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Development of Performance-Based Assessment Methods for Conventional and Smart Ventilation in Residential Buildings

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ABSTRACT

In future building regulations, 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 mostly based on prescriptive approaches, setting airflows requirements. A performance-based approach for ventilation would insure that ventilation airflows are designed to avoid risks for occupant's health. An extensive review work combined with complementary analysis allows us to come up with the development of a performance-based approach for house ventilation to be used at the design stage in a calculation. We select the use of five relevant IAQ performance indicators, based on CO_2, formaldehyde and $PM_{2.5}$ exposures, and RH-based indicators assessing both condensation and health risks. We propose also pollutant emission data and occupancy schedules to be used. Importantly, we demonstrate that our proposed performance-based method was applicable, applying it to a low-energy house case study. We assume being at the design stage of a house which should comply with a hypothetical regulation, requiring IAQ performance indicators and associated thresholds.

INTRODUCTION

In new European labels and future building regulations, building performancs, 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, Directive EPBD 2003:2010). 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). 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 (Wargocki 2012). Against such prescriptive approaches, it is possible to develop performance-based approach**es** 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. In order to develop such a performance-based approach, we need to address the following topics, these three steps being scientific barriers that we propose to come down in this work.:

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 scenario?
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?

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DEVELOPMENT OF A PERFORMANCE-BASED APPROACH IN THREE STEPS

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 (Durier, Carrié, et Sherman 2018) has been investigated. The analysis of performance-based approaches that both enable and reward smart ventilation used in five countries (France, Belgium, The Netherlands, USA, Spain) revels emission scenarii, often multizone modelling levels and indicators taken into account (Guyot, Walker, et Sherman 2018). Through a meta-analysis on the performance reported in 38 studies of various residential smart ventilation systems since 1983, (Gaelle Guyot, Walker, et Sherman 2017b) identified a very clearly lack of ventilation performance indicators, because most of them being only CO_2 and humidity based indicators. 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. 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.

First: Indoor Air Quality performance Indicators proposition

In the first step, we propose to use the five IAQ performance indicators identified by (Guyot 2018b) as output data. They are calculated using x, the simulation duration (in hours), and are normalized by their acceptable thresholds, proposed as comparison values for a better analyse of the ventilation performance ouput results (Poirier et al. 2020a). A ratio higher than one signifies than the ventilation system in the building does not comply with the threshold.

1. **I^n_{CO2}**: The ratio between the maximum cumulative exceeding CO_2 exposure over 1000 ppm in the bedrooms, and the acceptable threshold = 1000.x ppm.h,
2. **I^n_{HCHO}**: The ratio between the maximum formaldehyde dose received by the occupants and the acceptable threshold = 9.x $\mu g.m^{-3}.h$,
3. **$I^n_{PM2.5}$**: The ratio between the maximum $PM_{2.5}$ dose received by the occupants and the acceptable threshold = 10.x $\mu g.m^{-3}.h$,
4. **I^n_{HR70}**: The ratio of the maximum of the percentage of time with Relative Humidity (RH) higher than 70% in all rooms for the condensation risk, and the acceptable threshold = 1000/x %
5. **$I^n_{HR30\_70}$**: The ratio of the maximum of the percentage of time with RH outside of the range [30%–70%] in the bedrooms for health risk, and the acceptable threshold = 800/x %

Second: Occupancy Schedules and Associated pollutant emission data proposition

In the second step, we proposed pollutant emission data and occupancy schedules to be used, from an extensive review (Poirier et al. 2020b). In this paper, we give the summary results from this article.

Humidity and CO_2. For the occupancy schedules, we propose to use data from the French national campaign on the IAQ of dwellings from 2005 (Zeghnoun, Dor, et Grégoire 2010), based on a representative sample of the population and included 567 dwellings and 1612 occupants. 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, which is consistent with the results of other surveys in Europe and the United States.

Based on (Persily 1997) (CEN 2006) and (Pallin, Johansson, et Hagentoft 2011) we propose to use humidity and CO_2 emission rates associated with occupancy schedules, as it is sum up later in Table 3.

$PM_{2.5}$. Several studies showed that cooking is indoor one of the most $PM_{2.5}$ emitting activity (Abt et al. 2000; He 2004; Ji 2010; Long, Suh, et Koutrakis 2000; Tuckett, Holmes, et Harrison 1998). We propose to use the recent study performed by (O'Leary et al. 2019) in a test chamber protocol with controlled ventilation to measure very precisely the $PM_{2.5}$ emission rate during the whole cooking process (28 min duration). The meals selected in this experiment are based on typical European cooking types. We build three realistic cooking scenarios (for a whole week), based on a combinaison of three meals from O'Leary's study (Table 1): the less emissive (meal 1, 0.62 mg.min-

[1]), the medium emissive (meal 3, 1.9mg.min^{-1}) and the higher emissive (meal 4, 3.2 mg.min^{-1}).

Table 1. PM$_{2.5}$ emission rate scenarios (O'Leary et al. 2019), meals combinaisons

Scenario proposed	Meal 1	Meal 3	Meal 4	Acceptable Threhold
Low-emitting cooking practice	1/2	1/2	-	1.26 mg.min^{-1}
Medium-emitting cooking practice	1/3	1/3	1/3	1.91 mg.min^{-1}
High-emitting cooking practice	-	1/2	1/2	2.55 mg.min^{-1}

Formaldehyde. Formaldehyde emissions can directly be expressed as a quantity per hour for specific activities, products and building materials (Howard-Reed, Polidoro, et Dols 2003; Abadie et Blondeau 2011; Missia et al. 2012).. This type of data brings up two types of limit: 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 (Chan et al. 2019; Hodgson et al. 2000; Ng et al. 2016; Sherman et Hodgson 2002), most particularly in low-energy dwellings. Consequently, we propose to use a simplified method detailed in (Guyot 2018b), based on the mass balance equation in steady-state conditions to calculate average formaldehyde emission rates, from the measurement campaign described in (Gaëlle Guyot et al. 2017).

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

$$V.\frac{dC}{dt} = C_{out}.Q + g - C(t).Q \tag{1}$$

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

Assuming steady state over the measurement period, since often only the average measured concentration is available because of the use of passive methods, the emission rate can be approached by :

$$g = Q.(C_{average} - C_{out}) \tag{2}$$

During the campaign of (Guyot et al. 2017) carried out on 10 recent French low-energy houses a measurement of airflow or pressure at each of the air-vents and an IAQ winter campaign. During 7 days, 16 VOC, 8 aldehydes, NO_2, PM$_{2.5}$, CO_2, temperature and relative humidity were measured in the living room and in the main bedroom.The outside concentration of formaldehyde was not measured during 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 (Qbasic and Qpeak) weighted by their duration of use (peak airflow used 1hour a day). In eight houses equipped with a balanced ventilation system (numbered n°1-5;7;9-10 in Table 1), airflows measurements were taken at each supply Air Terminal Device (ATD) and at each exhaust ATD of each house. For the airflow values (Qbasic and Qpeak), we decided to select the highest value between the total supplied and extracted airflows, as infiltrations would balance both airflows. As a result, we used (Equation 3).

$$\begin{cases} Q = \frac{23}{24}.Q_{basic} + \frac{1}{24}.Q_{peak} \\ Q_{basic} = \max\{Q_{basic,supplied}; Q_{basic,extracted}\} \\ Q_{peak} = max\{Q_{pointe,supplied}; Q_{peak,extracted}\} \end{cases} \tag{3}$$

For the two houses equipped with humidity controlled ventilation (numbered n° 6 and 8 Table 1), pressure measurements were taken at each exhaust ATD of each house. The total airflow was estimated using the average airflow proposed in the corresponding technical agreement, called "Avis technique" (CCFAT 2015). 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 ATD and the theoretical minimum pressure of the range (P_{min}). This correction factor (δQ) was calculated according to (Equation 4), using the measured pressures (P_i) at the N exhaust ATD.

$$\delta Q = \left(\frac{\sum_{i=1}^{N} P_i}{N * P_{min}}\right)^{0.5} - 1 \tag{4}$$

All tested houses comply with the envelope airtightness requirement in the French EP regulation: the indicator q_{a4} (leakage rate per unit of envelope area at 4Pa [$m^3.h^{-1}.m^{-2}$]) must be under 0.6 $m^3.h^{-1}.m^{-2}$. 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 3).

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 $\mu g.m^{-3}$, measured in a study on nursery schools in the same region as the IAQ campaign (DRASS Rhône-Alpes 2007).

The reteained input data from the campaign for calculation and the calculated formaldehyde emission rates per floor area square meter are given later for each house in Table 2. Based on these measurements, we propose to define three classes of formaldehyde emissions to be used as input data for IAQ modelling, and for ventilation performance-based approaches at the design stage of low-energy houses:

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

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

Table 2. Formaldehyde emission rates from the (Guyot et al. 2017) campaign.

House	Floor area [m²]	Volume [m³]	Q[m³.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

In summary, Table 3 gives an overview of our porpositions of emission rates and scenarios, which could be used in a performance-based approach at the design stage for ventilation (Table 3).

Table 3. Overview of proposed emission rates for a performance-based approach

Pollutant or parameter	Emission rates and associated durations
CO_2	Awake: 18 L.h⁻¹/person; Asleep: 15 L.h⁻¹/person
Humidity	Awake: 55 g.h⁻¹/person; Asleep: 40 g.h⁻¹/person
Moisture due to activities :	A total of 6 kg/day :
1 shower per person per day	1440 g.h⁻¹, 10 min per shower.
3 cooking periods per day	1512 g.h⁻¹ breakfast, 15 min; 2268 g.h⁻¹ lunch, 30 min; 2844 g.h⁻¹ dinner, 40 min.

1 laundry per person per week 5 laundry drying per week (same days):	252 $g.h^{-1}$ for 2 h 136.8 $g.h^{-1}$ during 11 h.
Formaldehyde	Low-emission class: 4.5 $\mu g.h^{-1}.m^{-2}$ Middle-emission class: 12.0 $\mu g.h^{-1}.m^{-2}$ High-emission class: 23. $\mu g.h^{-1}.m^{-2}$
$PM_{2.5}$	Low-emission cooking: 1.3 $mg.min^{-1}$. For 28 min for lunch and dinner. Middle-emission cooking: 1.9 $mg.min^{-1}$. For 28 min for lunch and dinner. High-emission cooking: 2.6 $mg.min^{-1}$. For 28 min for lunch and dinner.

Third: Multizone-Modelling assumptions

In the third step, (Guyot et al. 2019) has shown notably that it is essential to use multizone modelling, with detailed airleakage distributions on internal partition and external walls. 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. We took also into account moisture buffering effect using the boundary layer diffusion model in CONTAM (Walton et Emmerich 1994). Then simplified particles phenoma where implemented in CONTAM with a default penetration rate equal to 1; a deposition velocity using 0.65 $m.h^{-1}$ and 9,90 $.10^{-7}$ h^{-1} as indoor particles resuspension rate based on (Thatcher et Layton 1995) measured median values in a 4 residents housing.

APPLICATION OF THE DEVELOPED METHOD TO A CASE STUDY

Case study

The case study is a low-energy house, a two-storey low-energy brick detached house, as shown on Figure 1. We assume 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.

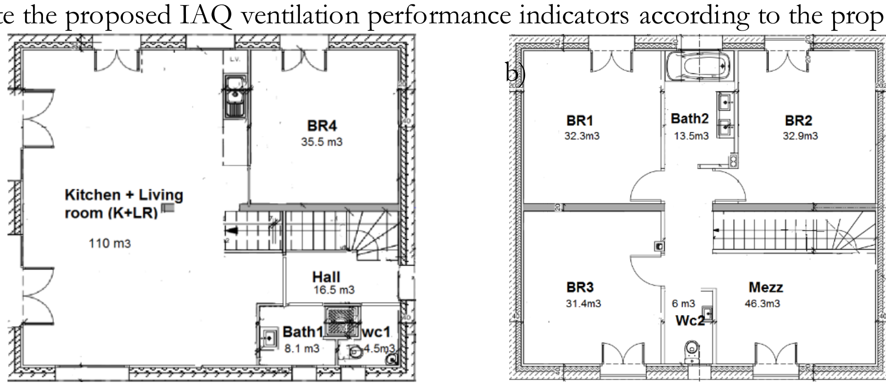

Figure 1. Plan of the house studied: (a) ground floor (b) first floor.

Airflows, relative humidity, CO_2 and formaldehyde concentrations are investigated using numerical modelling with CONTAM software. Each room is one zone, which accounts for 11 zones. We use a 10-min time step, with dynamic meteorological data of a typical year in Lyon (ASHRAE IWEC Weather file, 2001). The calculation is performed over the heating period, from October 15th 00:00 AM to April 14th 12:00 PM, accounting for 4366 simulated hours. The inside temperature is assumed to be 20°C during this period. The wind at the building is 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 are used, assuming no barrier, i.e. +0.5 on the upwind facades and −0.7 on the downwind facades.

Doors and airleakage distribution

Doors are assumed to be closed and the door undercuts are 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 use a case with uneven external and internal airleakage distribution, "d4 case" among the seven studied in (Guyot et al. 2019)

Studied ventilation systems

We study several options for the ventilation system, which should be a whole house system complying with the French airing regulation (J.O. 1983):

1. An exhaust-only constant airflow ventilation system (EV)
2. A balanced constant airflow ventilation system (Extracted airflows are the same for 1 and 2) (BV)
3. An humidity based demand controlled ventilation (DCV) system, considered as a reference in France.

For our case study, a seven-room house with two bathrooms and two toilets, a constant-airflow ventilation system must provide 30 $m^3.h^{-1}$ in each bathroom, 15 $m^3.h^{-1}$ in each toilet, and 45 $m^3.h^{-1}$ in the kitchen. A high-speed ventilation must also be able to provide 135 $m^3.h^{-1}$ in the kitchen during peak periods. As a result, the total extract airflow in the whole house is 135 $m^3.h^{-1}$ during basic mode and 225 $m^3.h^{-1}$ during peak mode. The basic mode accounts for an average dwelling air change rate of 0.4 h^{-1}.

The humidity DCV system adjusts the airflows according to the direct relative humidity (RH) measurement, through the extensions and retractions of a hygroscopic fabric modifying the cross-section of inlets and outlets (Jardinier et al. 2018). In our case study, this system includes:

- A kitchen exhaust ATD providing an airflow between 15 and 55 $m^3.h^{-1}$, and a peak airflow of 135 $m^3.h^{-1}$ for 30 minutes if activated by the user,
- Bathrooms exhaust ATD providing an airflow between 5 and 45 $m^3.h^{-1}$,
- Toilets exhaust ATD providing a constant airflow of 5 $m^3.h^{-1}$ which could be switched to 30 $m^3.h^{-1}$ for 20 minutes thanks to an occupancy sensor,
- A trickle ventilator in every bedroom and two in the living room, with an operating rate between 4 $m^3.h^{-1}$ and 31 $m^3.h^{-1}$ (reference pressure of 10 Pa).

Ventilation performance assessment: results and discussion

For each of the three scenarios (low/medium/high ; formaldehyde and $PM_{2.5}$), defined in Table 1, the Figure 2 shows the performance of the three ventilation systems, assessed according to the five IAQ indicators calculation for this case study.

First, we can observe that none of these three-ventilation systems provides the best IAQ performance results. Indeed, the IAQ performance results from one system to another one are close depending on the indicators, no system is the most performant one for the five indicators. For example, the balanced ventilation system (BV) seems to provide better IAQ in terms of CO_2 (EV 1.17; DCV 1.16; BV **0.72**) and formaldehyde results (low/medium/high EV 0.52/1.06/1.88; DCV 0.53/1.09/1.94; BV **0.43/0.82/1.41**). Logically, the humidity-controlled ventilation system (DCV) provides better IAQ from the humidity-based indicators point of view I^n_{RH70}/$I^n_{RH30\_70}$ (EV 0.89/0.58; DCV **0.55/0.51**; BV 0.71/0.85). The exhaust only ventilation system (EV) has almost the same performances than the DCV, except for the I^n_{RH70} where this system is less efficient than DCV. That is confirming the humidity based ventilation strategy with DCV systems provides a clear benefice on EV, not compromising IAQ.

At last, the three systems responses are close together concerning the $I^n_{PM2.5}$ indicators and none reaches the acceptable thresholds (low/medium/high EV **1.21**/1.76/2.31; DCV 1.30/1.78/2.33; BV 1.24**/1.76/2.29**).

With this performance-based approach, applied to this study case, these 3-ventilation systems provide globally good IAQ performance with RH based indicators, close to the acceptable IAQ threshold with the I^n_{CO2}, but the performances are far from acceptable with the $I^n_{PM2.5}$ and I^n_{HCHO}, except for the low and medium formaldehyde emission scenario. That is reinforces the interest in this method taking into account other IAQ aspects than the traditional CO_2 and Humidity performance indicators, for a better IAQ consideration.

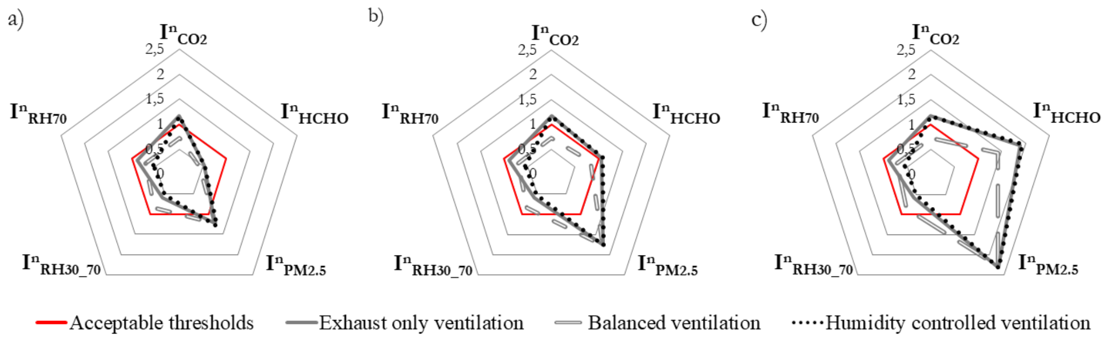

Figure 2. Ventilation Performance, (a) Low emission scenarios, (b) Medium scenarios, (c) High scenarios

CONCLUSION

We propose a performance-based method in order to assess ventilation performance, from an IAQ point of view, at the design stage of every new residential buildings. Then, we show that this method was applicable, applying it on a case study. This method allows to assess the IAQ performance through a radar scheme based on five relevant IAQ performance indicators, based on CO_2, formaldehyde and $PM_{2.5}$ exposures, and RH-based indicators assessing both condensation and health risks.

This works show that it is possible to include in future regulations or labels performance-based approaches for ventilation at the design stage of buildings. It highlights the need for such methodologies to include multizone models for assessing ventilation and IAQ performance at the room scale, especially in bedrooms, not only at the whole building scale.

The formaldehyde emission scenario propositions of this paper should be considered as a first base in the presented IAQ performance approach, built on an in-situ measurement campaign that could be consolited in the future by other data. The five indicators give a first evaluation of the ventilation systems performance tested. These results also highlighted the importance of taking into account other air pollutants than CO_2 and Humidity, for a better IAQ assessment, at least formaldehyde and $PM_{2.5}$. However, it is necessary to reduce the dependence of the indicators on emission rate scenarios by improving their reliability.

The proposed method should now be further investigated with several house geometries, several ventilation systems, including other smart ones, several envelope airleakage levels, etc. Performance indicators could also improved, depending on the countries and already existing methodologies. As a general perspective, to assess ventilation IAQ performance at the design stage, there is also a need for precise emissions for different pollutants: formaldehyde as well as particles, not only at the material scale but also at the room and dwelling scale. For this purpose, we propose in this paper to use a simplified method to calculate constant emission rates in future publication and works.

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