- the maximum of the percentage of time with RH higher than 70% in all rooms (condensation risk),
- the maximum of the percentage of time with RH outside of the range [30%–70%] in the bedrooms (health risk).

In the second step, we proposed pollutant emission data and occupancy schedules to be used, from an extensive review. Face to the lack of data, we focus on chronic exposure and gave up at the moment PM_{2.5}. We proposed a method to calculate average constant formaldehyde emission rates and applied it on a sample of ten low-energy houses. As a result, we proposed to use three levels of formaldehyde emissions: the low-emission class: 4.5 µg.h⁻¹.m⁻², the medium-emission class: 12.0 µg.h⁻¹.m⁻², the high-emission class: 23.6 µg.h⁻¹.m⁻². We also proposed emission data and associated schedules for relative humidity and CO₂.

In the third step, we described the modelling laws and assumptions to be used. We showed notably that it was essential to use multizone modelling. Then, we describe the physical model and its resolution, the building modelling, and the boundary conditions to be used in such an approach.

Then, we showed that this method was applicable. Indeed, we applied the proposed performance-based approach on a case study, a low-energy house. We assumed being at the design stage of this house which must comply with a hypothetical regulation, code or label, requiring to calculate the proposed IAQ ventilation performance indicators according to the proposed method. We showed that the method allows to assess the IAQ performance through a radar scheme. We also demonstrated how such an approach could help at the design stage in key choices as the type of structure (regarding its impact on airleakage distributions), the type of ventilation system, the level of pollutant emissions. Indeed, in the studied case, only the balanced ventilation combined with low or medium-emission class of formaldehyde emissions allow to fulfill the IAQ requirements.

We showed also that such an approach could help in the ventilation design, notably the distribution of the air inlets and/or outlets. We showed that with the same total exhaust airflow it was possible to adjust these distributions to fulfill the IAQ requirements.

Lastly, we proposed also a complementary discussion about the non-equivalence of “reference” ventilation systems. “Reference” ventilation systems being usually defined as the widely used ventilation systems, or the ventilation systems directly providing the constant airflows required by the regulation. We showed also that both studied reference ventilation systems: balanced and exhaust-only ventilation system, were not IAQ equivalent with relative gaps between 26 and 70% depending the indicators.

General conclusion and perspectives

This work allows to fulfill the two initially set objectives:

1. Quantify impacts of a multizone modelling taking into account unevenly distributions of envelope and internal partition walls airleakage on the ventilation performance assessment,
2. Develop a performance-based approach for ventilation to be used at the design stage of a low energy house.

6.1 Quantify impacts of a multizone modelling taking into account unevenly distributions of envelope and internal partition walls airleakage on the ventilation performance assessment.

We referred in the introduction to some experimental studies showing that envelope airleakage was not evenly distributed and that internal airleakage was unneglectable and which suggested that additional research was needed both:

- to get precise data on these uneven external and internal airleakage distributions,
- to quantify their impacts on IAQ.

In Part 3 of this thesis, we built an original detailed database including air leakage of 456 exterior and internal partition walls measured in 23 detached houses, most of them being low-energy ones. Those measurements clearly contradict the assumption that envelope airleakage is evenly distributed, as often claimed in energy performance calculations used in energy regulations. Measurements also show that internal partition air leakage is significant compared to door undercuts. Indeed, the median value can reach 120 cm² for a two-level wooden structure. As a conclusion of this analysis, we recommended input values on envelope and internal partition wall air leakage to be used in dwellings multizone IAQ models, depending their structure type (wooden structure / heavy structure).

Then, in Part 4, we quantified the impacts of detailed envelope and internal partition wall airleakage distributions on the ventilation IAQ performance of a low-energy house. We studied seven airleakage

cases based on seven different airleakage distributions. We assumed two types of constant-airflow ventilation: exhaust-only and balanced ventilation, both complying with the French airing regulation. We used a multizone modelling approach performed with CO₂, humidity and formaldehyde to calculate IAQ performance indicators in each room over the heating period. We used three constant levels of formaldehyde emissions (4.5–12.0 and 23.6 µg.m⁻²). We observed that impacts on the IAQ indicators depend strongly upon the ventilation system and the type of structure and are generally higher with exhaust-only ventilation and with a wooden structure.

A detailed envelope airleakage distribution has a large impact on the bedroom ACRs (maximum, -24.3%) with exhaust-only ventilation. Maximum impacts on the CO₂ and RH indicators and formaldehyde concentrations are strong with the exhaust-only ventilation, respectively up to 31%, 39% and 27%, respectively. With balanced ventilation, they are negligible on CO₂ indicators and formaldehyde concentrations, respectively 2.6% and 1.8%, but considerable on RH indicators, up to -10%. Impacts on maximum formaldehyde exposure are negligible whatever ventilation system is used (up to -5% only).

The impact of internal partition wall airleakage is low on the envelope ACR (maximum, -5.5%), but high on bedroom ACRs (up to 28% with exhaust-only and balanced ventilation). Stronger impacts are observed with exhaust-only ventilation on CO₂ and RH indicators and formaldehyde concentrations, respectively up to 49%, -54% and 39%, than with balanced ventilation, respectively up to 15%, -18% and -1.7%. Impacts on maximum exposure are significantly lower for all the ventilation systems (up to -9% only).

We concluded that impacts of unevenly distributed envelope airleakage on selected IAQ performance indicators are generally significant for either ventilation system. The impact of internal partition wall airleakage is generally greater with exhaust-only ventilation but can be strong on some IAQ indicators (bedroom ACR, RH) with balanced ventilation as well.

Moreover, we highlighted that there is no direct relation between the envelope ACR, bedroom ACRs and pollutant concentrations, because these concentrations have a complex dependence upon the air pathways through the house. We observed that the main rooms and the cases where impacts on bedroom ACRs are the highest are not the same as the rooms where impacts on IAQ indicators are the highest. Indeed, considering internal airleakage involves short-circuits and complex air pathways through the house and between rooms. Pollutants are also diluted in some zones and concentrated in others, given that the envelope ACR remains nearly constant. As a result, impacts on evenly emitted pollutants such as formaldehyde are lower than others. Moreover, with balanced ventilation, supplying the same airflow rate in each bedroom contributes to decreasing the effects of short-circuits on concentrations.

Conclusions on the performance indicators' relevance for ventilation performance assessment could also be addressed based on this analysis, since we showed that some indicators are not adapted to demonstrating the impacts that others are able to show, for instance the Icone index or the whole building ACR. Hence, to assess the performance of a ventilation system different indicators should be used: bedroom ACRs should be complemented with at least one "constant emission" pollutant such as formaldehyde and with at least one "variable emission" pollutant such as humidity (for both health and condensation risk).

In conclusion:

1. We confirmed the need of multizone models for assessing ventilation IAQ performance at the room scale, especially in bedrooms, not only at the whole building scale,
2. We also highlighted the need for using detailed input data for envelope and internal partition wall airleakage, especially for wooden structures with exhaust-only ventilation systems, to go beyond the simplifying assumption of even distributions,
3. We proposed detailed input data for envelope and internal partition wall airleakage to be used,
4. We were able to identify some relevant IAQ performance indicators.

6.2 Develop a performance-based approach for ventilation to be used at the design stage of a low energy house

Based on an extensive review of literature and ventilation regulations, notably in the residential smart ventilation field (Part 2 and Part 5), and on complementary analysis (Part 4), we developed and proposed in Part 5 a performance-based approach to be used at the design stage of a given residential building, during the regulatory compliance stage. The proposed method could be called a “design assessment method”.

We described the method with three steps. In the first step, we identified from a literature review five relevant IAQ performance indicators to be used as output data of such an approach, based on CO₂, formaldehyde and PM_{2.5} exposures, and RH-based indicators assessing both condensation and health risks. We proposed to keep the air change rate indicator as an intermediate performance indicator, if such a performance-based approach at the design stage would be combined with in-situ measurements at initial commissioning or later during building’s life. In the second step, we proposed pollutant emission data and occupancy schedules to be used. Face to the lack of data, we focused on chronic exposure and temporarily excluded PM_{2.5}. In the third step, we described the modelling laws and assumptions to be used, highlighting multizone modelling. We described the physical model, the building modelling, and the boundary conditions to be used in such an approach.

Importantly, we demonstrated that our proposed method was applicable, applying it to a low-energy house. We assumed being at the design stage of this house which should comply with a hypothetical regulation, code or label, requiring to calculate the proposed IAQ ventilation performance indicators. It was possible to assess the IAQ performance through a radar scheme. We also demonstrated how such an approach could help at the design stage in key choices as the type of structure (regarding its impact on airleakage distributions), the type of ventilation system, the level of pollutant emissions. Indeed, in the studied case, only the balanced ventilation combined with low or medium-emission class of formaldehyde emissions allow to fulfill the IAQ requirements.

We showed also that such an approach could help in the ventilation design, notably the distribution of the air inlets and/or outlets. We showed that with the same total exhaust airflow it was possible to adjust these distributions to fulfill the IAQ requirements.

6.3 Additional issues

Additional issues were also addressed in this PhD thesis.

We highlighted the lack of data on pollutant emissions rates at the building scale. Facing a lack of data, we proposed a method to calculate average constant formaldehyde emission rates and applied it on a sample of ten low-energy houses. As a result, we were able to propose and to use three levels of formaldehyde emissions: the low-emission class: $4.5 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, the medium-emission class: $12.0 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, the high-emission class: $23.6 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$. For instance, it would be possible to decide at the design stage of a new building:

- If only A-class IAQ labelled materials are used and there is an awareness of occupants, low-emission formaldehyde class can be used in the IAQ calculation.
- If no information is given, or only D-class IAQ labelling materials are used, high-emission formaldehyde class must be used.
- In other cases, medium-emission formaldehyde class can be used.

In addition, we proposed an extensive review of residential smart ventilation both IAQ and energy performances, and of the regulations throughout the world (Spain, France, The Netherlands, Belgium, USA) concerning this type of emerging ventilation.

We proposed also a complementary discussion about the non-equivalence of “reference” ventilation systems. “Reference” ventilation systems being usually defined as the widely used ventilation systems, or the ventilation systems directly providing the constant airflows required by the regulation. We showed that the both studied reference ventilation systems: balanced and exhaust-only ventilation systems, are not IAQ equivalent with relative gaps between 26 and 70% depending the indicators.

6.4 Limitations and perspectives

At the end of this thesis, several limitations and perspectives could be highlighted.

Facing a lack of data on pollutant emissions rates at the building scale, it was not possible to include $\text{PM}_{2.5}$ and peak exposure in our approach, but it should definitively be completed later as soon as additional data are published. The three classes we proposed for formaldehyde emission rates should be readjusted with a larger sample of houses, for instance from the French IAQ observatory (OQAI). Our sample is indeed rather small (10 houses) and our results need further validation. Therefore, we hope the method we developed to calculate average constant formaldehyde emission rates could be used in future publications and works.

Our study on IAQ impacts of uneven airleakage distributions on envelope and internal partition walls should now be further investigated. We should implement more house geometries, different types of ventilation systems, including smart ones, different levels of ventilation airflows, different levels of envelope airleakage, ... to study how it could impact our primary conclusions. Moreover, CO_2 and temperatures measurements have been carried out during 2 years on the studied house equipped with a weather station. Those data should now be used for a comparison with modelling results.

We showed that the proposed performance-based approach for ventilation was already applicable on houses equipped with constant-airflow reference ventilation systems. We should now check the

applicability of our method when applied to smart ventilation systems, as the humidity-based one being also a reference system for France.

From a general perspective, this would be now suitable to study how such a performance-based method at the design stage of a building, could be combined with IAQ or airflows in-situ measurements, to secure the performance at initial commissioning and its sustainability for the whole residential building life. We are thinking to two special issues.

Firstly, we showed how the method could allow to adjust the air inlets distribution in order to fulfill IAQ requirements with the same total exhaust airflow. It should be outlined that *in situ* ventilation performance has been reported to be rather low in the literature, with often a high non-compliance rate (Boerstra, 2012; Caillou et al., 2012; Jobert and Guyot, 2013; Guyot et al., 2017a). So that, already with very simple ventilation installations (same trickle ventilator module for each bedroom), we can notice several malfunctions. We proposed in this work to adapt air inlets distribution. This was almost all to illustrate how the method could help to assess IAQ ventilation performance and notably to show that the whole house extracted ventilation airflows was not necessary a good IAQ indicator. But we have in mind that it would not be applicable, at least temporarily. In conclusion on this point, every change in ventilation design practices should be secured with a change in ventilation installation practices ...

Secondly, in this work, we illustrated how the method could help in key design choices, considering ventilation airflows set according to a prescriptive regulation. We could also consider a performance-based approach taken to its logical conclusion. The hypothetical regulation/ code/ standard would not set airflows but only IAQ performance indicators. The analysis tools developed during this PhD thesis are not yet optimized for this purpose but could but may become it as a perspective. In such an approach, it will be however difficult to imagine an IAQ in situ check at initial commissioning. Indeed, pollutant emission scenarii took into account in the method are not necessary the ones of the “real life”. Notably, if occupant would add a lot of pollutant indoor sources in their house, the IAQ check will be bad, but it will not necessary reflect that the ventilation does not work well. Moreover, some of the proposed indicators, based on exposures, are difficult to be measured on a short period and need to get precise data about occupant schedules. For all those reasons, ACR and airflows at in- and out-lets would be very useful intermediate performance indicators. Indeed, relevant and reliable protocols have been developed (Bailly and Berthault, 2016) including not only measurements but also a visual inspection.

Lastly, ventilation performance has been restricted to IAQ performance in this work. It is absolutely necessary to extend our method to the global performance of a building, including the energy performance issue, the indoor environment quality (not only IAQ but also comfort ...), life-cycle and environmental performance...

7

Publications

7.1 Journal publications (2013 – 2018)

- Ancelet, S., Baysson, H., Dereumeaux, C., Fervers, B., **Guyot, G.**, Hanoune, B., Laurent, O., Laurier, D., Likhvar, V., Medina, S., Pascal, M., Rigou, A., Mandin, C., 2013. Conférence Environnement Santé, 19-20 août 2013. Environnement, Risques & Santé 12, 539–545. <https://doi.org/10.1684/ers.2013.0668>
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- Guyot, G.**, Geoffroy, H., Ondarts, M., Migne, L., Bobee, M., Lesage, A., Woloszyn, M., Gonze, E., 2018. Impact of multizone air leakage modelling on ventilation performance and indoor air quality assessment in low-energy houses. Submitted.
- Guyot, G.**, Melois, A., Bernard, A.-M., Coeudevez, C.-S., Déoux, S., Berlin, S., Parent, E., Huet, A., Berthault, S., Jobert, R., Labaume, D., 2017. Ventilation performance and indoor air pollutants diagnosis in 21 French low energy homes. International Journal of Ventilation 0, 1–9. <https://doi.org/10.1080/14733315.2017.1377393>
- Guyot, Gaëlle**, Sherman, M.H., Walker, I.S., 2018a. Smart ventilation energy and indoor air quality performance in residential buildings: A review. Energy and Buildings 165, 416–430. <https://doi.org/10.1016/j.enbuild.2017.12.051>
- Guyot, Gaëlle**, Walker, I.S., Sherman, M.H., 2018b. Performance based approaches in standards and regulations for smart ventilation in residential buildings: a summary review. International Journal of Ventilation 0, 1–17. <https://doi.org/10.1080/14733315.2018.1435025>

7.2 Publications in conference proceedings (2013 – 2018)

- Bailly, A., **Guyot, G.**, Leprince, V., 2016a. 6 years of envelope airtightness measurements performed by French certified operators: analyses of about 65,000 tests, in: Proceedings of the 12th REHVA World Congress CLIMA 2016. Aalborg, Denmark.
- Bailly, A., **Guyot, G.**, Leprince, V., 2016b. Analyses of about 90 000 Airtightness Measurements Performed in France on Residential and Non-Residential Buildings from 2008 to 2014, in: Proceedings IAQ 2016 Defining Indoor Air Quality: Policy, Standards and Best Practices Co-Organized by ASHRAE and AIVC. Alexandria, VA, USA.
- Bailly, A., **Guyot, G.**, Leprince, V., 2015. 6 years of envelope airtightness measurements performed by French certified operators: analyses of about 65,000 tests, in: Proceedings of the 36th AIVC Conference “ Effective Ventilation in High Performance Buildings.” Madrid, Spain.
- Bailly, A., Jiang, Y., **Guyot, G.**, Desfougères, F., 2013. Preliminary analysis of French buildings airtightness database, in: Proceedings of the 34th AIVC-3rd TightVent-2nd Cool Roofs’-1st Venticool Conference. Athens, Greece, pp. 25–26.
- Charrier, S., **Guyot, G.**, Jobert, R., Carrié, F.R., Coeudevez, C., 2018. Development and test of quality management approach for ventilation and indoor air quality in single-family buildings, in: Smart Ventilation for Buildings. Presented at the AIVC Conference 2018, Juan les Pins, France.
- Geoffroy, H., **Guyot, G.**, Ondarts, M., Woloszyn, M., Gonze, E., 2018. Développement d’une approche performantielle de la qualité de l’air - Impact d’une prise en compte fine des distributions de perméabilité à l’air externe et interne sur la modélisation multizone d’une maison basse consommation, in: IBPSA France - Garantie de Performance. Bordeaux, France, p.
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9

Appendices

9.1 - Modelling moisture buffering effect in CONTAM: identification of input parameters using the Duforestel's model

9.2 - Detailed information about used airleakage distributions and ventilation scenarii in cases a, b, c, d, d2, d3, d4, with exhaust-only ventilation and with balanced ventilation.

9.1 Modelling moisture buffering effect in CONTAM: identification of input parameters using the Duforestel's model

9.1.1 Overview of three lumped-capacity-type methods

Modelling humidity transfers in dwellings should take into account the moisture buffering effect to be precise and representative (Plathner, 2002; Steeman et al., 2009; Van den Bossche et al., 2007; Woloszyn et al., 2009a).

There are several more or less accurate lumped-capacity-type methods described in the literature to simulate this effect (Woloszyn et al., 2009b), for example, the equivalent absorbing area (CCFAT, 2015), the boundary layer diffusion model (Axley, 1991; White, 1988) used in CONTAM (Dols and Polidoro, 2015) and the moisture buffering model (Duforestel and Dalicieux, 1994). We describe here these three methods.

The equivalent absorbing area is a method used in the French agreement procedure for humidity demand-controlled ventilation (CCFAT, 2015). The method gives for all types of room the entry data to be used. They are expressed as an equivalent surface area (A_{eq}), having an equivalent moisture buffering action as the whole materials and furniture in this type of room. The equation used in this method is described in (Equation 16) found in (Koffi, 2009) but not described in (CCFAT, 2015). This method is very simple to use but is based on very simplified assumptions. The input data given in this method are: 2m² for the hall, 25m² for the living room, 15m² for the bedrooms, and 0m² for all the humid-rooms.

$$\frac{dm_{mob}}{dt} = 0,035 \cdot A_{eq} \cdot \varphi - 0,018 \cdot m_{mob}$$

(Equation 16)

Where: m_{mob} is the water mass buffered in the room [kg], A_{eq} is the equivalent surface area [m²], φ is the relative humidity [-]. Given the non-homogeneity of the equation, we assume the first constant (0.035) to be in [kg.m⁻².h⁻¹], and the second one (0.018) in [h⁻¹].

The boundary layer diffusion model (Axley, 1991) also used in CONTAM (Dols and Polidoro, 2015) describes the mass transfer between the ambient air and the surface based on some simplifications of the boundary layer theory (White, 1988). Firstly, this model supposes state equilibrium at the border between the gas and the solid surface due to a quasi-immediate adsorption. Secondly, that the heat production caused by the adsorption could be neglected and isothermal system assumed. In our case, assuming that the concentration in the material is uniform, the mass transfer becomes a function of the concentration and the field velocity, as shown by (Equation 17).

$$S_{\alpha}(t) = ctrl.h.d.A_s \cdot (C_{\alpha}(t) - \frac{C_s(t)}{k})$$

(Equation 17)

Where: $S_{\alpha}(t)$ is the source of contaminant α (in our case the humidity) at time t [$\text{kg}_{\alpha}\cdot\text{s}^{-1}$], $ctrl$ is the schedule [no unit], h is the average film mass transfer coefficient over the sink [$\text{m}\cdot\text{s}^{-1}$], d is the film density of the air [$\text{kg}_{\text{air}}\cdot\text{m}^{-3}$], A_s is the surface area of the adsorbent [m^2], C_{α} is the concentration in the air [$\text{kg}_{\alpha}\cdot\text{kg}_{\text{air}}^{-1}$], C_s is the concentration in the adsorbent [$\text{kg}_{\alpha}\cdot\text{kg}_{\text{surf}}^{-1}$], K is the Henry adsorption coefficient or the partition coefficient [$\text{kg}_{\text{air}}\cdot\text{kg}_{\text{surface}}^{-1}$].

Lastly, the moisture buffering model of (Duforestel and Dalicieux, 1994) assumes that the effect of adsorption, restitution of all hygroscopic materials in a room, can be represented as a fictive two-depth buffer. The first layer would be the buffer's surface, exchanging with the ambient air and with the second layer called the buffer's heart. The second layer exchanges with the buffer's surface only. In this model, the moisture density in the first layer is variable, but the buffer's heart moisture concentration is assumed to be constant. In reality, this inside moisture density is variable between different cases or seasons. Nevertheless, as the inside moisture evolution is very slow, this assumption can be useful for short time simulation. This model is described in Table 28 and by the (Equation 18). Input parameters to be used in Duforestel's model for low- and high-absorption rooms are given in Table 28. Those parameters are experimentally determined global room hygroscopic coefficients.

$$\frac{d\rho_{vap,surf}(t)}{dt} + (\eta_{vap} \cdot \alpha_{vap} + \lambda_{vap}) \cdot \rho_{vap,surf}(t) - \eta_{vap} \cdot \alpha_{vap} \cdot \rho_{vap,int}(t) = \lambda_{vap} \cdot \rho_{vap,heart}$$

(Equation 18)

Where: $\rho_{vap,surf}$ is the vapor density on the buffer's surface [$\text{kg}\cdot\text{m}^{-3}$], $\rho_{vap,int}$ is the vapor density in the room [$\text{kg}\cdot\text{m}^{-3}$], $\rho_{vap,heart}$ is the vapor density in the buffer's heart [$\text{kg}\cdot\text{m}^{-3}$], η_{vap} is a transfer coefficient [h^{-1}], λ_{vap} is a transfer coefficient [h^{-1}], α_{vap} is a parameter about the surface capacity [no unit], t is the time in [h].

Type of furniture	η_{vap} [h^{-1}]	α_{vap} [-]	λ_{vap} [h^{-1}]
High-absorption room	2.903	0.3	0.3025
Low-absorption room	4.478	0.175	0.05495

Table 28. Input parameters to be used in Duforestel's model for low- and high-absorption rooms. Source: (Duforestel and Dalicieux, 1994)

We can also notice that Duforestel has also proposed a more sophisticated model, described in (Peuportier et al., 2015), which is not developed here. In this other model "the heart" have also a variable capacity.

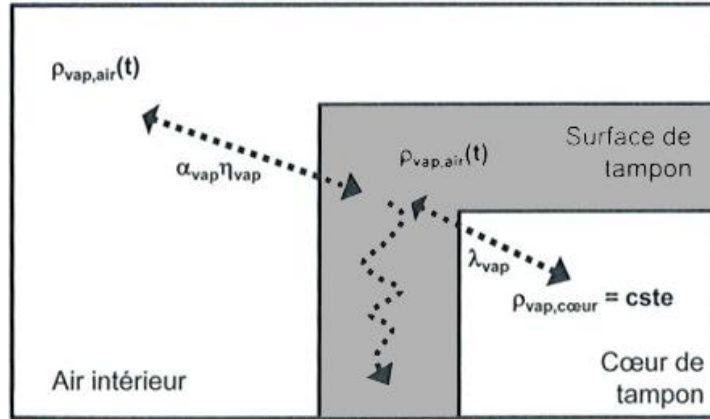


Figure 12. Scheme explaining the moisture buffering model of (Duforestel and Dalicieux, 1994).
Source : (Peuportier et al., 2015)

9.1.2 Modelling parameters identification: method

The latter moisture buffering model of (Duforestel and Dalicieux, 1994) has been shown to satisfactorily represent the joint effect of furniture and construction materials in real houses (Plathner and Woloszyn, 2002). Therefore, it has been selected for our study. Its general principle (lumped capacity) is similar to the model already implemented in CONTAM. However, the main variables and corresponding parameters are different. Consequently, preliminary simulations were needed to model Duforestel's moisture buffer correctly using the Axley's equation implemented in CONTAM.

To this aim, we recreated a case study. This case study is a 16.3 m³ - volume room with an air change rate of 0.5 vol.h⁻¹, an inside temperature of 20°C and an outside water weight of 5 g.m⁻³, with a water production of 53 g.h⁻¹ during 8 hours every 24h. This case was duplicated with two types of room: high-absorbing (bedroom, kitchen and living room...) and low-absorbing room (bathroom and WC).

We used analytical solution of the Duforestel model as the reference. Then, using a least-squares method, we fitted the three parameters of the Axley equation to be used in CONTAM: the film mass transfer coefficient "h", the Henry adsorption constant "k" and "A" a surface mass (Table 24). In this annex, we give more details about this parameter identification.

The evolution of the inside moisture concentration in a room according to the Duforestel model can be expressed thanks to the water mass balance in the zone, **Erreur ! Source du renvoi introuvable.** Equation 19.

$$\frac{d\rho_{vap,int}(t)}{dt} = \rho_e \cdot n_e - n_s \cdot \rho_{vap,int} + p + \bar{h} \cdot (\rho_{vap,surf} - \rho_{vap,int})$$

Equation 19

With:

$\rho_{vap,surf}$ the vapor density on the buffer's surface [kg.m⁻³], $\rho_{vap,int}$ the vapor density in the room [kg.m⁻³], ρ_e the outdoor vapor density [kg.m⁻³], n_e the ACR calculated on entering air [h⁻¹], n_s the ACR

calculated on outgoing air [h^{-1}], p is vapor production mass flow by room volume unit [$\text{kg}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$], \bar{h} is a characteristic coefficient [h^{-1}], t is the time [h].

We can easily outline that the term $\bar{h}\cdot(\rho_{vap,surf} - \rho_{vap,int})$, is the source/sink term describing the moisture buffering effect.

Similarly, the source/sink term of the Axley's model $S_\alpha(t)$ given by the (Equation 17), can be included in the mass balance equation, Equation 19:

$$V \cdot \frac{d\rho_{vap,int}}{dt} = Q_e \cdot \rho_{out} - Q_s \cdot \rho_{vap,int} + P + S_\alpha(t) \quad (\text{Equation 20})$$

Where:

$\rho_{vap,int}$ is the vapor density in the room [$\text{kg}\cdot\text{m}^{-3}$], V is the volume of the room [m^3], ρ_{out} is the outdoor vapor density [$\text{kg}\cdot\text{m}^{-3}$], Q_e is the entering airflow [$\text{kg}\cdot\text{h}^{-1}$], Q_s is the outgoing airflow [$\text{kg}\cdot\text{h}^{-1}$], P is vapor production mass flow [$\text{kg}\cdot\text{s}^{-1}$].

Thanks to a least-squares method, and more particularly the Levenberg-Marquardt algorithm implemented in Matlab, we fit the values of the three inputs variables of the Axley model implemented in CONTAM, the film mass transfer coefficient " h ", the Henry adsorption constant " k ", and " A " a "surface mass", using the Duforestel model as a reference.

9.1.3 Modelling parameters identification: results

We decided to fit the better equilibrium on a simulation with maximal moisture emission duration of 10 hours, and not 8 hours as proposed in the Duforestel's case, because it was the longest production of our study according to the schedule. The Figure 14 gives the results of the simulation of adsorption phase in the high-absorbing room, and Figure 13 the results of the desorption. The Figure 16 and Figure 15 give the results for the low-adsorbing room.

They were obtained for the following values for the three parameters given in Table 24 sooner in the Part 5, and repeated just after.

Parameters	High-adsorbing room	Low-adsorbing room
Film mass transfer (h)	0.0051 $\text{m}\cdot\text{s}^{-1}$	0.0066 $\text{m}\cdot\text{s}^{-1}$
Henry adsorption coefficient or the partition coefficient (k)	331.6 $\text{kg}\cdot\text{kg}^{-1}$	300 $\text{kg}\cdot\text{kg}^{-1}$
Surface mass (A)	12.3% of the room volume	2.4% of the room volume

Table 24. Parameters calculated for the boundary layer diffusion model used in CONTAM

As we can see, obtained curves after parameter identification fit imperfectly but they give a good approximation of the inside relative humidity on our simulation time.

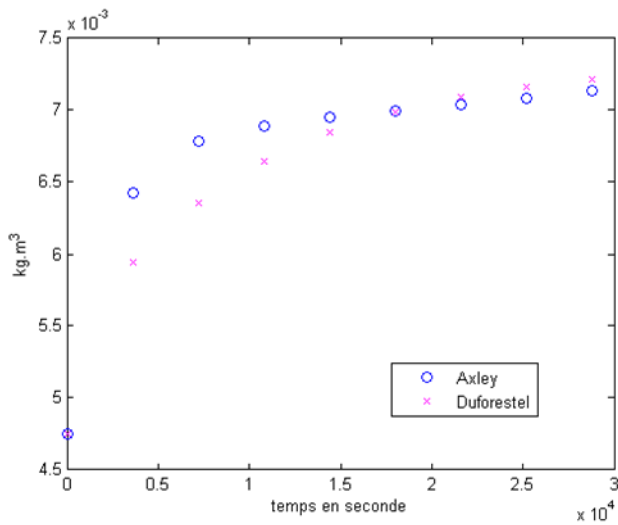


Figure 14 : Adsorbing room - adsorption results

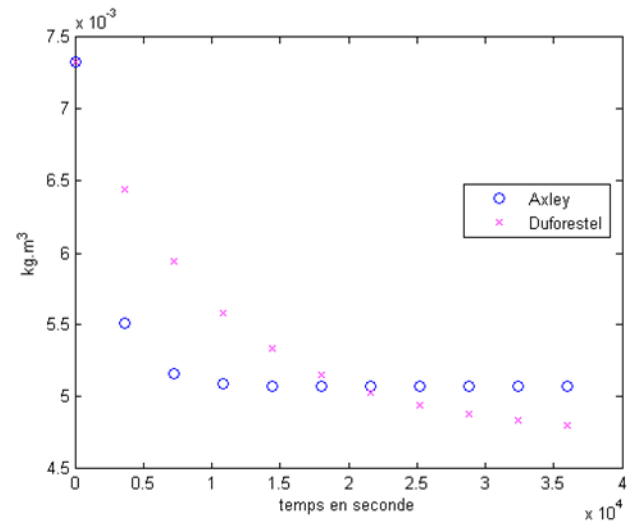


Figure 13 : Adsorbing room - desorption results

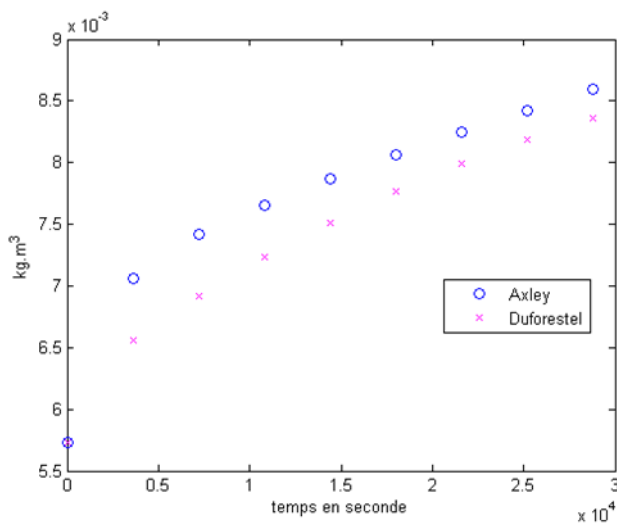


Figure 15 : Low-adsorbing room adsorption results

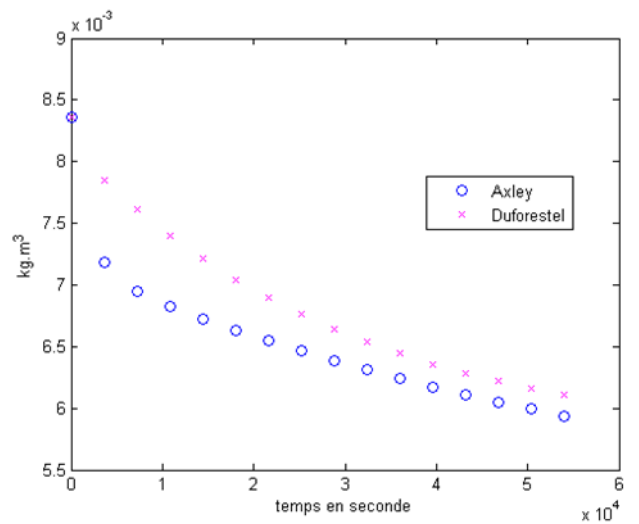


Figure 16 : Low-adsorbing room desorption results

9.1.4 Limits

Our parameters identification is valid only on periods shorter than ten hours.

Values used for the three parameters should not be considered as physically representative. They only come from a numerical identification.

Results from the Duforestel's model are valid only on the heating period.

9.2 Detailed information about used airleakage distributions and ventilation scenarii in cases a, b, c, d, d2, d3, d4, with exhaust-only ventilation and with balanced ventilation.

The following tables describe the values used as entry data in CONTAM for performing the simulations described in this thesis concerning:

- The doors undercuts,
- The ventilation airflows used with exhaust-only and balanced ventilation,
- The envelope airleakage distributions (cases b,c,d,d2,d3,d4),
- The internal airleakage distributions (cases b,c,d,d2,d3,d4).

Doors undercuts

Number of the air path - exhaust V	Number of the air path - balanced V	type	name	area (cm ²)	
15	17	porte	73B	73	<i>Power law - leakage are data (dP=10 Pa ;Cd=0.6 ; n = 0.65)</i>
17	19	porte	73B	73	<i>Power law - leakage are data (dP=10 Pa ;Cd=0.6 ; n = 0.65)</i>
18	20	porte	73B	73	<i>Power law - leakage are data (dP=10 Pa ;Cd=0.6 ; n = 0.65)</i>
24	26	porte	73B	73	<i>Power law - leakage are data (dP=10 Pa ;Cd=0.6 ; n = 0.65)</i>
26	28	porte	73B	73	<i>Power law - leakage are data (dP=10 Pa ;Cd=0.6 ; n = 0.65)</i>
49	52	porte	78B	78	<i>Power law - leakage are data (dP=10 Pa ;Cd=0.6 ; n = 0.65)</i>
52	59	porte	115B	115	<i>Power law - leakage are data (dP=10 Pa ;Cd=0.6 ; n = 0.65)</i>
53	60	porte	ENTREE	9	<i>Power law - leakage are data (dP=10 Pa ;Cd=0.6 ; n = 0.65)</i>
54	61	porte	73B	73	<i>Power law - leakage are data (dP=10 Pa ;Cd=0.6 ; n = 0.65)</i>
56	63	porte	73B	73	<i>Power law - leakage are data (dP=10 Pa ;Cd=0.6 ; n = 0.65)</i>

Ventilation airflows - Balanced ventilation

Number of the air path	type	zone	name	Q (kg/s)	Q (m ³ /h)
5	ventil	Bath2	EXTRACT	1,00E-02	30
34	ventil	WC2	EXTRACT	5,02E-03	15
47	ventil	K+LR	EXTRACT	1,51E-02	45 Base rate
46	ventil	K+LR	EXTRACT	4,52E-02	135 Peak rate (3 times a day)
67	ventil	Bath1	EXTRACT	1,00E-02	30
68	ventil	WC1	EXTRACT	5,02E-03	15
15	ventil	BR1	SUPPLY	6,45E-03	19,3 Base rate
16	ventil	BR1	SUPPLY	1,08E-02	32,1 Peak rate (3 times a day)
12	ventil	BR2	SUPPLY	6,45E-03	19,3 Base rate
13	ventil	BR2	SUPPLY	1,08E-02	32,1 Peak rate (3 times a day)
32	ventil	BR3	SUPPLY	6,45E-03	19,3 Base rate
33	ventil	BR3	SUPPLY	1,08E-02	32,1 Peak rate (3 times a day)
36	ventil	Mezz	SUPPLY	6,45E-03	19,3 Base rate
38	ventil	Mezz	SUPPLY	1,08E-02	32,1 Peak rate (3 times a day)
50	ventil	BR4	SUPPLY	6,45E-03	19,3 Base rate
51	ventil	BR4	SUPPLY	1,08E-02	32,1 Peak rate (3 times a day)
54	ventil	K+LR	SUPPLY	6,45E-03	19,3 Base rate
55	ventil	K+LR	SUPPLY	1,08E-02	32,1 Peak rate (3 times a day)
57	ventil	K+LR	SUPPLY	6,45E-03	19,3 Base rate
58	ventil	K+LR	SUPPLY	1,08E-02	32,1 Peak rate (3 times a day)

Ventilation airflows - Exhaust-only ventilation

Number of the air path	type	zone	name	Q (kg/s)	Q (m ³ /h)
7	ventil	Bath2	EXTRACT	0,010	30
30	ventil	WC2	EXTRACT	0,005	15
44	ventil	K+LR	EXTRACT	0,015	45 Base rate
45	ventil	K+LR	EXTRACT	0,045	135 Peak rate
60	ventil	Bath1	EXTRACT	0,010	30
61	ventil	WC1	EXTRACT	0,005	15
2	ventil	BR1	EA22	<i>Power law - test data (2 points)</i>	
5	ventil	BR2	EA22	<i>Power law - test data (2 points)</i>	
36	ventil	BR3	EA22	<i>Power law - test data (2 points)</i>	
38	ventil	Mezz	EA22	<i>Power law - test data (2 points)</i>	
41	ventil	BR4	EA22	<i>Power law - test data (2 points)</i>	
42	ventil	K+LR	EA22	<i>Power law - test data (2 points)</i>	
48	ventil	K+LR	EA22	<i>Power law - test data (2 points)</i>	

Ventilation airflows - Exhaust-only ventilation - variant 2 (adjusting air inlets distribution)

Number of the air path	type	zone	name	Q (kg/s)	Q (m ³ /h)
7	ventil	Bath2	EXTRACT	0,010	30
30	ventil	WC2	EXTRACT	0,005	15
44	ventil	K+LR	EXTRACT	0,015	45 Base rate
45	ventil	K+LR	EXTRACT	0,045	135 Peak rate
60	ventil	Bath1	EXTRACT	0,010	30
61	ventil	WC1	EXTRACT	0,005	15
2	ventil	BR1	5/3* EA22	<i>Power law - test data (2 points)</i>	
5	ventil	BR2	4/3 * EA22	<i>Power law - test data (2 points)</i>	
36	ventil	BR3	4/3 * EA22	<i>Power law - test data (2 points)</i>	
38	ventil	Mezz	0,44 * EA22	<i>Power law - test data (2 points)</i>	
41	ventil	BR4	4/3 * EA22	<i>Power law - test data (2 points)</i>	
42	ventil	K+LR	0,44 * EA22	<i>Power law - test data (2 points)</i>	
48	ventil	K+LR	0,44 * EA22	<i>Power law - test data (2 points)</i>	

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Envelope airleakage - case b (evenly distributed)

Number of the air path	Zones	surface area (m ²)	Multiplier	C _L (m ³ /s.Pa ⁻ⁿ)	n	Azimut angle (°)	C _p (-)	Path - height (m)
1	Bath2 / out (roof)	5,4	2,32E-02	1,10E-02	0,68	270	-0,7	0
3	BR1 / out	8,1	3,48E-02	1,10E-02	0,68	0	0,5	1,25
4	Bath2 / out (W)	4,6	1,96E-02	1,10E-02	0,68	0	0,5	1,25
6	BR2 / out (W)	8,1	3,48E-02	1,10E-02	0,68	0	0,5	1,25
11	BR2 / out (roof + N)	21,0	9,05E-02	1,10E-02	0,68	90	-0,7	1,875
12	BR1 / out (roof + S)	20,5	8,82E-02	1,10E-02	0,68	270	-0,7	1,875
25	BR3 / out (roof + S)	20,5	8,82E-02	1,10E-02	0,68	270	-0,7	1,875
28	Mezz / out (E)	12,5	6,39E-02	1,10E-02	0,68	90	-0,7	1,25
35	BR3 / out (E)	8,1	3,48E-02	1,10E-02	0,68	180	-0,7	1,25
37	WC2 / out (E)	5,5	2,38E-02	1,10E-02	0,68	180	-0,7	1,875
39	Mezz out (roof + N)	23,0	1,17E-01	1,10E-02	0,68	180	-0,7	1,875
40	K+LR / out (W)	13,8	7,04E-02	1,10E-02	0,68	0	0,5	1,25
43	BR4 / out (W)	9,1	3,90E-02	1,10E-02	0,68	0	0,5	1,25
47	BR4 / out (N)	10,0	4,31E-02	1,10E-02	0,68	90	-0,7	1,25
50	K+LR / out (S)	20,5	1,05E-01	1,10E-02	0,68	270	-0,7	1,25
59	WC1 / out (N)	3,9	1,66E-02	1,10E-02	0,68	90	-0,7	1,25
62	K+LR / out (E)	14,3	7,32E-02	1,10E-02	0,68	180	-0,7	1,25
63	Bath1 / out (E)	4,2	1,79E-02	1,10E-02	0,68	180	-0,7	1,25
64	WC1 / out (E)	3,7	1,58E-02	1,10E-02	0,68	180	-0,7	1,25

Envelope airleakage - cases c, d, d2, d3, d4 (unevenly distributed)

Number of the air path - exhaust V	Number of the air path - balanced V	Zones	surface area (m ²)	Multiplier	C _L (m ³ /s.Pa ⁻ⁿ)	n
1	1	Bath2 / out (roof)	5,4	0,54	2,00E-05	1,34
3	2	BR1 / out	8,1	0,28	4,17E-04	0,86
4	3	Bath2 / out (W)	4,6	0,46	2,00E-05	1,34
6	4	BR2 / out (W)	8,1	0,28	4,17E-04	0,84
11	9	BR2 / out (roof + N)	21,0	0,72	4,17E-04	0,84
12	10	BR1 / out (roof + S)	20,5	0,72	4,17E-04	0,86
25	27	BR3 / out (roof + S)	20,5	0,72	5,51E-04	0,71
28	30	Mezz / out (E)	12,5	0,35	4,17E-04	0,84
35	41	BR3 / out (E)	8,1	0,28	5,51E-04	0,71
37	42	WC2 / out (E)	5,5	0,30	4,61E-04	0,73
39	43	Mezz out (roof + N)	23,0	0,65	4,17E-04	0,84
40	44	K+LR / out (W)	13,8	0,28	7,44E-03	0,65
43	45	BR4 / out (W)	9,1	0,48	6,54E-04	0,74
47	49	BR4 / out (N)	10,0	0,52	6,54E-04	0,74
50	53	K+LR / out (S)	20,5	0,42	7,44E-03	0,65
59	66	WC1 / out (N)	3,9	0,51	5,33E-04	0,65
62	69	K+LR / out (E)	14,3	0,29	7,44E-03	0,65
63	70	Bath1 / out (E)	4,2	1,00	2,95E-04	0,65
64	71	WC1 / out (E)	3,7	0,49	5,33E-04	0,65

Internal partition walls airleakage - case d (unevenly distributed)

Number of the air path - exhaust V	Number of the air path - balanced V	Zones	surface area (m ²)	Multiplier	C _L (m ³ /s.Pa ⁻ⁿ)	n
8	6	Bath2 / BR2	8,9	1	0,00E+00	0,67
9	7	BR2 / BR4 (floor)	14,58	1	5,81E-05	0,65
10	8	Bath2/BR1	7,45	1	3,69E-04	0,65
13	11	K+LR/Bath2 (floor)	5,38	1	4,82E-04	0,65
14	14	K+LR/BR1 (floor)	14,14	1	6,31E-05	0,65
16	18	Bath2 / Mezz	2,89	1	1,96E-04	0,65
19	21	Mezz (floor)	2,92	1	7,04E-05	0,68
20	22	BR1 / BR3	8,08	1	0,00E+00	0,71
21	23	BR2 / Mezz	9,5	1	5,37E-04	0,65
22	24	BR3 / Mezz	3,25	1	2,92E-04	0,65
23	29	WC2 / Mezz	0,83	0,05	4,61E-04	0,73
27	31	Mezz / Hall (floor)	16,1	1	3,88E-04	0,68
31	35	BR3 / K+LR (floor)	14	1	2,80E-05	0,65
32	37	WC2 / Mezz	4,78	0,26	4,61E-04	0,73
33	39	BR3 / WC2	4,78	0,00	0,00E+00	0,65
34	40	WC2 /K+LR (floor)	2,39	0,13	4,61E-04	0,73
46	48	BR4 / K+LR	7,53	0,45	8,84E-05	0,74
51	56	BR4/Hall	9,05	0,55	8,84E-05	0,74
55	62	Bath1/Hall	2,13	0,18	4,76E-04	0,69
57	64	Bath1 // K+LR	4,95	0,41	4,76E-04	0,69
58	65	WC1/Bath1	5,05	0,42	4,76E-04	0,69

Internal partition walls airleakage - case d2 (unevenly distributed)

Number of the air path - exhaust V	Number of the air path - balanced V	Zones	surface area (m ²)	Multiplier	C _L (m ³ /s.Pa ⁻ⁿ)	n
8	6	Bath2 / BR2	8,9	1	8,82E-05	0,67
9	7	BR2 / BR4 (floor)	14,58	1	4,71E-03	0,67
10	8	Bath2/BR1	7,45	1	6,56E-05	0,67
13	11	K+LR/Bath2 (floor)	5,38	1	4,95E-05	0,67
14	14	K+LR/BR1 (floor)	14,14	1	4,57E-03	0,67
16	18	Bath2 / Mezz	2,89	1	5,24E-05	0,67
19	21	Mezz (floor)	2,92	1	2,30E-04	0,67
20	22	BR1 / BR3	8,08	1	2,56E-03	0,67
21	23	BR2 / Mezz	9,5	1	5,78E-04	0,67
22	24	BR3 / Mezz	3,25	1	2,29E-04	0,67
23	29	WC2 / Mezz	0,83	0,05	9,34E-05	0,67
27	31	Mezz / Hall (floor)	16,1	1	5,94E-04	0,67
31	35	BR3 / K+LR (floor)	14	1	4,26E-03	0,67
32	37	WC2 / Mezz	4,78	0,26	9,34E-05	0,67
33	39	BR3 / WC2	4,78	0,00	1,16E-04	0,67
34	40	WC2 /K+LR (floor)	2,39	0,13	5,75E-05	0,67
46	48	BR4 / K+LR	7,53	0,45	2,28E-03	0,67
51	56	BR4/Hall	9,05	0,55	4,03E-04	0,67
55	62	Bath1/Hall	2,13	0,18	4,78E-05	0,67
57	64	Bath1 // K+LR	4,95	0,41	1,00E-05	0,67
58	65	WC1/Bath1	5,05	0,42	2,97E-05	0,67

Internal partition walls airleakage - case d3 (unevenly distributed)

Number of the air path - exhaust V	Number of the air path - balanced V	Zones	surface area (m ²)	Multiplier	C _L (m ³ /s.Pa ⁻ⁿ)	n
8	6	Bath2 / BR2	8,9	1	2,72E-03	0,67
9	7	BR2 / BR4 (floor)	14,58	1	4,61E-03	0,65
10	8	Bath2/BR1	7,45	1	2,28E-03	0,65
13	11	K+LR/Bath2 (floor)	5,38	1	2,14E-03	0,65
14	14	K+LR/BR1 (floor)	14,14	1	4,33E-03	0,65
16	18	Bath2 / Mezz	2,89	1	1,15E-03	0,65
19	21	Mezz (floor)	2,92	1	1,07E-03	0,68
20	22	BR1 / BR3	8,08	1	2,65E-03	0,71
21	23	BR2 / Mezz	9,5	1	1,40E-02	0,65
22	24	BR3 / Mezz	3,25	1	4,78E-03	0,65
23	29	WC2 / Mezz	0,83	0,05	1,90E-03	0,73
27	31	Mezz / Hall (floor)	16,1	1	5,21E-03	0,68
31	35	BR3 / K+LR (floor)	14	1	5,11E-03	0,65
32	37	WC2 / Mezz	4,78	0,26	1,90E-03	0,73
33	39	BR3 / WC2	4,78	0,00	1,46E-03	0,65
34	40	WC2 /K+LR (floor)	2,39	0,13	8,72E-04	0,73
46	48	BR4 / K+LR	7,53	0,45	1,11E-02	0,74
51	56	BR4/Hall	9,05	0,55	2,86E-03	0,74
55	62	Bath1/Hall	2,13	0,18	1,26E-03	0,69
57	64	Bath1 // K+LR	4,95	0,41	1,51E-03	0,69
58	65	WC1/Bath1	5,05	0,42	2,07E-04	0,69

Internal partition walls airleakage - case d4 (unevenly distributed)

Number of the air path - exhaust V	Number of the air path - balanced V	Zones	surface area (m ²)	Multiplier	C _L (m ³ /s.Pa ⁻ⁿ)	n
8	6	Bath2 / BR2	8,9	1	7,62E-04	0,67
9	7	BR2 / BR4 (floor)	14,58	1	2,04E-02	0,67
10	8	Bath2/BR1	7,45	1	5,56E-04	0,67
13	11	K+LR/Bath2 (floor)	5,38	1	4,48E-04	0,67
14	14	K+LR/BR1 (floor)	14,14	1	1,94E-02	0,67
16	18	Bath2 / Mezz	2,89	1	2,64E-04	0,67
19	21	Mezz (floor)	2,92	1	9,74E-04	0,67
20	22	BR1 / BR3	8,08	1	1,06E-02	0,67
21	23	BR2 / Mezz	9,5	1	2,75E-03	0,67
22	24	BR3 / Mezz	3,25	1	9,64E-04	0,67
23	29	WC2 / Mezz	0,83	0,05	4,89E-04	0,67
27	31	Mezz / Hall (floor)	16,1	1	4,17E-03	0,67
31	35	BR3 / K+LR (floor)	14	1	1,80E-02	0,67
32	37	WC2 / Mezz	4,78	0,26	4,89E-04	0,67
33	39	BR3 / WC2	4,78	0,00	5,79E-04	0,67
34	40	WC2 /K+LR (floor)	2,39	0,13	2,87E-04	0,67
46	48	BR4 / K+LR	7,53	0,45	9,15E-03	0,67
51	56	BR4/Hall	9,05	0,55	2,56E-03	0,67
55	62	Bath1/Hall	2,13	0,18	2,43E-04	0,67
57	64	Bath1 // K+LR	4,95	0,41	1,00E-05	0,67
58	65	WC1/Bath1	5,05	0,42	1,77E-04	0,67

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Résumé substantiel en français

10.1 Chapitre 1 - Contexte et objectifs

Dans les nouveaux labels et les futures réglementations, la performance du bâtiment devrait s'étendre à une performance plus globale intégrant notamment les enjeux de qualité des environnements intérieurs. Dans le domaine de l'énergie, les réglementations successives ont permis de développer des approches performantielles, fixant notamment un niveau de consommation maximal pour le chauffage et/ou le refroidissement au stade de la conception. D'un autre côté, dans le domaine de la ventilation des bâtiments, les réglementations à travers le monde sont toujours majoritairement basées sur des approches prescriptives, imposant des débits d'air ou des taux de renouvellement d'air minimums. La différence entre approche prescriptive et performantielle est illustrée sur la Figure 1.

"Turn left at the next traffic lights, then take the fourth street to the right, go right ahead at the first roundabout, turn to the right at the second roundabout and keep the left lane, then turn"



Spekkink, D. 2005. Key note presentation on PeBBu, CIB Conference, Helsinki, 2005

"To the airport!"



Spekkink, D. 2005. Key note presentation on PeBBu, CIB Conference, Helsinki, 2005

Figure 17. Illustration d'une (a) approche prescriptive (« Tournez à gauche au prochain feu, puis prenez la 4^e rue à droite, allez tout droit au 1^{er} rond-point, tournez à droite au 2^e rond-point et gardez la voie de gauche, ensuite tournez... »); (b) d'une approche performantielle (« A l'aéroport ! »). Source : (Spekkink, 2005)

Des approches performantielles pour la ventilation permettraient de s'assurer, au stade de la conception, que celle-ci permet bien d'éviter tout risque pour la santé des occupants et tout dommage au bâtiment. Ce type d'approche peut être envisagé à différents stades du bâtiment :

4. Au stade de la conception, comme une véritable méthode de dimensionnement ;
5. **Plus tard lors de la conception, pendant le processus d'étude réglementaire requise, comme une méthode d'évaluation du dimensionnement ;**
6. A la réception du bâtiment, ou ultérieurement lorsque le bâtiment est occupé, comme une méthode d'évaluation de la performance *in situ*.

Face au manque de données pour développer une méthode pertinente, nous proposons dans cette thèse de développer une approche performantielle pour la ventilation au stade de la conception d'un bâtiment résidentiel, comme le fait un calcul thermique réglementaire pour la performance énergétique. Nous proposons donc de nous positionner en réponse au point numéro 2 développé ci-avant. Afin de développer une telle approche, il nous faut répondre aux questions suivantes, qui constituent autant de verrous scientifiques qu'il s'agit de lever :

4. Etape 1 : Quels sont les polluants et/ou les paramètres pertinents à prendre en compte et comment les utiliser dans des indicateurs de performance de la ventilation eux-mêmes suffisamment pertinents ?
5. Etape 2 : Quelles sont les données d'entrées pertinentes pour évaluer cette performance, concernant notamment les scénarios d'occupation et de pollution intérieure ?
6. Etape 3 : Enfin, avec quel niveau de détail modéliser les échanges aérauliques et les transferts de polluants à travers le bâtiment, notamment quelles hypothèses générales de modélisation (modélisation multizone, prise en compte de la météo, ...) et plus spécifiques (distributions de perméabilité à l'air, tampon hygroscopique) devons-nous retenir ?

Dans un contexte de généralisation de bâtiments à quasi zéro énergie en Europe à l'horizon 2020, la perméabilité à l'air est un paramètre de plus en plus intégré dans les calculs thermiques réglementaires. Ceux-ci sont très souvent basés sur des modèles représentant le bâtiment comme une seule zone avec une répartition uniforme de la perméabilité à l'air sur son enveloppe. Comme l'énergie recueille beaucoup plus d'attention que la qualité de l'air intérieur (QAI), les défauts de perméabilité à l'air situés sur les parois intérieures (appelés ici **perméabilité intérieure**) sont souvent négligés, ainsi que les non-uniformités de distribution des défauts sur l'enveloppe des bâtiments. Pourtant, ces défauts court-circuitent les cheminements théoriques des débits de ventilation, avec des conséquences possibles sur la QAI de certaines pièces, comme illustré sur la Figure 3.

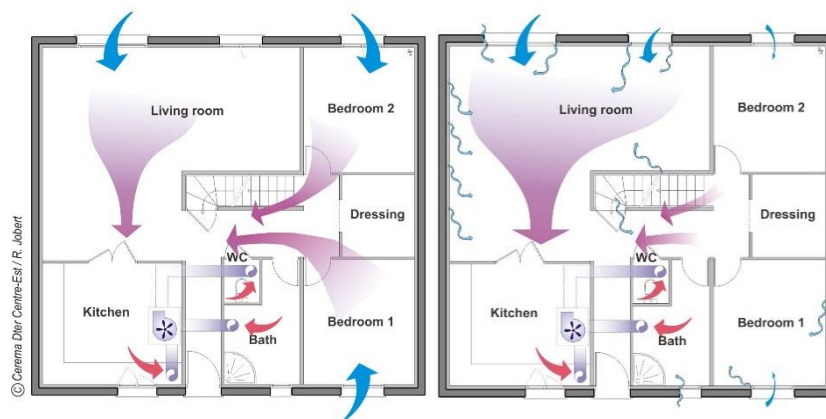


Figure 18. (a) Chemins théoriques de la ventilation and (b) Court-circuits dus à des défauts de perméabilité sur l'enveloppe non uniformément répartis. Source: (Carrié et al., 2006).

Plusieurs études expérimentales montrent que la perméabilité à l'air d'enveloppe est non uniformément répartie et que la perméabilité intérieure est non négligeable (Bossaer et al. 1998; Du et al. 2012; Guyot, Limoges, and Carrié 2012, Bekö et al., 2010; Koffi, 2009). Ces auteurs proposent que de nouveaux travaux de recherche permettent de:

- Caractériser précisément ces distributions de perméabilité à l'air d'enveloppe et intérieure,
- Quantifier leur impact sur la qualité d'air intérieur.

Au vu de ce contexte, les deux objectifs de cette thèse sont :

3. Quantifier les impacts sur la performance de la ventilation d'une modélisation multizone prenant en compte des distributions non uniformes de perméabilité à l'air d'enveloppe et intérieure,
4. Développer une approche performantielle pour la ventilation à utiliser à la conception d'une maison basse consommation, incluant les trois étapes identifiées comme verrous scientifiques ci-dessus.

10.2 Chapitre 2 – Revue des approches performantielles existantes et des indicateurs de performance utilisés dans le cadre de la ventilation « intelligente »

Comme l'étude du champ de la ventilation "intelligente" offrait une littérature fournie, combinées à des parties de réglementations performantielles, nous avons investigué cette thématique. La ventilation intelligente a été définie comme « *un procédé d'adaptation du système de ventilation continue dans le temps, et optionnellement par localisation, afin de fournir les bénéfices souhaités de qualité d'air intérieur, tout en minimisant la consommation d'énergie, la facture des services publics et autre coûts non directement liés à la QAI (comme l'inconfort thermique ou le bruit)* » (Durier et al., 2018). La ventilation contrôlée à la demande (DCV) est une catégorie de ventilation intelligente. Les systèmes DCV utilisent un ou des paramètre(s) mesuré(s) dans le logement pour contrôler les débits de ventilation, soit par une commutation des débits au dépassement de valeurs seuils, soit par une adaptation continue de ces débits au paramètre mesuré.

Notre analyse du contexte réglementaire de la ventilation dans de nombreux pays montre que même si généralement les réglementations sont prescriptives, certains pans de la réglementation, et notamment ceux concernant la ventilation intelligente peuvent basculer sur des approches performantielles. Ces approches sont souvent un prérequis pour autoriser ce type de ventilation innovante, et/ou pour valoriser sa faible consommation énergétique dans le calcul thermique réglementaire. Notre analyse des approches utilisées dans cinq pays en particulier (France, Belgium, The Netherlands, USA, Spain) révèle les scénarios d'émission pris en compte, le niveau de modélisation souvent multizone et les hypothèses liées, ainsi que les indicateurs utilisés.

Le point commun entre toutes ces méthodes est l'utilisation des indicateurs : exposition à un polluant généré à l'intérieur, souvent le dioxyde de carbone (CO₂), et risque de condensation, et très rarement l'exposition à un autre polluant d'influence majeure sur la santé des occupants. De telles approches sont rarement utilisées à l'échelle d'un bâtiment, comme dans notre travail de recherche, mais plutôt à l'échelle d'un système de ventilation, c'est-à-dire mettant en œuvre des scénarios standards d'occupation et de pollution mais non directement adaptés à un bâtiment donné.

Nous pouvons conclure de ce travail que les approches performantielles pour la ventilation et les indicateurs de performance associés varient d'un pays à l'autre. Même si elles présentent des points communs concernant les indicateurs choisis (notamment l'exposition cumulée au dioxyde de carbone dépassant une certaine concentration), les seuils utilisés pour les calculer, et les valeurs seuils associées sont toujours différents.

Par ailleurs, nous avons réalisé une méta-analyse de la performance reportée dans 38 études, portant sur des stratégies variées de ventilation intelligente depuis 1983. Cette analyse nous a permis de mettre en évidence, encore une fois, qu'un contrôle de la ventilation par le CO₂ ou l'humidité était le type de contrôle de la ventilation le plus courant et le plus étudié parmi les types de ventilation intelligente. Notre étude met en évidence le réel potentiel des stratégies de ventilation intelligente tant d'un point de vue de l'amélioration de la qualité de l'air intérieur, que des économies d'énergie réalisées. Celles-ci peuvent en effet atteindre 60%, même si parfois les économies sont nettement plus faibles.

Un verrou scientifique très clairement mis en évidence dans ce travail d'analyse de la littérature porte sur le manque d'indicateurs pertinents pour évaluer la performance de la ventilation du point de vue de la qualité de l'air intérieur. En effet, la plupart du temps, les auteurs concluent en utilisant seulement des indicateurs basés sur le CO₂ ou l'humidité. Une fois de plus, les indicateurs de performance du point de vue de la QAI varient d'une étude à l'autre, et même si certains indicateurs communs sont souvent utilisés (concentration moyenne en CO₂, pourcentage moyen d'humidité relative, temps passé en dehors d'une plage d'humidité relative, exposition cumulée au CO₂, au-delà d'un seuil, ...) les seuils utilisés pour les calculer, et les valeurs seuils associées sont toujours différents.

En conclusion, si la performance de la ventilation intelligente est clairement illustrée dans la littérature, celle-ci met également en évidence le besoin de nouvelles approches performantielles plus robustes, permettant notamment de calculer des indicateurs plus pertinents du point de vue de la QAI.

Ce travail a été publié respectivement dans *International Journal of Ventilation* (Guyot et al., 2018) et dans *Energy and Building* (Guyot et al., 2017).

10.3 Chapitre 3 – Développement d’une base de données originale provenant de mesures détaillées de la perméabilité à l’air d’enveloppe et interzone dans vingt-trois maisons.

Dans le but de collecter des données précises portant sur les distributions de perméabilité à l’air d’enveloppe et interzone, nous avons organisé une campagne de mesure sur 23 maisons, la plupart étant des maisons basse consommation. Nous avons ainsi pu développer une base de données inédite incluant 456 valeurs de perméabilité à l’air, collectées soit sur des murs extérieurs, soit sur des parois intérieures. Pour chaque mesure collectée sur un mur, la base de données inclut des informations générales sur le bâtiment (localisation, ...), les caractéristiques techniques du bâtiment (label, structure, ventilation ...), le type de mur (intérieur/extérieur), et les résultats de mesures associés ($C_{i,n}$, q_{50} et l’indice de confiance développé). L’analyse de cette base de données révèle des corrélations intéressantes. Par exemple, le niveau de perméabilité à l’air sur les parois n’est pas du tout corrélé au niveau de perméabilité à l’air de l’enveloppe, mais beaucoup plus au type de structure (légère/lourde). A travers cette étude, nous avons mis en évidence que la perméabilité à l’air des parois était rarement négligeable devant un détalonnage de porte, en particulier dans les structures de type ossature bois. En effet, dans ce type de structure, la valeur médiane des perméabilités à l’air intérieures atteint 120 cm^2 dans une pièce. Enfin, ces mesures contredisent clairement l’hypothèse d’une répartition uniforme de la perméabilité à l’air sur l’enveloppe d’un bâtiment, souvent réalisée dans les calculs de performance énergétique réglementaires. Nous avons donc proposé des données d’entrée pour les modélisations multizones de la pollution de l’air intérieur, concernant les valeurs de perméabilité à retenir, et les facteurs de dispersions à utiliser, comme résumé dans le Table 29.

Cette étude fournit donc de nouvelles données sur les distributions détaillées de perméabilité à l’air à retenir dans les modèles, avec des conséquences probables sur l’évaluation de la qualité de l’air dans nos chambres où nous passons le plus de notre temps.

Ce travail a été publié dans *Building and Environment* (Guyot et al., 2016).

Perméabilité à l'air interzone – valeurs de référence à utiliser	Perméabilité à l'air interzone – Dispersion à prendre en compte	Perméabilité à l'air d'enveloppe – Dispersion à prendre en compte
Structure lourde : $q_{50}=1.2 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ ou $q_{50}/q_{a4} = 2$	Structure lourde : Ecart interquartile (q_{50})= $3 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ Ou Ecart interquartile (q_{50}/q_{a4})= 4	Structure lourde : Ecart interquartile = 150% de la perméabilité à l'air d'enveloppe exprimée en q_{50}
Ossature bois : $q_{50}=6 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ or $q_{50}/q_{a4} = 17.5$	Ossature bois : Ecart interquartile (q_{50})= $12 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ Ou Ecart interquartile (q_{50}/q_{a4})= 38.5	Ossature bois : Ecart interquartile = 75% de la perméabilité à l'air d'enveloppe exprimée en q_{50}

Table 29. Valeurs proposées en entrée des modèles multizones de maisons pour évaluer la QAI.

10.4 Chapitre 4 – Impacts de la prise en compte de distributions détaillées de perméabilité à l'air sur l'évaluation de la performance de la ventilation d'un point de vue de la qualité de l'air des maisons basse consommation

Suite au chapitre 3, des données détaillées sont disponibles permettant de décrire finement les distributions de perméabilité à l'air. Il s'agit à présent de quantifier leur impact sur la qualité de l'air et ainsi sur la performance de la ventilation. Nous avons étudié sept cas de distributions détaillées de la perméabilité à l'air, allant d'une modélisation très simple (pas de perméabilité à l'air) à des distributions très détaillées (distributions non-uniformes sur l'enveloppe et sur les parois intérieures), en passant par des niveaux de modélisation intermédiaire (distribution uniforme sur l'enveloppe sans perméabilité à l'air intérieure, distribution non-uniforme sur l'enveloppe sans perméabilité à l'air intérieure). Nous avons étudié deux variantes de ventilation respectant toutes deux la réglementation française sur l'aération des logements : un système de ventilation simple-flux auto-réglable et un système de ventilation double-flux auto-réglable, nommées ci-après « simple-flux » et « double-flux ». Nous avons mis en œuvre une modélisation de type multizone, avec des émissions de CO_2 , humidité et formaldéhyde, et avons calculé différents indicateurs de performance d'un point de vue de la QAI dans chaque pièce et sur la période de chauffe. Nous avons utilisé trois niveaux d'émissions constantes de formaldéhyde (4.5 , 12.0 et $23.6 \mu\text{g} \cdot \text{m}^{-2}$).

Une distribution non uniforme de la perméabilité à l'air d'enveloppe présente un impact important sur le taux de renouvellement d'air des chambres (maximum, -24.3%) en présence d'une ventilation simple-flux. Les impacts maximums obtenus sur les indicateurs basés sur les concentrations en CO_2 ,

humidité relative et formaldéhyde sont également importants en présence d'une ventilation simple-flux, respectivement jusqu'à 31%, 39% et 27%. En présence d'une ventilation double-flux, ils sont plutôt négligeables, avec un maximum de -10 %, obtenu sur les indicateurs mettant en œuvre l'humidité relative. Quel que soit le système de ventilation, l'indicateur d'exposition maximale au formaldéhyde n'est pas sensible, avec un maximum de seulement -5%.

Une distribution non uniforme de la perméabilité intérieure présente un impact faible sur le taux de renouvellement d'air d'enveloppe (maximum, -5.5%), mais élevé sur celui des chambres (jusqu'à 28% quel que soit le système de ventilation). Des impacts plus importants sont observés avec le système de ventilation simple-flux sur les indicateurs basés sur les concentrations en CO₂, humidité relative et formaldéhyde, respectivement jusqu'à 49%, -54% and 39%. Avec la ventilation double-flux, ils sont plus faibles respectivement de 15%, -18% and -1.7%. Les impacts sur le critère d'exposition maximale au formaldéhyde sont faibles quel que soit le type de ventilation (maximum -9%).

Nous avons pu conclure que ces impacts étaient généralement importants. Les impacts d'une distribution détaillée de la perméabilité intérieure sont plus importants avec un système de ventilation simple-flux. Ils peuvent cependant être également importants sur certains indicateurs (taux de renouvellement d'air des chambres, indicateurs portant sur l'humidité) en présence d'une ventilation double-flux.

De plus, nous avons souligné l'absence de relation directe et évidente entre le taux de renouvellement d'air de l'enveloppe, le taux de renouvellement d'air des chambres et les niveaux de concentrations en polluants. En effet, les concentrations dépendent de manière complexe de l'ensemble des chemins empruntés par l'air à travers le réseau de défauts de perméabilité à l'air situés aussi bien sur l'enveloppe du bâtiment, que sur l'ensemble des parois intérieures, dont les planchers. Nous avons pu observer que les pièces pour lesquelles les impacts sur les taux de renouvellement d'air étaient les plus importants n'étaient pas les mêmes que celles où l'impact sur les indicateurs de la QAI étaient les plus importants. En effet, prendre en compte la perméabilité à l'air des parois intérieures entraîne de nombreux court-circuits et des cheminements complexes entre les pièces. Les polluants peuvent seconcentrer dans certaines pièces et être dilués dans d'autres, pour un même taux de renouvellement d'air d'enveloppe. Ainsi, nous avons observé des impacts plus faibles sur les indicateurs de QAI basés sur des polluants émis de manière uniforme et continue comme le formaldéhyde. De plus, en présence d'un système de ventilation double-flux, insuffler le même débit d'air dans chaque chambre contribue à diminuer les impacts des court-circuits.

Nous avons également pu établir quelques conclusions intéressantes sur le choix des indicateurs de QAI à sélectionner dans une approche performantielle pour la ventilation. En effet, nous avons pu montrer que certains indicateurs ne sont pas adaptés puisqu'ils ne permettent pas de mettre en évidence des impacts ; c'est le cas par exemple de l'indice Icone et du taux de renouvellement d'air global d'un logement. Ainsi, pour évaluer la performance de la ventilation, nous conseillons d'accompagner le taux de renouvellement d'air des chambres de deux indicateurs au moins, l'un basé sur un polluant émis de manière constante comme le formaldéhyde et l'autre un polluant d'émission variable comme l'humidité qui permettent d'évaluer les risques pour la santé et les risques de condensation.

En conclusion, ces résultats permettent de:

4. Confirmer le besoin de modèles multizones afin d'évaluer la performance de la ventilation sur la QAI à l'échelle des pièces, et notamment des chambres, et non à l'échelle du bâtiment dans son ensemble.
5. Souligner la nécessité de données d'entrées concernant les distributions détaillées de perméabilité à l'air sur l'enveloppe et les parois intérieures, pour dépasser les hypothèses simplificatrices souvent retenues.
6. Identifier des indicateurs de performance plus pertinents que d'autres.

Ce travail a été soumis au *Journal of Building Performance Simulation* (G. Guyot et al., 2018).

10.5 Chapitre 5 – Vers une approche performantielle pour la ventilation – méthodologie proposée

Dans ce dernier chapitre de la thèse, nous nous inspirons à la fois de notre travail d'analyse de la littérature scientifique et réglementaire dans le champ de la ventilation intelligente (Chapitres 2 et 5), et de nos analyses complémentaires (Chapitre 4), afin de développer et proposer une approche performantielle qui pourra être utilisée au stade de la conception d'un bâtiment, dans un calcul réglementaire. La méthode proposée peut être vue comme une évaluation du dimensionnement.

Nous décrivons cette méthode en trois étapes. Dans la première étape, nous proposons de retenir 5 indicateurs de performance de la ventilation portant sur la QAI en tant que « sorties » de notre approche :

- Le maximum de l'exposition cumulée à une concentration en CO₂ excédant 1000 ppm dans les chambres,
- La dose de formaldéhyde maximale reçue parmi l'ensemble des occupants,
- Le pourcentage maximal de temps passé en dehors de la plage d'humidité [30%–70%] dans les chambres (risque pour la santé),
- Le pourcentage maximal de temps passé au-delà de 70% dans toutes les pièces (risque de condensation).

Dans la seconde étape, nous proposons des méthodes et scénarios à utiliser en données d'entrée d'une telle approche performantielle, portant sur l'occupation et les émissions de polluants. Face au manque de données dans la littérature, nous nous sommes concentrés sur l'exposition chronique et avons momentanément laissé de côté les particules. Nous avons proposé une méthode afin de calculer des taux d'émission moyens à l'échelle de logements et l'avons appliqué à un petit échantillon de 10 maisons pour lesquelles les données nécessaires au calcul étaient disponibles. Au final, nous avons proposé de retenir trois niveaux d'émission de formaldéhyde : la classe d'émission faible : 4.5 $\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, la classe d'émission moyenne : 12.0 $\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, la classe d'émission élevée : 23.6 $\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$.

Dans la troisième étape, nous décrivons les modèles généraux utilisés, leurs lois physiques et les hypothèses à utiliser *a minima*. Nous insistons notamment sur la nécessité d'employer une modélisation de type multizone. Puis nous décrivons les modèles physiques, le modèle de bâtiment, et les conditions limites à utiliser dans une telle approche.

Le schéma proposé en Figure 19 résume notre approche.

Towards a better integration of indoor air quality and health issues in low-energy dwellings:
Development of a performance-based approach for ventilation

Chose importante, nous avons pu démontrer l'applicabilité de notre méthode en la testant sur un cas d'étude, une maison basse consommation. Nous avons supposé nous trouver à l'étape de la conception d'une maison soumise à une hypothétique réglementation, label ou norme rendant obligatoire le calcul de cinq indicateurs de la QAI, comme proposé par notre méthode. Nous avons montré que celle-ci permettait d'évaluer la performance de la ventilation du point de vue de la QAI, notamment via une représentation graphique de type radar.

Nous avons pu illustrer comment une telle approche permettrait, en outre, d'aider à une meilleure prise en compte au stade de la conception de l'impact de choix clés sur la QAI, comme le type de structure (au regard de son impact sur les distributions détaillées de perméabilité à l'air), le type de ventilation, le niveau d'émission en polluants. En effet, dans notre cas d'étude, le respect des exigences sur la QAI n'est possible qu'en présence d'une ventilation double-flux, et à condition que la classe d'émission en formaldéhyde ne soit pas la classe la plus élevée.

Nous avons également observé qu'une telle approche permettrait aussi d'aider à la conception de la ventilation, en jouant notamment sur la distribution des entrées d'air et/ou extractions. Ainsi, avec un même niveau de taux de renouvellement d'air d'enveloppe, il est possible d'ajuster ces distributions pour respecter les exigences portant sur la QAI.

Figure 19 : Schéma d'ensemble illustrant notre approche performantielle proposée pour la ventilation des logements basse consommation.



Données de conception sur le bâtiment

- Données géométriques pour chaque pièce
- Valeur de perméabilité à l'air d'enveloppe visée
- Type de structure: lourde/légère (lien avec l'impact sur les distributions de perméabilité à l'air)
- Système de ventilation (simple-flux, double-flux, contrôlé, ...) et débits d'air associés au niveau de chaque composant d'entrée ou de sortie d'air
- Portes (localisation, taille et détalonnage)
- Etiquetage QAI des produits et matériaux de construction => niveau des émissions (élevé/moyen/faible)

Conditions et scénarios standards

1-Conditions aux limites standards (aussi représentatives que possible):

- Météo : vitesse et direction du vent, température, pression atmosphérique, humidité relative,
- Profils de concentrations extérieures en polluants

2-Scénario standard d'occupation:

- Nombre d'occupants = f(nombre de chambres), uniquement des adultes
- A chaque pas de temps, nombre d'occupants dans chaque pièce + activités, pour la France:
- chaque jour le même scénario,
- le temps passé est divisé pour chaque occupant: 9h20 dans sa chambre, 2h50 dans le séjour, 2h40 dans la cuisine divisé en 3 périodes pour le petit déjeuner, le déjeuner et le dîner, 40 minutes dans la salle de bains.

- Une ventilation de pointe dans la cuisine durant 1h deux fois par jour.

3-Scénario standard de pollution:

- a minima: CO₂, humidity, formaldéhyde, PM_{2,5}
- Voir Table 14 du manuscrit.

Modèle Physique

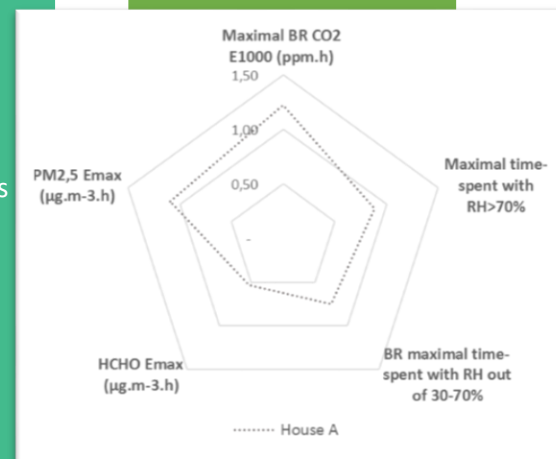
- Besoin du multizone (CONTAM, COMIS, ...)
- Tirage thermique et hypothèses,
- Modèle de vitesse de vent and coefficients de pression associés c_p ,
- Modèle de tampon hygroscopique et hypothèses,
- Période de calcul adaptée au climat et aux habitudes du pays,
- Pas de temps > 10 minutes,

Modèle du bâtiment

- Portes fermées,
- Distributions détaillées non uniformes de la perméabilité à l'air d'enveloppe et des parois intérieures utilisant le tableau du chapitre 3,
- Lois utilisées pour le calcul des débits de ventilation au niveau de chaque composant,
- Réseaux de ventilation et perméabilité à l'air des réseaux peuvent aussi être modélisés dans une approche plus détaillée.

Indicateurs de performance sur la QAI

- Au moins 5 indicateurs, voir le tableau 6 pour les seuils associés:
- 1. Maximum de l'exposition cumulée à une concentration en CO₂ excédent 1000ppm dans les chambres,
- 2. Dose de formaldéhyde maximale reçue,
- 3. Dose de PM_{2,5} maximale reçue,
- 4. Pourcentage maximal de temps passé en dehors de la plage d'humidité [30%-70%] dans les chambres (risque pour la santé),
- 5. Pourcentage maximal de temps passé au-delà de 70% dans toutes les pièces (risque de condensation).



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- Taux de renouvellement d'air des pièces utiles comme indicateurs intermédiaires.

10.6 Références

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