



**HAL**  
open science

## **Pollutants emission scenarios for residential ventilation performance assessment. A review**

Baptiste Poirier, Gaëlle Guyot, Hugo Geoffroy, Monika Woloszyn, Michel Ondarts, Evelyne Gonze

### ► **To cite this version:**

Baptiste Poirier, Gaëlle Guyot, Hugo Geoffroy, Monika Woloszyn, Michel Ondarts, et al.. Pollutants emission scenarios for residential ventilation performance assessment. A review. *Journal of Building Engineering*, 2021, 42, pp.102488. 10.1016/j.job.2021.102488 . hal-03669500

**HAL Id: hal-03669500**

**<https://hal.science/hal-03669500>**

Submitted on 24 Apr 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

# 1 **Pollutants emission scenarios for residential ventilation** 2 **performance assessment. A review**

3 Baptiste Poirier<sup>a,b\*</sup>, Gaëlle Guyot<sup>a,b</sup>, Hugo Geoffroy<sup>b</sup>, Monika Woloszyn<sup>b</sup>, Michel Ondarts<sup>b</sup>, Evelyne Gonze<sup>b</sup>

4 <sup>a</sup> Cerema, BPE Research team, 46, rue St Théobald, F-38080, L'Isle d'Abeau, France ;

5 <sup>b</sup> Univ. Savoie Mont Blanc, CNRS, LOCIE, 73000 Chambéry, France

6 \* Corresponding email: [baptiste.poirier@cerema.fr](mailto:baptiste.poirier@cerema.fr)

## 7 **Abstract**

8 Performance-based approaches for energy consumption in new buildings are increasingly used in  
9 codes and standards. Similarly, there is ongoing research on performance-based approaches for  
10 ventilation systems. The aim is to assess indoor air quality (IAQ) performance in low-energy houses  
11 at the design stage. In this context, the whole-building IAQ performance modelling process raises a  
12 very important question: What are the emission scenarios and occupancy schedules to be used as  
13 entry data to calculate the selected performance indicators? We focus on this issue through a  
14 literature review: firstly oriented toward the occupancy considerations so as to define the emission  
15 rates for CO<sub>2</sub>, moisture, formaldehyde and PM<sub>2.5</sub> to be use as input for ventilation performance  
16 assessment.

17 Based on this review, we propose daily schedules for the occupants and their associated moisture  
18 and CO<sub>2</sub> emissions. We completed them with emission rate values for the main pollutant sources  
19 from indoor activities regarding moisture emissions from laundry, showering and cooking; PM<sub>2.5</sub>  
20 emissions from cooking and formaldehyde from building materials and furniture. Finally, from these  
21 values we built three emission rates classified for PM<sub>2.5</sub> and formaldehyde: high, medium and low.

22 **Keywords:** Ventilation, indoor air quality, performance, residential buildings, scenarios, review

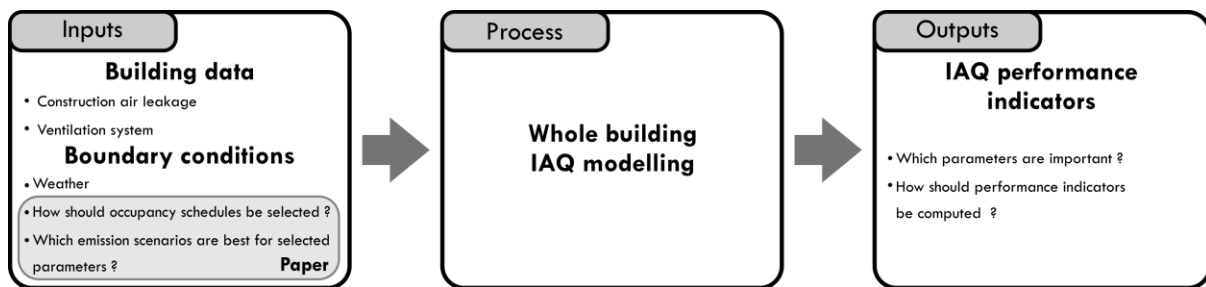
## 23 **1 Introduction**

24 Net zero-energy residential buildings are in increasing demand in Europe because of the energy  
25 performance building directive [1]. Ventilation strategies have a large impact on the heat balance  
26 and the associated air conditioning energy need. Improving ventilation strategies also has great  
27 potential to reduce the contribution of residential buildings to total energy consumption.

28 Ventilation systems and strategies play another important role in buildings' indoor air quality (IAQ),  
29 significantly affecting public health [2–6]. People spend 60–90% of their life in indoor environments  
30 (homes, offices, schools, etc.). The current damage to public health estimated by Logue et al. [7] in  
31 disability-adjusted life years ( $\mu$ DALY) per person per year from all sources attributable to IAQ,  
32 excluding second-hand smoke (SHS) and radon, ranged between the health effects of road traffic  
33 accidents ( $4,000 \mu$ DALY.pers<sup>-1</sup>.year<sup>-1</sup>) and heart disease from all causes ( $11,000 \mu$ DALY.(pers<sup>-1</sup>.year<sup>-1</sup>).  
34 Health gains in Europe (EU-26) attributed to effective implementation of the energy performance  
35 building directive, which includes indoor air quality issues, have been estimated at more than  
36 300,000 DALYs per year.

37 In this context, in new certifications and future building regulations, building performance should be  
38 extended to indoor environment quality, beyond simply energy performance. In the energy  
39 performance field, successive regulations encouraged a performance-based approach, based on an  
40 energy consumption requirement for heating and/or cooling at the design stage [8]. In the building  
41 ventilation field, regulations throughout the world are mainly still based on prescriptive approaches,  
42 with airflow or air change rate requirements [9]. There is ongoing research on performance-based  
43 approaches for residential building ventilation; aiming to replace prescriptive approaches. Indeed,  
44 the latter methods, with prescribed ventilation rates only, are an imperfect way to achieve a given  
45 IAQ. On the opposite, a performance-based approach, using for example IAQ performance indicators  
46 instead of ventilation rates, should be more appropriate.

47 Given the lack of relevant performance evaluation method for ventilation systems, we previously  
 48 developed a performance-based approach for assessing ventilation performance at the building  
 49 scale, at the end of the design stage, much like the regulatory energy performance calculation. This  
 50 would ensure that ventilation is designed to avoid risks for occupants' health. We should also keep  
 51 in mind, that Indoor Air Quality relies on two main principles: reduction of indoor pollution sources  
 52 and efficient ventilation. Indeed, the ventilation system can not ensure the all pollutant dilution  
 53 without a significant impact on the building energy performances. The need to reduce sources of  
 54 indoor pollution is also a key element in ensuring good IAQ, for example by avoiding smoking  
 55 cigarettes indoors, burning candles etc... Sources reduction is out of the frame of the developed  
 56 method, which is focussing exclusively on the ventilation performance assessment. The following  
 57 scheme gives an overview of the whole building IAQ modelling process for this performance-based  
 58 approach, the inputs and outputs needed, and identifies the scope of the present paper (Figure 1).



59  
60 Figure 1. Performance-based approach for ventilation.

61 To develop this type of performance-based approach, the following two scientific barriers had to be  
 62 considered:

- 63 - What are the relevant parameters, including pollutants, to use for calculating performance  
 64 indicators and what indicators should be used?
- 65 - What are the corresponding relevant input data to use regarding occupancy and emission  
 66 scenario parameters?

67 Relevant pollutants and performance indicators have been investigated and are often based on at  
 68 least moisture, CO<sub>2</sub>, formaldehyde and particle matter PM<sub>2.5</sub> [10,11]. Indeed, formaldehyde and

69 PM<sub>2.5</sub> are considered as two pollutants of concern in residential indoor air and were identified among  
70 the five pollutants with the highest median DALY loss estimates [13, 7]. In detail, the indoor sources  
71 contributing to elevated indoor particle matter levels are mainly related to human activities that  
72 generate peak emissions [14]. On the contrary, the sources of formaldehyde emissions are more  
73 uniformly distributed, both in space and time, and related to building construction materials,  
74 furniture and decorative materials [12,7,13–17]. This makes PM<sub>2.5</sub> and formaldehyde interesting for  
75 their complementarity. Moisture and CO<sub>2</sub> were selected as historical parameters widely used in the  
76 standards and in ventilation systems controls [10,18]. Indoor humidity level should be controlled in  
77 order to avoid problems related to condensation, mould growth and material durability. CO<sub>2</sub>  
78 concentration is related to human presence and is recognised as a marker for other bioeffluents.  
79 Several other pollutants could have been selected, but for the performance-based method to be  
80 applied in practice, it is important to promote a low number of pollutants in order to build calculable  
81 and useful IAQ indicators.

82 To calculate IAQ performance indicators as cumulative exposures, we also need the occupancy  
83 schedules and parameters emission rates at the design stage of a building. In this paper, we focus on  
84 this second barrier aspect through an extensive literature review on the occupancy schedule  
85 considerations in a building and CO<sub>2</sub>, humidity, PM<sub>2.5</sub> and formaldehyde emission rate scenarios.

## 86 **2 Methodology**

87 We reviewed the available literature (Standards, Research reports, Scopus, Elsevier, AIVC database)  
88 using the following terms :

- 89 - First: “ventilation performance”, “smart ventilation performance”, “ventilation assessment”,  
90 “ventilation IAQ performance”.
- 91 - Second: “occupancy patterns”, “occupancy schedules”, “occupancy IAQ” and “occupant  
92 IAQ”.

93 - Last: "IAQ emission", "IAQ rate", "IAQ sources", "emission rate", "cooking emission rate",  
94 combined with "CO<sub>2</sub> "a", "moisture", "humidity", "formaldehyde", "fine particle matter",  
95 "PM<sub>2.5</sub>", "pollutant", "occupant".

96 The first important point we have to consider in this review is the accuracy of the emission rates.  
97 These data are not directly measured but are calculated using mass balance equations, combining  
98 airflows or air change rate measurements and parameter concentration measurements. As a result,  
99 several sources of uncertainty exist: measurement uncertainties on airflows and air change rates,  
100 measurement uncertainties on parameter concentrations, and modelling uncertainties (mass  
101 balance includes assumptions on occupancy, room configuration, weather data, etc.). Measurement  
102 uncertainties include the precision and bias of the measurement device, the impact of the user, the  
103 impact of the weather data (for air change rates and airflows), and is well documented in the ISO  
104 guide [19]. Air change rates [20–23], ventilation airflows [24,25] and pollutant concentration  
105 measurement accuracy, notably sensor accuracy [26–31], are a broad area of research for *in-situ* and  
106 laboratory measurements. We selected only research papers and literature with consistent data on  
107 emission rates, with sufficient description of calculation methodology and of measurement  
108 uncertainties.

109 In addition, at the design stage of a residential building, it is difficult to fully describe occupancy for  
110 the entire life span of a building: number and age of the occupants, activities, schedules, etc. It is  
111 also impossible to precisely describe all the parameter emission rates for the occupants, their  
112 activities, the building materials and furnishings. In a performance-based approach at the design  
113 stage of a building, the standards and regulations dealing with this issue must also be considered.  
114 We therefore preferred using cyclic schedules (fixed schedules which are reiterated every week),  
115 differentiating metabolic emissions, building and occupants' activity emissions, as proposed for  
116 humidity and CO<sub>2</sub> in several standards and regulations [10,32–37]. The approach aims to provide a  
117 relative comparison of the performance of several ventilation systems, configurations and airflow

118 rates, building design choices related to ventilation, IAQ labelling products, and even several  
119 occupant IAQ awareness levels.

120 Then we selected references allowing us to build a scenario to be used as entry data to calculate the  
121 performance indicators, in order to assess the ventilation performance of a building at its design  
122 stage.

123 This paper describes a detailed daily life required to calculate IAQ performance indicators. CO<sub>2</sub> and  
124 moisture performance indicators use occupants' metabolism and activity (only for humidity)  
125 emissions, combined with occupancy schedules, as input data. To calculate the cumulative exposure  
126 indicators (for instance, for formaldehyde and PM<sub>2.5</sub>), we also need detailed occupancy schedules for  
127 each occupant. In this literature review, the duration of occupation by room throughout the day and  
128 the type of occupant (adult/child) were sought because they could influence the emission rates. In  
129 this section, we reviewed 10 papers.

130 Then the rates and scenarios for moisture, CO<sub>2</sub> and HCHO, PM<sub>2.5</sub> emissions were studied. CO<sub>2</sub> and  
131 moisture emissions from human metabolism and activities are quite well documented. We reviewed  
132 12 papers and then built and proposed a scenario based on this analysis.

133 In contrast, formaldehyde and PM<sub>2.5</sub> emission rates remain exploratory, especially in a design  
134 approach for ventilation performance assessment. These pollutant emission and concentration  
135 measurements and modelling are complex, because of the physics of phenomena involved (e.g.  
136 diffusion, resuspension for PM, combined effects for formaldehyde) and available measurement  
137 techniques. In addition, formaldehyde emissions are highly dependent on building and furnishing  
138 materials. Consequently, we attempted to build low-, medium- and high-polluting emission rate  
139 scenarios and chiefly focus on measured pollutant emission rates stemming from the building, the  
140 furnishings and the occupants' activities. However, multiple types of data are available and cannot  
141 be directly used together for scenario proposals, so they were categorised in the formaldehyde and  
142 PM<sub>2.5</sub> sub-sections in three measurement types:

- 143 - *Chamber-tested loads*: Pollutant emissions due to specific activities, products and building  
144 materials obtained using test chambers under standardised conditions as described for VOC  
145 in ISO 16000-9 [38]. We found more data on formaldehyde than PM<sub>2.5</sub> emission rates.
- 146 - *Lab kitchen*: PM<sub>2.5</sub> emissions due to specific activities measured in unoccupied homes or in  
147 experimental setups.
- 148 - *In-situ loads*: Emission rates measured at the dwelling scale in occupied or unoccupied  
149 buildings, resulting from the combination of pollutant concentration and air change rate  
150 measurements in dwellings. We found few data on formaldehyde and PM<sub>2.5</sub> emission rates.

151 For PM<sub>2.5</sub> emissions, of the first 29 references analysed on emission sources and particle exposure in  
152 indoor environments, we selected eight published articles to build and propose a scenario based on  
153 this analysis. For formaldehyde emissions, we reviewed 22 references to build a scenario.

154 At the end, based on 73 articles reviewed, we provide a summary of the occupancy and emission  
155 rate scenarios selected. For emission rates, we conducted a review of the international literature,  
156 then we selected the rates and built the scenarios for a European, or even French application.

### 157 **3 Occupancy considerations**

#### 158 **3.1 Residential occupancy schedules in the literature**

159 Precisely described data fitting our purposes are rarely found in the literature. Energy performance  
160 calculation methods use global occupancy schedules at a whole building scale (indoor/outdoor),  
161 whereas a multizone approach requires assuming an occupancy scenario in each room of the house,  
162 at each time step, both for the emission rates and exposure aspects.

163 In energy performance calculations, [39] proposed seven discrete occupancy profiles based on a  
164 time survey on more than 3000 Belgian dwellings. They differentiated outside, inside awake and  
165 inside asleep contexts.



166 A French IAQ national campaign based on a representative sample of the population included 567  
167 homes and 1612 occupants [5]. A total of 1375 occupants provided precise information on their  
168 schedules and occupation in the rooms (25% of the sample) so that a database of 1,386,000 ten-  
169 minute time steps with precise information on occupant location was available and analysed in this  
170 study. The results show that people spend on average 67.3% of their time in their homes. This is  
171 consistent with results of other surveys in Europe (EXPOLIS, 56–66%) and in the United States  
172 (NHAPS: 68.7%). Other interesting results are available in this study:

- 173 - The differences between weekend days and week days are minimal: the 3 days with the  
174 highest occupancy duration are Sunday (16.6 h), Wednesday (16.5 h) and Saturday (16.3 h),  
175 followed by Thursday (16.1 h). Friday is the least occupied day (15.7 h).
- 176 - There is no statistical difference between working periods and holidays.
- 177 - Occupants are more likely to be at home between 12.00 pm and 2 pm and between 7 pm  
178 and 7 am.
- 179 - Time spent at home is divided, on average, into 9 h 16 min spent in bedrooms, 2 h 49 min  
180 spent in the living room, 2 h 40 min spent in the kitchen and 38 min spent in the bathroom.

181 To achieve the occupancy consideration in a building this schedule information needs to be  
182 completed by a description of the occupants. Human emissions stem from the metabolic functions  
183 such as respiration, transpiration and perspiration, depending on different factors such as age [40]  
184 (contradicted by [41]) and activity level. Because of the development and growth of the organs of a  
185 child, its basic metabolism can reach twice the adult rate. The basic metabolism is defined as the  
186 minimum energy expenditure of an organism to ensure daily functions at rest. It decreases between  
187 6 years and 18 years: from 19% for boys to 27% for girls [42]. As a result, as explained by [43], even  
188 if their body surface area is lower, children's CO<sub>2</sub> and humidity emission rates are as high as those of  
189 adults and may even be higher. Measures taken in 20 occupied apartments showed that children's  
190 emissions were often under-estimated in the literature and were closer to adults' emissions [44],  
191 with emissions measured at 13 L.h<sup>-1</sup> for a child and 16 L.h<sup>-1</sup> for an adult. The ECA guidelines for

192 ventilation requirements in buildings [41] compiles data from three studies [45–47], giving emission  
193 rates for adults and children (Table 1).

194

	<b>CO<sub>2</sub> emissions [L.h<sup>-1</sup>.occupant<sup>-1</sup>]</b>	<b>Water vapour [g.h<sup>-1</sup>.occupant<sup>-1</sup>]</b>
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

195 Table 1. Pollutant load caused by occupants. Source: [41]

196

### 197 **3.2 Occupancy schedule proposal**

198 For our purposes, we used the detailed data from the French IAQ national campaign [5]. The  
 199 following daily occupancy duration (rounded for a 10-min time step simulation) was retained:

- 200 - 9 h 20 min in bedrooms,
- 201 - 2 h 50 min in the living room,
- 202 - 2 h 40 min in the kitchen,
- 203 - 40 min in the bathrooms,
- 204 - For a total of 9 h 20 min asleep, 14 h 40 min awake, 9 h outside and 15 h inside.

205 These occupancy schedules should be carefully adapted depending on countries and their habits  
 206 (meal times, school times, work times, etc.).

207 The number of occupants must be assumed, taking into account the size of the house, to avoid  
 208 under-estimating the ventilation airflow rates. We would suggest setting the number of occupants  
 209 based on the number of bedrooms, assuming two occupants in one bedroom and one in each of the  
 210 others. At the design stage of a building, we could also assume that all occupants are adults, based  
 211 on the data reported in Table 1.

212 In the next section, emissions due to occupants will occur where and when occupants are assumed  
 213 to be present.

214 **4 Emission rate scenarios for a ventilation performance assessment at the design stage**  
 215 **of a residential building**

216 **4.1 Moisture**

217 **4.1.1 Moisture emission rates in the literature**

218 In a building the main moisture sources are linked to the occupants' activities such as showering,  
 219 cooking, dish washing and laundry drying. In addition, the building envelope helps to regulate indoor  
 220 humidity by exchanging moisture flows with the indoor air. This phenomenon must be represented  
 221 in the model in order to provide realistic results. We consider this phenomenon of moisture  
 222 exchange as a buffer (part of the model) and not as an emission source.

223 In most of the references analysed, mainly including standards, related production is given for a  
 224 precise activity with a duration per day, sometimes depending on the number of occupants [32–  
 225 35,37] (Table 2). Note that two normative documents [34,48] proposing the schedule approach also  
 226 alternatively suggest using an average constant moisture emission rate, depending on the overall  
 227 moisture production and the number of occupants. Alternative approaches based on experimental  
 228 measurements are also proposed [49,50] (Table 2).

229 Table 2: Moisture emission rates of activities

Activities	Emission rate	Duration	Reference
<i>Cooking /person</i>			
- Breakfast	100 g.h <sup>-1</sup>	0.5 h	CCFAT [37]
- Lunch (weekend)	75 g.h <sup>-1</sup> (150 g.h <sup>-1</sup> )	1 h	
- Dinner	300 g.h <sup>-1</sup>	1 h	
Shower <sup>(a)</sup> CCFAT / EN 15665	300 g	0.5 h / 6 min	EN 15665 [35]
Laundry <sup>(b)</sup>	100g.h <sup>-1</sup>	2 h	
Laundry drying <sup>(b)</sup>	50g.h <sup>-1</sup>	20 h	
Electric cooking device	2000 g.day <sup>-1</sup> 3000		British standard, 1991 [48] & TR-14788 [34] (called A)
Gas cooking device	g.day <sup>-1</sup>		
Hand dish washing	400 g.day <sup>-1</sup>		
WC/shower/dish washing	200 g.day <sup>-1</sup> .person <sup>-1</sup>		
Laundry	500 g.day <sup>-1</sup>		
Inside drying <sup>(c)</sup>	1500 g.day <sup>-1</sup> .person <sup>-1</sup>		
<i>Cooking</i>			
- Breakfast	0.6 l.s <sup>-1</sup>	10 min	TR-14-88 [34]
- Lunch	1 l.s <sup>-1</sup>	10 min	(called B)

- Dinner	1.5 l.s <sup>-1</sup>	10 min	
Shower/person	0.5 l.s <sup>-1</sup>	10 min	
Laundry drying	0.06 l.s <sup>-1</sup>	12 h	
<i>Moisture generation rate</i>	Low/medium/high		
- 1 person	3.5/6/9 kg.day <sup>-1</sup>		British standard, 1991 [48] & TR-14-788 [34] (called C)
- 2 persons	4/8/11 kg.day <sup>-1</sup>		
- 3 persons	4/9/12 kg.day <sup>-1</sup>		
- 4 persons	5/10/14 kg.day <sup>-1</sup>		
- 5 persons	6/11/15 kg.day <sup>-1</sup>		
<i>Cooking meals</i>			
- Breakfast	109 ± 20 g	15 ± 5 min	
- Lunch	288 ± 68 g	30 ± 2 min	
- Dinner	518 ± 152 g	40 ± 10 min	<i>Experimental data</i>
<i>Dish washing</i>			
- Breakfast	25 ± 3 g	29 ± 3 min	[49,50] cited in [52]
- Lunch	20 ± 3 g	29 ± 3 min	
- Dinner	240 ± 9 g	29 ± 3 min	
Showering	250 ± 50 g	10 min	
Laundry drying <sup>(d)</sup>	1850 ± 670 g	11 ± 2 h	

(a) With 1 shower.day<sup>-1</sup>.person<sup>-1</sup>

(b) With x laundry.week<sup>-1</sup> (CCFAT, 2015) (x = 1–4 depending on the number of inhabitants) EN 15 665 (CEN, 2009) (x = 1)

(c) Naturally or with dryer without vent

(d) 20% of the total emissions during the first 2 h

230 The occupants' metabolism is also a source of humidity. The most frequent distinction between  
 231 activity levels is when occupants are asleep or awake. For a household of three people, a study used  
 232 a value of 2.4 kg.day<sup>-1</sup> of water production in each room [51]. Experimental studies also give useful  
 233 information with confidence intervals comparable to [49,50] (Table 3).

Metabolism emission data	Awake	Asleep	At rest	Sources	234	Tabl
- 3–6 years			90 g.h <sup>-1</sup>	ECA guidelines for	235	e 3:
- 14–16 years			50 g.h <sup>-1</sup>	ventilation requirements	236	Met
- Adult			50 g.h <sup>-1</sup>	in buildings [41]		
- <2 years	30 g.h <sup>-1</sup>	10 g.h <sup>-1</sup>			237	abol
- 10–13 years	45 g.h <sup>-1</sup>	15 g.h <sup>-1</sup>		[40]		
- >15 years	55 g.h <sup>-1</sup>	30 g.h <sup>-1</sup>			238	ism
- per person	55 g.h <sup>-1</sup>	38.5 g.h <sup>-1</sup>		[37] & [53]		
- per person	55 g.h <sup>-1</sup>	40 g.h <sup>-1</sup>		[35]	239	mois
<i>Recommended duration of emissions</i>	55 g.h <sup>-1</sup> Living room 4 h	40 g.h <sup>-1</sup> Bedroom 10 h		[34] & [48]	240	ture
					241	emis
- Active people	70 ± 5 g.h <sup>-1</sup>	30 ± 2 g.h <sup>-1</sup>	50 ± 5 g.h <sup>-1</sup>	<i>Experimental data</i> [49,50] cited in [52]	242	sion
- for 3 people		2.4 kg.day <sup>-1</sup> (average 33 g.h <sup>-1</sup> per person)		[51]	243	rate

244 s

245 Finally, a review on the indoor moisture also showed sources ranging from very simplified to more  
246 realistic sources [54]. The simplest is an average constant emission based on [55] which reviewed  
247 nine studies, suggesting the average emission of  $270 \text{ g.h}^{-1}$  to be used for a 1-year simulation. This  
248 review [54] also showed that several experimental and numerical studies preferred using typical  
249 cyclic schedules. Lastly, stochastic scenarios could also be used, as demonstrated by [56,57] in office  
250 buildings. For a one-zone experimental building, [54] showed how constant emission rates could  
251 result in increasing the comfort range by 10–20%, compared to the use of stochastic scenarios.

#### 252 4.1.2 Analysis and scenario proposals

253 First of all, all the metabolism moisture emission rates in the literature reviewed are within the same  
254 range, so we suggest using the moisture generation rates for the metabolism emission of  $55/40 \text{ g.h}^{-1}$   
255 (awake/asleep). Next step is to quantify the dispersion of moisture emissions rates due to activities,  
256 given in Table 2. In order to compared them, we calculated for each reference ([34]-A, [34]-  
257 B,[35],[37],[50]) the related daily moisture emissions, assuming one or five occupants, taking into  
258 account metabolism, cooking, showering, laundry and clothes drying. We assumed one laundry, one  
259 clothes drying per person and per week, and we calculated an average weighted emission rate per  
260 day. Lastly, we compared the calculated results expressed as an average emission rate in kg per day  
261 to the thresholds given in TR 14 788-C [34] (Table 4,Table 5). From these tables, we can observe that  
262 no standard gives high emission rates, and that these are in most cases low, and become medium if  
263 we consider five occupants.

	Reference	Calculated daily emissions [kg.day <sup>-1</sup> ]	Low 3.5 kg.day <sup>-1</sup>	Medium 6 kg.day <sup>-1</sup>	High 9 kg.day <sup>-1</sup>
<b>1 occupant</b>	TR 14-788-A [34]	4.1	-	X	-
	TR 14-788-B [34]	2.6	X	-	-
	EN-15-665 [35]	1.4	X	-	-
	CCFAT, 2015 [37]	1.6	X	-	-

Experimental Data [50]

2.0

X

-

-

264 Table 4. Comparing calculated daily moisture emissions with thresholds given in TR 14-788-C (CEN,  
265 2006a), one occupant.

266

267 Table 5. Comparing calculated daily moisture emissions with thresholds given in TR 14-788-C [34],  
268 five occupants.

	Reference	Calculated daily emissions [kg.day <sup>-1</sup> ]	Low 6 kg.day <sup>-1</sup>	Medium 11 kg.day <sup>-1</sup>	High 15 kg.day <sup>-1</sup>
5 occupants	TR 14-788-A [34]	8.4	-	X	-
	TR 14-788-B [34]	7.2	-	X	-
	EN-15-665 [35]	4.9	X	-	-
	CCFAT, 2015 [37]	7.9	-	X	-
	Experimental Data [50]	5.2	X	-	-

269

270 Consequently, for our analysis, for the activity emissions, we suggest using the TR 14-788-A [34]  
271 data, because it is the most handicapping reference. We combined them with the emission duration  
272 given by [49,50] because these data came from in-situ measurements, published in an IEA Annex  
273 and cited in [52]. The following moisture generation scenarios could be used:

- 274 - One shower per person per day, with an emission of 1440 g.h<sup>-1</sup> for 10 min per shower;
- 275 - Cooking periods per day: 1512 g.h<sup>-1</sup> for breakfast for 15 min; 2268 g.h<sup>-1</sup> for lunch for 30 min;  
276 2844 g.h<sup>-1</sup> for dinner for 40 min;
- 277 - One laundry per person per week: 252 g.h<sup>-1</sup> for 2 h;
- 278 - One laundry drying per person per week (same days): 136.8 g.h<sup>-1</sup> for 11 h.

279 This results in an average production of 6 kg.day<sup>-1</sup> for five occupants, which is a rather low emission  
280 scenario.

281 **4.2 Carbon dioxide**

282 **4.2.1 Emission rates in the literature: analysis and proposal**

283 CO<sub>2</sub> emission rates are due to occupant metabolism and depend on the occupants' size and activity.  
 284 The literature gives the same order of magnitude and generally proposes making a difference  
 285 between asleep and awake times, adults and children, as summarised in Table 6, which shows a  
 286 quite good consensus around the value of 18 L.h<sup>-1</sup> for an awake adult with a low level of activity. For  
 287 a sleeping adult, the emission rates vary between 10 and 16 L.h<sup>-1</sup>.

288 Table 6: CO<sub>2</sub> metabolism emission rates

<b>Emission rates</b>	<b>[L.(h.person)<sup>-1</sup>]</b>	<b>Sources</b>
<i>Sedentary</i>		
- 3–6 years	18	[41]
- 14–16 years	19	
- Adult	19	
Awake	16	[35]+ [37]
Asleep	10	
<i>Awake/asleep</i>		
- <2 year-old	8/4	<i>Annex 27 IEA [40]</i>
- 10- to 13-year-old	12/8	
- >15-year-old	18/12	
<i>Asleep, measured in occupied apartments</i>		
- Child	13	[44]
- Adult	16	
Child (medium exercise)	10	[58]
Adult (office work)	18	
Adult (asleep)	15	

289  
 290 Given this data, and as we are at the design stage of a building with generally no idea of occupant  
 291 age, we considered that all occupants are adults, as explained in the above section. Finally, we used  
 292 the emission rates proposed by Persily [58]: 18 L.h<sup>-1</sup> and 15 L.h<sup>-1</sup> for an “awake” or “asleep” occupant  
 293 of a residential building. The first value shows quite good consensus and the second allows one to  
 294 avoid over-estimating ventilation performance.



## 295 **4.3 Formaldehyde**

### 296 **4.3.1 Formaldehyde emission rates**

#### 297 **4.3.1.1 General considerations**

298 For formaldehyde, several authors have highlighted the correlation of concentrations and emissions  
299 with temperature, relative humidity and air exchange rates [59]. Using a multivariate model fit on  
300 observational data testing temperature, humidity, the air change rate and outdoor concentration,  
301 [60] considered temperature to be the best correlated with the increase in the formaldehyde  
302 concentration. A chamber test study proposed a semi-empirical correlation law between the initial  
303 material's emittable concentration and the combined effect of humidity and temperature [61].  
304 Moreover, the formaldehyde emissions of new houses from construction materials, such as wood  
305 products, are known to be constant for approximately nine months and then start to decrease [62],  
306 to reach a steady state emission rate after a few years [59].

#### 307 **4.3.1.2 Rates obtained in chamber-tested loads**

308 The study reported by Plaisance et al. [63] used a passive flux sampler for 6 h to define a linear  
309 equation between the formaldehyde mass collected and the emission rate of the tested material in a  
310 test chamber, according the ISO 16000-9 standard [38]. Depending on the surface tested, they  
311 calculated emission rates within the range [11.2; 682]  $\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ .

312 Several databases have been developed to verify such chamber-tested data. Pandora is a very large  
313 free-access database for indoor pollutant emission rates [64], with more than 8000 emission rates  
314 from the literature classified by sources, including formaldehyde and  $\text{PM}_{2.5}$ . Other databases were  
315 found such as the one developed in the EPEHCT project [65] and the NIST Database [66], including  
316 formaldehyde. In these databases, formaldehyde emission rates for common materials can be found  
317 with a large spread, as for example for gypsum board (Pandora: in range [0.3; 42]  $\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ ) or  
318 fibreboard medium (NIST: in range [14; 640]  $\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ , Pandora: [237 – 320]  $\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ ). As a

319 conclusion, the range of emission values is quite different from one database to another and the  
320 relationship with the in situ rates obtained in houses is complex.

#### 321 4.3.1.3 In-situ rates obtained in houses

322 The EN-15251 standard [67] provides two emission rates for formaldehyde:  $50 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$  for low-  
323 polluting buildings (glass, steel, rock) and  $20 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$  for very-low-polluting buildings (without  
324 tobacco), considering the material surface areas. EN-16798-1 [68] updates these emission rates to  
325  $100$  and  $50 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ , respectively, based on the results calculated for the European Reference  
326 Room as specified in CEN/TS-16516.

327 A test conducted by [62,69] was repeated three times on seven unoccupied prefabricated houses  
328 and on seven unoccupied site-built houses, located in eastern and southern USA, under two  
329 different climates, hot-humid and mixed-humid. The formaldehyde concentration was measured  
330 using two active samplers, inside and outside. The indoor sampler was located in the living/dining  
331 room 1.5 m above the floor. In addition,  $\text{SF}_6$  was used as a tracer gas to measure the air change  
332 rates. The average constant emission rate was calculated from the average concentrations measured  
333 and the air change rate measured, using the mass conservation equation on the whole house  
334 considered as one zone. The result was an average emission rate of  $44.17 (\pm 36\%) \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ ,  
335 considering the houses floor surface areas.

336 The study conducted by [60] took measurements of 24 student residence rooms with five different  
337 surfaces (flooring, ceiling and walls, doors, bed and other furniture), for three construction ages.  
338 Formaldehyde concentrations were measured over 6 h with both conventional active samplers and  
339 passive samplers. Thirteen to 15 passive samplers were used per student room, with measurements  
340 taken in the room, in the common corridor adjacent to the room, and outside. Air change rates were  
341 measured using a  $\text{CO}_2$  (tracer gas) injection method. Depending on the age of the building and the  
342 type of surface, the resulting average emission rates were within the range  $[1.4; 87.3] \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ ,  
343 considering the material surface areas. Table 7 summarises all the emission rates reviewed.

<b>Materials</b>	<b>Emission rates [<math>\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}</math>] per <math>\text{m}^2</math> of material surface area <i>unless specified otherwise</i></b>	<b>Reference</b>
Low-polluting building (glass, steel, rock)	50	EN-15-251 [67] <i>In-situ loads</i>
Very-low-polluting building (without tobacco)	20	
Low-polluting building (stone, glass, ceramics and non-treated metal)	100	EN-16798-1 [68] <i>In-situ loads</i>
Very-low-polluting building	30	
7 Unoccupied and 7 Occupied houses	[per $\text{m}^2$ of floor surface area] average: $44.17 \pm 36\%$ median: 41.72	[62,70] <i>In-situ loads</i>
<i>H1 (built in 1998)</i>	[Average $\pm$ std dev (range)]	
- Flooring	$2.3 \pm (1.2-5.5)$	
- Ceiling and wall	$3.6 \pm 1.7 (1.2-6.3)$	
- Door	$4.0 \pm 2.0 (1.2-6.4)$	
- Bed	$3.3 \pm 1.8 (1.2-6.7)$	
- Other furniture	$2.8 \pm 0.9 (1.2-3.6)$	
<i>H2 (built in 1975, renovated in 2003)</i>		
- Flooring	$1.4 \pm 0.7 (1.2-2.4)$	
- Ceiling and wall	$3.2 \pm 2.0 (1.2-7.1)$	[60]
- Door	$2.6 \pm 1.6 (1.2-5.5)$	<i>In-situ loads</i>
- Bed	$2.8 \pm 1.7 (1.2-5.8)$	
- Other furniture	$3.4 \pm 0.6 (2.8-4.4)$	
<i>H3 (built in 1991)</i>		
- Flooring	$5.3 \pm 3.5 (2.5-13.0)$	
- Ceiling and wall	$8.8 \pm 2.8 (4.1-12.1)$	
- Door	$7.0 \pm 4.2 (1.2-14.7)$	
- Bed	$87.3 \pm 37.5 (21.3-131.3)$	
- Other furniture	$2.9 \pm 1.9 (1.2-7.0)$	
Fibreboard medium 1	92.5	
Fibreboard medium 2	135.5	
Fibreboard medium 3	133.3	[63]
Sealing plaster	43.4	<i>Chamber-tested loads</i>
Finishing plaster	682	
OSB	11.2	
Chipboard	244.4	
		Pandora Database [71] EPEHCT project [65] NIST Database [72] <i>Chamber-tested loads</i>
More than 8000 emission rates from consumer products and building materials		

344 Table 7: Overview of formaldehyde emission rates found in the literature

### 345 4.3.2 Analysis and scenario proposals

346 Few of these formaldehyde data are fully useful for a performance-based approach to ventilation.

347 We found either few or no data on average in-situ loads directly measured at the dwelling scale, and

348 especially in low-energy dwellings considered as representative. Consequently, the available data  
349 pose two problems:

- 350 - Firstly, it is difficult to extrapolate emission rate behaviours from test chamber conditions to  
351 *in-situ* conditions, notably because of the complex physical phenomena (combined effects,  
352 resuspension, etc.). As illustrated in Table 7, the order of magnitude of emission rates  
353 between chamber-tested loads in [63] and *in-situ* loads in [60] varies by a factor of a 10 to  
354 100.
- 355 - Secondly, it is difficult to build robust scenarios from the material, product and activity scale  
356 to the dwelling scale, as highlighted in [73]. Indeed, due to the wide variety of materials  
357 available, the emission per m<sup>2</sup> of floor area varies from one building to another. In addition,  
358 the type of building materials and furniture and the quantities used (floor coverings, wall  
359 paintings, etc.) depend on the purpose of the buildings as well as on the design or  
360 construction methods used. Precise data are not yet described in scientific studies. In  
361 addition, emission rates for common materials are available with a high variability and even  
362 within the same type of material emission properties can vary considerably, as shown by the  
363 diversity of values presented in the databases [64], [66] or as illustrated in [63] for the  
364 Fibreboard medium 1,2,3. Consequently, arbitrary choices must be made to establish input  
365 data (using databases such as Pandora) for a detailed IAQ modelling at the scale of a  
366 residential building, as shown by [74].

367 We accordingly suggest using the simplified calculation method in [75] and applying it to  
368 unpublished data gathered on French low-energy homes to calculate average *in-situ* loads at the  
369 dwelling scale.

370 Based on these measurements, we define three classes of formaldehyde emissions to be used  
371 as input data for IAQ modelling, and for ventilation performance-based approaches at the  
372 design stage of low-energy houses:

- 373 - *The low-emission class:*  $4.5 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ , per  $\text{m}^2$  of floor surface area, defined by the  
374 minimum calculated value;
- 375 - *The medium-emission class:*  $12.0 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ , per  $\text{m}^2$  of floor surface area, defined by the  
376 median calculated value;
- 377 - *The high-emission class:*  $23.6 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ , per  $\text{m}^2$  of floor surface area, defined by the  
378 maximum calculated value.

#### 379 **4.4 *PM<sub>2.5</sub> particles***

##### 380 **4.4.1 *PM<sub>2.5</sub> emission rates in the literature***

###### 381 **4.4.1.1 General considerations**

382 The most widely studied  $\text{PM}_{2.5}$  indoor emission sources are principally candle combustion, smoking  
383 and cooking activities. The emission values of hairspray [76] are usually occasional and relatively low,  
384 in comparison with candle combustion [77] or incense [78,79], cooking activities [80] and smoking  
385 emissions. As described in the introduction, this work focuses on the assessment of ventilation  
386 performance, which should be seen as complementary to the reduction of indoor pollution sources.  
387 Smoking is a significant indoor emission source but it is not included in this review because it is more  
388 relative to the performance of occupants than to ventilation system performance. The source of the  
389 emissions can easily be reduced by influencing the habits of the occupants. From this perspective,  
390 Borsboom et al. [17] propose that tobacco smoke should not be considered in setting ventilation  
391 standards. A similar choice is made for candles and incense: they are related to habits and are  
392 excluded from our study.

393 Several studies showed that cooking is one of the most  $\text{PM}_{2.5}$ -emitting activities [13,81–83]. Ji et al.  
394 [80] corroborated this, providing measurements in an experimental house to quantify occupant  
395 exposure to ultrafine particles. They directly calculated this indicator from concentration  
396 measurements using occupancy schedules, without calculating emission rates. Each source was

397 tested at least three times, and the concentration was measured in three different spaces to  
398 quantify the impact of the pollutant on the entire dwelling. We could thus classify the source into  
399 four categories depending on its global impact intensity (high, medium, limited, low). This study  
400 highlighted that the largest sources were: cooking and extra-heating for the high-impact sources, the  
401 toaster for the medium-impact sources, and incense, cigarettes, and candles for the limited-impact  
402 sources.

403  $PM_{2.5}$  concentrations and emissions were also strongly correlated with outdoor conditions, intensity  
404 and type of ventilation, air leakage level and deposition and resuspension conditions [81,82,84,85].  
405 Given their mass, particle matter is deposited on surfaces by gravity and various common actions  
406 can resuspend these particles. Moreover, particle matter can be formed by a chemical gaseous  
407 reaction such as between ozone and terpene [86].

408 Based on this first literature analysis, we retained only emissions from cooking activities to build the  
409  $PM_{2.5}$  emission rate scenarios. Two review papers on the chemical components of particle matters  
410 [87] and their impact on cooking emission rates [88] have recently been published.

#### 411 4.4.1.2 Rates obtained in test chambers

412 A study was carried out in a 32-m<sup>3</sup> test chamber in a research laboratory to characterise emissions  
413 from various activities (frying, gas stove, smoking, vacuuming, heater, radiator, scented candle, pure  
414 wax candle) [78]. The  $PM_{2.5}$  concentration was measured by two different particle counters: a  
415 condensation particle counter and an optical particle counter. The concentration was continuously  
416 monitored before, during and after all the emission tests. A tracer gas decay method was used to  
417 determine the air change rate, based on concentration measurements made continuously over 2h  
418 with a photo-acoustic spectroscopy device. Emission rates were lastly calculated through air change  
419 rate concentration measurements and expressed as particles per minute. Unfortunately, these  
420 emission rates in particles per minute cannot be used in cooking emission rate research, because  
421 conversion into  $mg \cdot min^{-1}$  is impossible.

422 Finally, the recent study conducted by O’Leary et al. [89] used a test-chamber protocol with  
423 controlled ventilation to very precisely measure the PM<sub>2.5</sub> emission rate throughout the cooking  
424 processes. The four meals selected for this experiment were based on typical European portions and  
425 food types from representative data, like the panel method [90] or the Western cooking type survey  
426 conducted by [91,92].

#### 427 4.4.1.3 Rates obtained in a lab kitchen

428 Firstly, the study of [93] characterised the particle emissions of several foods (cheese, chips, bacon)  
429 by testing the impact of the oil used (sunflower, peanut, olive), the cooking method (frying/grilling)  
430 and temperature. These cooking tests were conducted in laboratory conditions in an 82-m<sup>2</sup> kitchen  
431 using electric and gas stoves. The results show that the higher the cooking temperature, the higher  
432 the particle emission rate is, as shown with the 50-g bacon experiment; 0.52 mg.min<sup>-1</sup> emitted with  
433 minimum power (171°C ± 17°C) versus 13 mg.min<sup>-1</sup> with maximum power (242°C ± 5.2°C). Oil type  
434 may also influence the emission rate (chips, sunflower oil, 1.20 mg.min<sup>-1</sup>; chips, olive oil, 2.80  
435 mg.min<sup>-1</sup>) and this confirms that grilling activities are the highest emission sources, especially with  
436 gas stove cooking.

437 Other in-situ studies focused on cooking only one food, e.g. [94] for the PM<sub>2.5</sub> emitted during the  
438 cooking of ground beef in a dwelling. In this study, the test conditions were set up to limit other  
439 indoor and outdoor emission sources, for example, by closing all the doors during the test period  
440 and ventilating before the experiment. The resulting measurements were divided into four rate  
441 ranges [3.3 µm >2.1 µm >1.1 µm >0.65 µm >0.43 µm] and the value retained was the total average  
442 emission rate equal to 44.9 mg.min<sup>-1</sup>.

443 Recently, [95] also measured the PM<sub>2.5</sub> and PM<sub>10</sub> generation rate *in situ* for cooking in an  
444 experimental building based on grilling and frying activities (fish, meat, egg). Measurements were  
445 taken for 30 min including the time for cooking the ingredients (fish broiling: 13 min; meat frying: 6  
446 min; egg frying: 4 min; meat broiling, 3 min). The comparison of experimental building results [95]

447 between frying (deep frying meat, 2.14 mg.min<sup>-1</sup>) and grilling (meat broiling, 16.08 mg.min<sup>-1</sup>)  
448 confirmed that higher particle emissions come from grilling/broiling activities.

449 In greater detail, [91,92] tested 25 typical Chinese dishes in a domestic kitchen based on an online  
450 survey of 309 families to determine common cooking behaviours in China. A professional cook  
451 performed five cooking methods with gas stoves (stir-frying, pan-frying, deep-frying, steaming and  
452 boiling), varying the weight of the ingredients, the type of meat, the meat/vegetable ratio and the  
453 type of oil. Measuring the emission generation rate includes the use of cooking tools during the  
454 process, with doors and windows closed and ventilation systems turned off. They found that water  
455 cooking methods such as boiling [0.08 mg.min<sup>-1</sup>] and steaming [0.05 mg.min<sup>-1</sup>] produce fewer  
456 emissions compared to other frying cooking methods (stir-frying [2.56 mg.min<sup>-1</sup>], pan-frying[1.61  
457 mg.min<sup>-1</sup>].

#### 458 4.4.1.4 In-situ rates obtained

459 The oldest *in-situ* study was conducted by [96] in the 1990s on a panel of 178 residents in Riverside,  
460 CA (USA). The PM<sub>10</sub> measurements were taken with personal exposure devices; at the same time the  
461 PM<sub>2.5</sub> rates were measured in each house using indoor and outdoor stationary monitors for two  
462 consecutive 12-h periods. The monitors used were based on a PM<sub>10</sub> filter behind an impactor plate.  
463 The PM<sub>10</sub> emission rate of cooking activities was estimated at 4.1 ± 1.6 mg.min<sup>-1</sup> with 40% of the  
464 particles smaller than 2.5 µm, with 1.7 ± 0.6 mg.min<sup>-1</sup> as the PM<sub>2.5</sub> cooking emission rate. Other  
465 sources excluding cooking and smoking were estimated to emit 0.093 mg.min<sup>-1</sup> for the PM<sub>10</sub> fraction,  
466 with 20% smaller than 2.5 µm (approximately 0.018 mg.min<sup>-1</sup>) as PM<sub>2.5</sub>. This study identified smoking  
467 and cooking as the two main indoor particle sources and provides an estimation of cooking emission  
468 rates but without distinguishing cooking methods.

469 In Australia, PM<sub>2.5</sub> measurements were conducted on 16 houses [13]. The concentration was  
470 estimated simultaneously with a condensation particle counter and a photometer (sampling time 10  
471 and 30 s) over more than 48 h in the kitchen. Air change rates were measured with a tracer gas



472 method using CO<sub>2</sub> during the unoccupied period. The emission rate was then calculated using  
 473 concentration, air change rate, volume, and penetration efficiency and deposition rate. The authors  
 474 published data on cooking, frying, grilling, toasting, smoking, vacuuming and other emission rates  
 475 within the range [0.07; 2.78] mg.min<sup>-1</sup>. The results confirm that cooking activities are the main PM<sub>2.5</sub>  
 476 sources in dwellings, with high emission levels during frying and grilling activities. The concentration  
 477 increased more than 30 times the normal background concentration level during frying and up to 90  
 478 times during grilling.

479 A study in the USA also took PM<sub>2.5</sub> measurements on 37 residential homes over 7 consecutive days  
 480 for each of four seasons [90]. Concentrations were monitored for 24 h inside and outside using a  
 481 filter-based monitor. The air change rate was measured with a tracer gas method, using  
 482 perfluorocarbon. The air change rate was calculated with a mass balance. At the same time, each  
 483 occupant carried a passive sample monitor, collecting the personal PM<sub>2.5</sub> data every minute, and had  
 484 to fill in a 15-min time-step schedule. This provided the occupants' location and activities so that  
 485 emission rates of specific cooking actions (frying, grilling, toast, stovetop, burned) could be  
 486 calculated with 36 mg.min<sup>-1</sup> as the average value within the range of [10; 470] mg.min<sup>-1</sup>.

487 Recently, an *in-situ* campaign was conducted on 30 residential buildings and one experimental  
 488 building to characterise PM<sub>10</sub> and PM<sub>2.5</sub> generated by Korean cooking activities over 1 month [95]. In  
 489 the residential buildings the emissions of soup cooking, broiling and frying activities were measured  
 490 for a total of 30 min including both cooking time limited to 15 min to prevent over-cooking and  
 491 preparation time. The results were compared with Western cooking types [13] [96]: Asian cooking  
 492 gave slightly higher emission rate values within the range [0.39 mg.min<sup>-1</sup>; 20.54 mg.min<sup>-1</sup>] (Table 8).

493 Table 8: Overview of PM<sub>2.5</sub> emission rates

Cooking activities	Emission rate [mg.min <sup>-1</sup> ]	Duration [min]	Reference
<i>Cooking</i> (any food preparation using stove, no frying or grilling)	0.11		[13]
<i>Frying</i> (any food preparation using frying)	2.68	10	<i>In-situ loads</i>
<i>Grilling</i> (any food preparation using grilling)	2.78		
<i>Frying</i>		8-10	[93]

- Mozzarella 50 g (sunflower oil) electric pan, 190°C	0.03		<i>Lab kitchen</i>
- Chips 50 g (sunflower oil) electric pan, 190°C	0.03		
- Chips 50 g (sunflower oil) gas stove, max power	1.20		
- Chips 50 g (peanut oil) electric frying pan, 190°C	0.06		
- Chips 50 g (peanut oil) gas stove, max power	1.80		
- Chips 50 g (olive oil) electric frying pan, 190°C	0.20		
- Chips 50 g (olive oil) gas stove, max power	2.80		
<i>Grilling</i>			
- Aubergine 30 g, gas stove, max power	0.52		
- Cheese 70 g, gas stove, max power	9.5		
- Wurstel 130 g, gas stove, max power	10		
- Bacon 50 g electric stove	1.5		
- Bacon 50 g gas stove, min power	0.52		
- Bacon 50 g gas stove, max power	13		
<i>Cooking</i>			
- Residential building, minimum value	0.39		
- Residential building, maximum value	20.54		
<i>Boiling</i>			
- Residential building, soup	2.01		[95]
<i>Frying</i>			
- Residential building	3.80	13	<i>Lab kitchen &amp; In-situ loads</i>
- Experimental building, deep frying meat	2.14		
- Experiment building, frying 4 eggs	10.85		
<i>Grilling</i>			
- Residential building	12,02		
- Experimental building, fish broiling	22.84		
- Experimental building, meat broiling	16.08		
<i>Grilling</i>			
- Ground beef	44.90	20	[94] <i>Lab kitchen</i>
<i>Cooking</i>			
- All cooking events	36		
- Multiple events	29		
- Stove top	17	11	[90]
- Oven	10		<i>In-situ loads</i>
- Burned	470		
<i>Frying</i>	60		
<i>Grilling</i>	173		
<i>Boiling</i>			
- Meal 2, chicken (oil), potatoes, green beans (water)	0.80		
- Meal 1, chicken, potatoes (oil), green beans (water)	0.62		[89]
<i>Frying</i>			
- Meal 3, pasta (water) ,onion, bacon, beef, tomatoes (oil)	1.90	28	<i>Chamber-tested loads</i>
- Meal 4, stir-fry, chicken, prechopped vegetable, noodles (oil)	3.20		
<i>Boiling</i>			
- Steaming	0.05		
- Boiling	0.08	3-33	[91,92]
<i>Frying</i>			
- Deep-frying	0.32	mean: 13	<i>Lab kitchen</i>
- Pan-frying	1.61		
- Stir-frying	2.56		

495 4.4.2 Analysis and scenario proposals

496 We grouped cooking emission sources in four cooking types: boiling, frying, grilling and a total  
 497 cooking category taking into account any food preparation (Table 9). As expected in the articles and  
 498 confirmed by the minimum, mean, maximum and median values, grilling is the highest and boiling is  
 499 the lowest PM<sub>2.5</sub> emission cooking type.

Cooking type	Emission rate [mg.min <sup>-1</sup> ]			
	<i>min</i>	<i>mean</i>	<i>max</i>	<i>median</i>
Boiling	0.05	0.74	2.01	0.44
Frying activities	0.03	5.32	60.00	1.85
Grilling activities	0.52	25.56	173.00	11.01
Total cooking	0.03	12.65	173.00	2.56

500 Table 9. Emission rate values

501

502 Finally, a few studies took into account the entire cooking process with several food types for a  
 503 complete meal and the associated duration, especially for a representative French cooking scenario  
 504 context.

505 Assessing ventilation systems and kitchen hood performance, the O’Leary study [89] is particularly  
 506 relevant and fits our overall performance evaluation approach for ventilation systems. It took into  
 507 account all the cooking steps in a European context. The authors proposed meal 1, with the lowest  
 508 emissions, with chicken and potatoes fried in oil and green beans boiled in water [0.62 mg.min<sup>-1</sup>].  
 509 Meal 3 with pasta bolognaise had an intermediary emission rate [1.9 mg.min<sup>-1</sup>]. Meal 4 had the  
 510 highest emissions with fried chicken and vegetable noodle wok cooking [3.2 mg.min<sup>-1</sup>]. This gave  
 511 three combinations of meal 1, 3 and 4 to propose three realistic cooking scenarios for 1 week:

- 512 - Low-emission cooking practices, with the hypothesis of 50% of the meals a week, emit fewer  
 513 emissions, like meal 1, and the other 50% of the meals have medium emissions, like meal 3.
- 514 - Intermediate-emission cooking practices use diversified cooking methods, where the meal  
 515 types are equally distributed over a week [1/3 meal 1; 1/3 meal 3; 1/3 meal 4].

516 - High-emission cooking practices, with the hypothesis that 50% of the meals a week emit a  
 517 high level of emissions, such as meal 4, and the other 50% meals emit a medium range of  
 518 emissions, such as meal 3.

519 These three scenarios are summarised in Table 10 as mean values repeated twice a day with a  
 520 cooking duration of 28 min.

Scenario	Emission rate [mg.min <sup>-1</sup> ]	Duration [min]
Low-emission cooking practice (mainly boiling)	1.26	28
Intermediate-emission cooking practice	1.91	28
High-emission cooking practice (mainly grilling)	2.55	28

521 Table 10. PM<sub>2.5</sub> emission rate scenarios

522

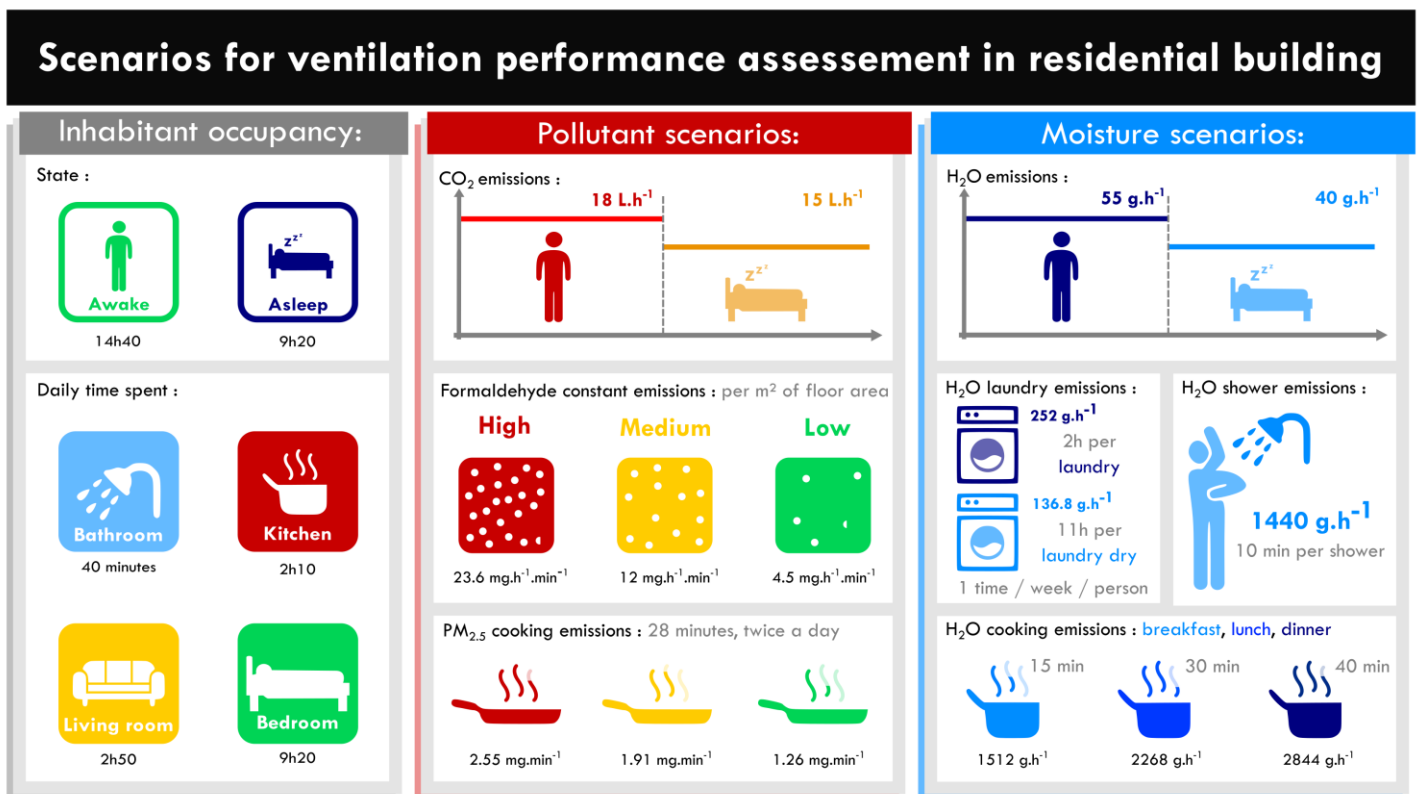
## 523 5 Synthesis of selected occupancy and emission input scenarios

524 Figure 2 summarises the input data for assessing ventilation performance at the design stage of a  
 525 building, classified into pollutant scenario data, moisture scenario data, and inhabitant occupancy  
 526 data. For PM<sub>2.5</sub> and formaldehyde emission rates, we propose three classes of emissions: high,  
 527 medium and low, to be selected depending on the available data at the design stage.

528 For formaldehyde for instance:

- 529 - If only A-class IAQ-labelled materials [97] are used and occupants are aware of this, the low-  
 530 emission formaldehyde rate can be used in the IAQ calculation. To achieve a low emission  
 531 rate, it is necessary to increase the occupants' awareness and help them become low-  
 532 emitting occupants in all their activities and furnishings. Tools have been developed for  
 533 occupants for this purpose [98]. An *in-situ* measurement campaign could also be required  
 534 once the building is occupied to encourage the low emission rate.
- 535 - If no information is given, or only D-class IAQ-labelling materials are used, a high-emission  
 536 formaldehyde rate must be used.

- 537 - In other cases, a medium-emission formaldehyde rate can be used.
- 538 For PM<sub>2.5</sub>:
- 539 - If the occupants are aware of IAQ, and their habits confirm they rarely use grilling, and if
- 540 they agree with an *in-situ* measurement campaign once the building is occupied, a low-
- 541 emission PM<sub>2.5</sub> rate can be used in the IAQ calculation.
- 542 - If no information is given, a high-emission PM<sub>2.5</sub> rate must be used.
- 543 - If the occupants are aware of IAQ, and their habits confirm they rarely use grilling, a
- 544 medium-emission PM<sub>2.5</sub> rate can be used.



545

546 Figure 2. Selected input data to be used in a performance-based approach for ventilation.

547

## 548 **6 Conclusion and perspectives**

549 We need a performance-based approach for assessing ventilation performance at the building scale,  
550 at the design stage, like the regulatory energy performance calculation to ensure energy  
551 performance. Ventilation performance assessment is often based on CO<sub>2</sub>, moisture, as they are  
552 commonly used, and on formaldehyde and PM<sub>2.5</sub> as they would be complementary. To calculate  
553 such IAQ performance indicators, few occupancy schedules and emission rate parameters are  
554 available today. This paper provides an extensive literature review of 73 articles covering detailed  
555 occupancy schedules throughout the day and the year in a house, with emission rates reflecting  
556 occupants and activities (e.g. showering, cooking), as well as building material and furniture emission  
557 rates.

558 We found relevant data on occupancy schedules, even if most of them were not precise enough to  
559 provide information on occupancy in all the rooms in a house. Substantial relevant data on CO<sub>2</sub> and  
560 humidity emissions due to inhabitants' metabolism and activities are available in the literature and  
561 we selected those that could be used in a performance-based approach at the design stage. We  
562 noted a lack of exploitable data that could be used to model PM<sub>2.5</sub> and formaldehyde average and  
563 peak emissions at the dwelling scale. As a result, we proposed using three levels of constant  
564 emission rates for formaldehyde: the low-emission rate: 4.5 µg.h<sup>-1</sup>.m<sup>-2</sup>; the medium-emission rate:  
565 12.0 µg.h<sup>-1</sup>.m<sup>-2</sup>; and the high-emission rate: 23.6 µg.h<sup>-1</sup>.m<sup>-2</sup>. For PM<sub>2.5</sub>, we also proposed three classes  
566 of emissions for cooking activities associated with a 28-min period twice a day: the low-emission  
567 rate: 1.26 mg.min<sup>-1</sup>; the medium-emission rate: 1.91 mg.min<sup>-1</sup>; and the high-emission rate: 2.55  
568 mg.min<sup>-1</sup>.

569 Our objective was to build emission scenarios for a European, or even French, application.  
570 Nevertheless, the data gathered in the present review, as well as the way of analysing them and  
571 constructing scenarios are sufficiently described and referenced here and can be easily adapted for  
572 applications in other countries.

573 We focused on long-term exposure but this approach should also be adapted to consider acute  
574 exposure, another topic of interest and a health concern.

575 As for the study's limitations, there is a lack of consistent emission data on both formaldehyde and  
576 PM<sub>2.5</sub> emissions at a building scale; consequently, the scenario proposals must be considered as a  
577 preliminary suggestion for overall ventilation performance assessment, which could be improved  
578 with further studies. The main objective of this work was to build a first baseline, directly usable in a  
579 method for assessing ventilation performance. Obviously, the proposed scenarios can evolve and be  
580 completed and improved in the future, as and when they are published, and according to the  
581 context of application in different regions or countries. One of the tracks would be to add relevant  
582 behaviours with other pollutant emissions, such as toasting toast for breakfast, for example, for  
583 PM<sub>2.5</sub>. Another would be to link formaldehyde emissions to a series of scenarios for materials and  
584 furniture depending on the type of building and occupants, when consistent data are available. In  
585 addition, it is also possible to extend the IAQ indicators by adding other pollutants, although this  
586 then adds to the knowledge of emissions data and complicates the indication of IAQ levels and the  
587 operational aspect of the performance-based approach.

588 Nevertheless, it is now possible to assess the ventilation performance at the design stage of a  
589 residential building from an IAQ point of view, using the proposed occupancy schedules and  
590 emission scenarios as input data. In future work, these scenarios will be applied in a standardised  
591 approach, by modelling ventilation systems and strategies, air inlets and outlets configurations,  
592 airflow rates, etc. Such a standardised approach will allow for example a relative comparison of the  
593 performance of classic ventilation strategies and innovative ones, as smart ventilation strategies. In  
594 order to help at the design stage, the method can be used to select a ventilation system that targets  
595 a level of energy and IAQ performance, to comply with an overall performance requirement, but also  
596 to achieve IAQ labelled products and even improve IAQ awareness among occupants.

597

- 599 [1] European Parliament, DIRECTIVE 2010/31/EU OF THE EUROPEAN  
600 PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy  
601 performance of buildings (recast), 2010. [http://eur-  
602 lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:en:PDF](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:en:PDF)  
603 (accessed November 28, 2016).
- 604 [2] N.E. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J.V.  
605 Behar, S.C. Hern, W.H. Engelmann, The National Human Activity Pattern Survey  
606 (NHAPS): a resource for assessing exposure to environmental pollutants, *J. Expo. Anal.*  
607 *Environ. Epidemiol.* 11 (2001) 231–252. <https://doi.org/10.1038/sj.jea.7500165>.
- 608 [3] European Commission, Communiqué de presse - Indoor air pollution: new EU research  
609 reveals higher risks than previously thought, (2003). [http://europa.eu/rapid/press-  
610 release\\_IP-03-1278\\_en.htm](http://europa.eu/rapid/press-release_IP-03-1278_en.htm) (accessed November 28, 2016).
- 611 [4] S. Brasche, W. Bischof, Daily time spent indoors in German homes--baseline data for  
612 the assessment of indoor exposure of German occupants, *Int. J. Hyg. Environ. Health.*  
613 208 (2005) 247–253. <https://doi.org/10.1016/j.ijheh.2005.03.003>.
- 614 [5] A. Zeghnoun, F. Dor, A. Grégoire, Description du budget espace-temps et estimation de  
615 l'exposition de la population française dans son logement, *Inst. Veille Sanit. Qual. L'air*  
616 *Intér.* Dispon. Sur [Www Air-Interieur Org.](http://www.air-interieur.org) (2010).  
617 [http://www.oqai.fr/userdata/documents/298\\_InVS\\_OQAI\\_BET\\_Logements\\_2010\\_Inter  
618 net.pdf](http://www.oqai.fr/userdata/documents/298_InVS_OQAI_BET_Logements_2010_Internet.pdf) (accessed August 4, 2016).
- 619 [6] M. Jantunen, E. Oliveira Fernandes, P. Carrer, S. Kephelopoulos, European  
620 Commission, Directorate General for Health & Consumers, Promoting actions for  
621 healthy indoor air (IAIAQ)., European Commission, Luxembourg, 2011.
- 622 [7] J.M. Logue, T.E. McKone, M.H. Sherman, B.C. Singer, Hazard assessment of chemical  
623 air contaminants measured in residences, *Indoor Air.* 21 (2011a) 92–109.  
624 <https://doi.org/10.1111/j.1600-0668.2010.00683.x>.
- 625 [8] D. Spekkink, Key note presentation on Performance-Based Building (PeBBu), in: *CIB*  
626 *Conf.*, Helsinki, Finland, 2005.
- 627 [9] C. Dimitroulopoulou, Ventilation in European dwellings: A review, *Build. Environ.* 47  
628 (2012) 109–125. <https://doi.org/10.1016/j.buildenv.2011.07.016>.
- 629 [10] G. Guyot, I.S. Walker, M.H. Sherman, Performance based approaches in standards and  
630 regulations for smart ventilation in residential buildings: a summary review, *Int. J. Vent.*  
631 0 (2018) 1–17. <https://doi.org/10.1080/14733315.2018.1435025>.
- 632 [11] G. Guyot, H. Geoffroy, M. Ondarts, L. Migne, M. Bobee, E. Gonze, M. Woloszyn,  
633 Modelling the impact of multizone airleakage on ventilation performance and indoor air  
634 quality in low-energy homes, *Build. Simul.* (2019). [https://doi.org/10.1007/s12273-019-  
635 0557-x](https://doi.org/10.1007/s12273-019-0557-x).
- 636 [12] J.M. Logue, P.N. Price, M.H. Sherman, B.C. Singer, A Method to Estimate the Chronic  
637 Health Impact of Air Pollutants in U.S. Residences, *Environ. Health Perspect.* 120  
638 (2011b) 216–222. <https://doi.org/10.1289/ehp.1104035>.
- 639 [13] C. He, Contribution from indoor sources to particle number and mass concentrations in  
640 residential houses, *Atmos. Environ.* 38 (2004) 3405–3415.  
641 <https://doi.org/10.1016/j.atmosenv.2004.03.027>.
- 642 [14] S. Kirchner, et. al., État de la qualité de l'air dans les logements français, *Environ.*  
643 *Risques Santé.* Vol. 6 (2007) 11 p.
- 644 [15] K. Koistinen, D. Kotzias, S. Kephelopoulos, C. Schlitt, P. Carrer, M. Jantunen, S.  
645 Kirchner, J. McLaughlin, L. Mølhave, E.O. Fernandes, B. Seifert, The INDEX project:



- 646 executive summary of a European Union project on indoor air pollutants, Allergy. 63  
647 (2008) 810–819. <https://doi.org/10.1111/j.1398-9995.2008.01740.x>.
- 648 [16] WHO, WHO Guidelines for Indoor Air Quality: Selected Pollutants, WHO Regional  
649 Office Europe, Bonn, Germany, 2010.
- 650 [17] W. Borsboom, W. De Gids, J. Logue, M. Sherman, P. Wargocki, TN 68: Residential  
651 Ventilation and Health, 2016.  
652 [http://www.aivc.org/sites/default/files/TN68\\_Heath%26Ventilation.pdf](http://www.aivc.org/sites/default/files/TN68_Heath%26Ventilation.pdf) (accessed  
653 March 18, 2016).
- 654 [18] G. Guyot, M.H. Sherman, I.S. Walker, Smart ventilation energy and indoor air quality  
655 performance in residential buildings: A review, *Energy Build.* 165 (2018) 416–430.  
656 <https://doi.org/10.1016/j.enbuild.2017.12.051>.
- 657 [19] ISO/IEC, ISO/IEC Guide 98-3:2008 - Uncertainty of measurement -- Part 3: Guide to  
658 the expression of uncertainty in measurement (GUM:1995), (2008).  
659 [http://www.iso.org/iso/catalogue\\_detail.htm?csnumber=50461](http://www.iso.org/iso/catalogue_detail.htm?csnumber=50461) (accessed July 7, 2016).
- 660 [20] G. Remion, B. Moujalled, M. El Mankibi, Review of tracer gas-based methods for the  
661 characterization of natural ventilation performance: Comparative analysis of their  
662 accuracy, *Build. Environ.* 160 (2019) 106180.  
663 <https://doi.org/10.1016/j.buildenv.2019.106180>.
- 664 [21] F. Haghghat, J. Rao, P. Fazio, The influence of turbulent wind on air change rates—a  
665 modelling approach, *Build. Environ.* 26 (1991) 95–109. [https://doi.org/10.1016/0360-](https://doi.org/10.1016/0360-1323(91)90017-6)  
666 [1323\(91\)90017-6](https://doi.org/10.1016/0360-1323(91)90017-6).
- 667 [22] B. Kvisgaard, P.F. Collet, The user’s influence on air change, *Air Change Rate*  
668 *Airtightness Build.* (1990). [http://inis.iaea.org/Search/search.aspx?orig\\_q=RN:22011804](http://inis.iaea.org/Search/search.aspx?orig_q=RN:22011804)  
669 (accessed July 30, 2019).
- 670 [23] M.P. Modera, D.J. Wilson, The Effects of Wind on Residential Building Leakage  
671 Measurements, *Air Change Rate Airtightness Build.* (1990).  
672 <https://doi.org/10.1520/STP17210S>.
- 673 [24] D. Cóstola, B. Blocken, M. Ohba, J.L.M. Hensen, Uncertainty in airflow rate  
674 calculations due to the use of surface-averaged pressure coefficients, *Energy Build.* 42  
675 (2010) 881–888. <https://doi.org/10.1016/j.enbuild.2009.12.010>.
- 676 [25] A. Bailly, S. Berthault, Reliability of Ventilation System Inspection for Dwellings:  
677 Comparisons of Measurements and Controls Protocols Tested during in-Situ Campaigns  
678 of the Promevent Project, in: *Proc. IAQ 2016 Defin. Indoor Air Qual. Policy Stand. Best*  
679 *Pract. Co-Organ. ASHRAE AIVC, Alexandria, VA, USA, 2016.*
- 680 [26] P. Fahlen, H. Andersson, IEA Annex 18. Demand Controlled Ventilation Systems:  
681 Sensor Tests, Swedish Council for Building Research, Stockholm, Sweden, 1992.
- 682 [27] W.J. Fisk, D. Faulkner, D.P. Sullivan, Accuracy of CO<sub>2</sub> sensors in commercial  
683 buildings: a pilot study, *Lawrence Berkeley Natl. Lab.* (2006).  
684 <https://escholarship.org/uc/item/4pq957zp.pdf> (accessed September 19, 2016).
- 685 [28] N. Barsan, D. Koziej, U. Weimar, Metal oxide-based gas sensor research: How to?,  
686 *Sens. Actuators B Chem.* 121 (2007) 18–35. <https://doi.org/10.1016/j.snb.2006.09.047>.
- 687 [29] P.-R. Chung, C.-T. Tzeng, M.-T. Ke, C.-Y. Lee, Formaldehyde Gas Sensors: A Review,  
688 *Sensors.* 13 (2013) 4468–4484. <https://doi.org/10.3390/s130404468>.
- 689 [30] G. Guyot, I.S. Walker, M. Sherman, J. Clark, Residential Smart Ventilation: A Review,  
690 LBNL Report, 2017. <https://eta.lbl.gov/sites/default/files/publications/lbnl-2001056.pdf>.
- 691 [31] AIVC, Webinar – IAQ sensors for smart ventilation of buildings, 2018.  
692 [http://www.aivc.org/event/6-march-2018-webinar-iaq-sensors-smart-ventilation-](http://www.aivc.org/event/6-march-2018-webinar-iaq-sensors-smart-ventilation-buildings)  
693 [buildings](http://www.aivc.org/event/6-march-2018-webinar-iaq-sensors-smart-ventilation-buildings) (accessed October 4, 2018).
- 694 [32] British standard, Ventilation principles and designing for natural ventilation, 1991.  
695 [http://www.aivc.org/sites/default/files/airbase\\_13035.pdf](http://www.aivc.org/sites/default/files/airbase_13035.pdf) (accessed March 1, 2017).

- 696 [33] L.G. Mansson, IEA ECBCS Annex 27 Evaluation and Demonstration of Domestic  
697 Ventilation Systems Simplified Tools Handbook, 2001.  
698 [http://www.ecbcs.org/docs/annex\\_27\\_handbook.pdf](http://www.ecbcs.org/docs/annex_27_handbook.pdf) (accessed March 1, 2017).
- 699 [34] CEN, EN FD/TR 14788. Ventilation des bâtiments - Conception et dimensionnement  
700 des systèmes de ventilation résidentiels, (2006).
- 701 [35] (Prénom) CEN, EN 15665 - Ventilation for buildings Determining performance criteria  
702 for residential ventilation systems, (2009).
- 703 [36] P. Johansson, S. Pallin, M. Shahriari, Risk Assessment Model Applied on Building  
704 Physics: Statistical Data Acquisition and Stochastic Modeling of Indoor Moisture  
705 Supply in Swedish Multi-family Dwellings, Copenhagen, Denmark., 2010.  
706 [https://www.researchgate.net/publication/275209340\\_Risk\\_Assessment\\_Model\\_Applied\\_on\\_Building\\_Physics\\_Statistical\\_Data\\_Acquisition\\_and\\_Stochastic\\_Modeling\\_of\\_Indoor\\_Moisture\\_Supply\\_in\\_Swedish\\_Multi-family\\_Dwellings](https://www.researchgate.net/publication/275209340_Risk_Assessment_Model_Applied_on_Building_Physics_Statistical_Data_Acquisition_and_Stochastic_Modeling_of_Indoor_Moisture_Supply_in_Swedish_Multi-family_Dwellings) (accessed June 12, 2018).
- 707 [37] CCFAT, VMC Simple Flux hygroréglable - Règles de calculs pour l'instruction d'une  
708 demande d'avis techniques - GS14.5 - Equipements / Ventilation et systèmes par  
709 vecteur air, (2015). <http://www.ccfat.fr/groupe-specialise/14-5/> (accessed July 20,  
710 2016).
- 711 [38] International Organization for Standardization (ISO), ISO 16000, part 9: Determination  
712 of the emission of volatile organic compounds from building products and furnishing e  
713 emission test chamber method, (2006).
- 714 [39] D. Aerts, J. Minnen, I. Glorieux, I. Wouters, F. Descamps, Discrete occupancy profiles  
715 from time-use data for user behaviour modelling in homes, in: Proc. BS 2013 13th Conf.  
716 Int. Build. Perform. Simul. Assoc., 2013.
- 717 [40] L.G. Mansson, IEA ECBCS Annex 27 Evaluation and Demonstration of Domestic  
718 Ventilation Systems Simplified Tools Handbook, 2001.  
719 [http://www.ecbcs.org/docs/annex\\_27\\_handbook.pdf](http://www.ecbcs.org/docs/annex_27_handbook.pdf) (accessed March 1, 2017).
- 720 [41] D. Bienfait, K. Fitzner, T. Lindvall, O. Seppanen, M. Woulliscroft, P.O. Fanger, M.  
721 Jantunen, E. Skaret, J. Schwer, Guidelines for Ventilation Requirements in Buildings,  
722 1992. [http://www.buildingecology.com/publications/ECA\\_Report11.pdf](http://www.buildingecology.com/publications/ECA_Report11.pdf) (accessed  
723 August 4, 2016).
- 724 [42] L.K. Knoebel, Energy metabolism, Physiology. (1963) 564–79.
- 725 [43] S. Déoux, Bâtir pour la santé des enfants, Médiéco éditions, 2010.
- 726 [44] A.-M. Bernard, Performance de la ventilation et du bâti - Phase 3 - Performance  
727 énergétique et QAI des systèmes hygroréglables, 2009.
- 728 [45] C. Rasmussen, G. Clausen, B. Berg-Munch, P.O. Fanger, The influence of human  
729 activity on ventilation requirements for the control of body odor, in: CLIMA 2000  
730 World Congr. Heat. Vent. Air-Cond., P O Fanger, Indoor Climate, Copenhagen,  
731 Denmark., 1985: pp. 357–361.
- 732 [46] J. Pejtersen, G. Clausen, Y. Zhang, J. Sorensen, T. Onishi, P.O. Fanger, Air Pollution  
733 Sources in Kindergartens, in: ASHRAE, Washington, DC, USA, 1991: p. 4.
- 734 [47] E. Thorstensen, C. Hansen, J. Pejtersen, G.H. Clausen, P.O. Fanger, Air pollution  
735 sources and indoor air quality in schools, in: Hum. Health Comf. Perform., Toronto,  
736 1990: pp. 531–536.
- 737 [48] British standard, Ventilation principles and designing for natural ventilation, 1991.  
738 [http://www.aivc.org/sites/default/files/airbase\\_13035.pdf](http://www.aivc.org/sites/default/files/airbase_13035.pdf) (accessed March 1, 2017).
- 739 [49] P. Johansson, S. Pallin, M. Shahriari, Risk Assessment Model Applied on Building  
740 Physics: Statistical Data Acquisition and Stochastic Modeling of Indoor Moisture  
741 Supply in Swedish Multi-family Dwellings, Copenhagen, Denmark., 2010.  
742 [https://www.researchgate.net/publication/275209340\\_Risk\\_Assessment\\_Model\\_Applied\\_on\\_Building\\_Physics\\_Statistical\\_Data\\_Acquisition\\_and\\_Stochastic\\_Modeling\\_of\\_Indoor\\_Moisture\\_Supply\\_in\\_Swedish\\_Multi-family\\_Dwellings](https://www.researchgate.net/publication/275209340_Risk_Assessment_Model_Applied_on_Building_Physics_Statistical_Data_Acquisition_and_Stochastic_Modeling_of_Indoor_Moisture_Supply_in_Swedish_Multi-family_Dwellings) (accessed June 12, 2018).

- 747 [50] S. Pallin, P. Johansson, C.-E. Hagentoft, Stochastic modeling of moisture supply in  
748 dwellings based on moisture production and moisture buffering capacity, in: Proc Build.  
749 Simul. 2011 12th Conf Int Build. Perform. Simul. Assoc. IBPSA, 2011.  
750 [http://www.ibpsa.org/proceedings/BS2011/P\\_1221.pdf](http://www.ibpsa.org/proceedings/BS2011/P_1221.pdf) (accessed April 4, 2017).
- 751 [51] M. Woloszyn, T. Kalamees, M. Olivier Abadie, M. Steeman, A. Sasic Kalagasidis, The  
752 effect of combining a relative-humidity-sensitive ventilation system with the moisture-  
753 buffering capacity of materials on indoor climate and energy efficiency of buildings,  
754 Build. Environ. 44 (2009) 515–524. <https://doi.org/10.1016/j.buildenv.2008.04.017>.
- 755 [52] Peuportier et al., *Energétique des bâtiments et simulation thermique - B.Peuportier,...* -  
756 Librairie Eyrolles, (2015). [http://www.eyrolles.com/BTP/Livre/energetique-des-](http://www.eyrolles.com/BTP/Livre/energetique-des-batiments-et-simulation-thermique-9782212142754)  
757 [batiments-et-simulation-thermique-9782212142754](http://www.eyrolles.com/BTP/Livre/energetique-des-batiments-et-simulation-thermique-9782212142754) (accessed April 12, 2017).
- 758 [53] J. Riberon, J.-R. Millet, Deux composants de l'air intérieur des locaux d'habitation : le  
759 gaz carbonique, la vapeur d'eau., (1991).
- 760 [54] M. Labat, M. Woloszyn, Moisture balance assessment at room scale for four cases  
761 based on numerical simulations of HAM transfers for a realistic occupancy scenario, J.  
762 Build. Perform. Simul. 9 (2015) 487–509.  
763 <https://doi.org/10.1080/19401493.2015.1107136>.
- 764 [55] I.S. Walker, M.H. Sherman, Humidity Implications for Meeting Residential Ventilation  
765 Requirements, ASHRAE J. (2007) 14.
- 766 [56] J. Page, D. Robinson, N. Morel, J.-L. Scartezzini, A generalised stochastic model for the  
767 simulation of occupant presence, Energy Build. 40 (2008) 83–98.  
768 <https://doi.org/10.1016/j.enbuild.2007.01.018>.
- 769 [57] W. Parys, D. Saelens, H. Hens, Coupling of dynamic building simulation with stochastic  
770 modelling of occupant behaviour in offices – a review-based integrated methodology, J.  
771 Build. Perform. Simul. 4 (2011) 339–358.  
772 <https://doi.org/10.1080/19401493.2010.524711>.
- 773 [58] A. Persily, Evaluating building IAQ and ventilation with indoor carbon dioxide,  
774 ASHRAE Trans. (1997).
- 775 [59] J.S. Park, K. Ikeda, Variations of formaldehyde and VOC levels during 3 years in new  
776 and older homes, Indoor Air. 16 (2006) 129–135. [https://doi.org/10.1111/j.1600-](https://doi.org/10.1111/j.1600-0668.2005.00408.x)  
777 [0668.2005.00408.x](https://doi.org/10.1111/j.1600-0668.2005.00408.x).
- 778 [60] A. Blondel, H. Plaisance, Screening of formaldehyde indoor sources and quantification  
779 of their emission using a passive sampler, Build. Environ. 46 (2011) 1284–1291.  
780 <https://doi.org/10.1016/j.buildenv.2010.12.011>.
- 781 [61] W. Liang, M. Lv, X. Yang, The combined effects of temperature and humidity on initial  
782 emittable formaldehyde concentration of a medium-density fiberboard, Build. Environ.  
783 98 (2016) 80–88. <https://doi.org/10.1016/j.buildenv.2015.12.024>.
- 784 [62] M.H. Sherman, A.T. Hodgson, Formaldehyde as a basis for residential ventilation rates,  
785 Lawrence Berkeley Natl. Lab. (2002). [http://escholarship.org/uc/item/2mm48667#page-](http://escholarship.org/uc/item/2mm48667#page-2)  
786 [2](http://escholarship.org/uc/item/2mm48667#page-2) (accessed December 12, 2013).
- 787 [63] H. Plaisance, A. Blondel, V. Desauziers, P. Mocho, Characteristics of formaldehyde  
788 emissions from indoor materials assessed by a method using passive flux sampler  
789 measurements, Build. Environ. 73 (2014) 249–255.  
790 <https://doi.org/10.1016/j.buildenv.2013.12.011>.
- 791 [64] M.O. Abadie, P. Blondeau, PANDORA database: A compilation of indoor air pollutant  
792 emissions, HVACR Res. 17 (2011) 602–613.  
793 <https://doi.org/10.1080/10789669.2011.579877>.
- 794 [65] D. Missia, T. Kopadinis, J. Bartzis, G. Ventura Silva, E. De Oliveira Fernandes, P.  
795 Carrer, P. Wolkoff, M. Stranger, E. Goelen, Literature review on product composition,  
796 emitted compounds and emissions rates and health end points from consumer products  
797 EPHECT project, WP4 report, 2012.

798 [https://sites.vito.be/sites/ephect/Working%20documents/EPHECT%20deliverables%20and%20documents/1.%20Existing%20knowledge%20and%20data%20inventory%20\(WP4\)/WP4%20Literature%20review%20final.pdf](https://sites.vito.be/sites/ephect/Working%20documents/EPHECT%20deliverables%20and%20documents/1.%20Existing%20knowledge%20and%20data%20inventory%20(WP4)/WP4%20Literature%20review%20final.pdf) (accessed March 1, 2017).

799

800

801 [66] C. Howard-Reed, B. Polidoro, Database Tools for Modeling Emissions and Control of

802 Air Pollutants from Consumer Products, Cooking, and Combustion, NIST, 2006.

803 (accessed March 20, 2017).

804 [67] CEN, EN 15251 - Indoor environmental input parameters for design and assessment of

805 energy performance of buildings addressing indoor air quality, thermal environment,

806 lighting and acoustics, (2007).

807 [68] CEN, EN 16798-1 Energy performance of buildings - Part 1 : Indoor environmental

808 input parameters for design and assessment of energy performance of buildings

809 addressing indoor air quality, thermal environment, lighting and acoustics - Module

810 M1-6, (2016). [https://sagaweb.afnor.org/fr-](https://sagaweb.afnor.org/fr-FR/splus/consultation/notice/1524454?recordfromsearch=True)

811 [FR/splus/consultation/notice/1524454?recordfromsearch=True](https://sagaweb.afnor.org/fr-FR/splus/consultation/notice/1524454?recordfromsearch=True) (accessed May 15,

812 2018).

813 [69] Hodgson et al., Volatile Organic Compound Concentrations and Emission Rates in New

814 Manufactured and Site-Built Houses, (2000). [http://cyber.sci-](http://cyber.sci-hub.cc/MTAuMTAzNC9qLjE2MDAtMDY2OC4yMDAwLjAxMDAwMzE3OC54/hodgson2000.pdf)

815 [hub.cc/MTAuMTAzNC9qLjE2MDAtMDY2OC4yMDAwLjAxMDAwMzE3OC54/hod](http://cyber.sci-hub.cc/MTAuMTAzNC9qLjE2MDAtMDY2OC4yMDAwLjAxMDAwMzE3OC54/hodgson2000.pdf)

816 [gson2000.pdf](http://cyber.sci-hub.cc/MTAuMTAzNC9qLjE2MDAtMDY2OC4yMDAwLjAxMDAwMzE3OC54/hodgson2000.pdf) (accessed April 3, 2017).

817 [70] M.H. Sherman, A.T. Hodgson, Formaldehyde as a basis for residential ventilation rates,

818 *Indoor Air.* 14 (2004) 2–8. <https://doi.org/10.1046/j.1600-0668.2003.00188.x>.

819 [71] CNRS & LaSIE, PANDORA Database, (2014).

820 [72] C. Howard-Reed, B. Polidoro, Database Tools for Modeling Emissions and Control of

821 Air Pollutants from Consumer Products, Cooking, and Combustion, NIST, 2006. Y.

822 (accessed March 20, 2017).

823 [73] X. Boulanger, L. Mouradian, C. Pele, F. Allard, A.-M. Bernard, J. Larbre, L. Broquedis,

824 N. Dufour, M. Jardinier, D. Labaume, S. Paris, P.Y. Pamart, J. Koffi, J. Boxberger,

825 QUAD BBC Project - Qualité d'air intérieur et systèmes de ventilation dans les

826 bâtiments à basse consommation d'énergie, 2012.

827 [74] L. Cony-Renaud-Salis, N. Belhaj, O. Ramalho, M. Abadie, Analysis of the need of

828 detailed modelling for the assessment of indoor air quality in residential buildings, in:

829 E3S Web Conf., Bucarest, Romania, 2019: p. 04043.

830 <https://doi.org/10.1051/e3sconf/201911104043>.

831 [75] B. Poirier, G. Guyot, M. Woloszyn, Development of Performance-Based Assessment

832 Methods for Conventional and Smart Ventilation in Residential Buildings, Accepted in

833 ASHRAE-AIVC Conference "IAQ 2020", Athens, 2021. (2020).

834 [76] C. Isaxon, A. Gudmundsson, E.Z. Nordin, L. Lönnblad, A. Dahl, G. Wieslander, M.

835 Bohgard, A. Wierzbicka, Contribution of indoor-generated particles to residential

836 exposure, *Atmos. Environ.* 106 (2015) 458–466.

837 <https://doi.org/10.1016/j.atmosenv.2014.07.053>.

838 [77] G. Bekö, C.J. Weschler, A. Wierzbicka, D.G. Karotki, J. Toftum, S. Loft, G. Clausen,

839 Ultrafine particles: Exposure and source apportionment in 56 Danish homes, *Environ.*

840 *Sci. Technol. Wash.* 47 (2013) 10240–10248. <https://doi.org/10.1021/es402429h>.

841 [78] A. Afshari, U. Matson, L.E. Ekberg, Characterization of indoor sources of fine and

842 ultrafine particles: a study conducted in a full-scale chamber, *Indoor Air.* 15 (2005)

843 141–150. <https://doi.org/10.1111/j.1600-0668.2005.00332.x>.

844 [79] E. Géhin, O. Ramalho, S. Kirchner, Size distribution and emission rate measurement of

845 fine and ultrafine particle from indoor human activities, *Atmos. Environ.* 42 (2008)

846 8341–8352. <https://doi.org/10.1016/j.atmosenv.2008.07.021>.

- 847 [80] X. Ji, Évaluation des expositions humaines aux particules ultrafines dans  
848 l'environnement domestique, Université Paris-Est, 2010. [https://hal.archives-](https://hal.archives-ouvertes.fr/hal-00688551/document)  
849 [ouvertes.fr/hal-00688551/document](https://hal.archives-ouvertes.fr/hal-00688551/document) (accessed August 29, 2016).
- 850 [81] E. Abt, H.H. Suh, P. Catalano, P. Koutrakis, Relative contribution of outdoor and indoor  
851 particle sources to indoor concentrations, *Environ. Sci. Technol.* 34 (2000) 3579–3587.
- 852 [82] C.M. Long, H.H. Suh, P. Koutrakis, Characterization of Indoor Particle Sources Using  
853 Continuous Mass and Size Monitors, *J. Air Waste Manag. Assoc.* 50 (2000) 1236–1250.  
854 <https://doi.org/10.1080/10473289.2000.10464154>.
- 855 [83] C.J. Tuckett, P. Holmes, P.T.C. Harrison, Airborne particles in the home, *J. Aerosol Sci.*  
856 29 (1998) S293–S294.
- 857 [84] H.K. Lai, M. Kendall, H. Ferrier, I. Lindup, S. Alm, O. Hänninen, M. Jantunen, P.  
858 Mathys, R. Colvile, M.R. Ashmore, P. Cullinan, M.J. Nieuwenhuijsen, Personal  
859 exposures and microenvironment concentrations of PM<sub>2.5</sub>, VOC, NO<sub>2</sub> and CO in  
860 Oxford, UK, *Atmos. Environ.* 38 (2004) 6399–6410.  
861 <https://doi.org/10.1016/j.atmosenv.2004.07.013>.
- 862 [85] L. Morawska, C. He, J. Hitchins, D. Gilbert, S. Parappukaran, The relationship  
863 between indoor and outdoor airborne particles in the residential environment, *Atmos.*  
864 *Environ.* 35 (2001) 3463–3473.
- 865 [86] A. Rohr, C. Weschler, P. Koutrakis, J. D. Spengler, Generation and Quantification of  
866 Ultrafine Particles through Terpene/Ozone Reaction in a Chamber Setting, *Aerosol Sci.*  
867 *Technol.* - AEROSOL SCI TECH. 37 (2003) 65–78.  
868 <https://doi.org/10.1080/02786820300892>.
- 869 [87] K.L. Abdullahi, J.M. Delgado-Saborit, R.M. Harrison, Emissions and indoor  
870 concentrations of particulate matter and its specific chemical components from cooking:  
871 A review, *Atmos. Environ.* 71 (2013) 260–294.  
872 <https://doi.org/10.1016/j.atmosenv.2013.01.061>.
- 873 [88] M. Amouei Torkmahalleh, S. Gorjinezhad, H.S. Unluevcek, P.K. Hopke, Review of  
874 factors impacting emission/concentration of cooking generated particulate matter, *Sci.*  
875 *Total Environ.* 586 (2017) 1046–1056. <https://doi.org/10.1016/j.scitotenv.2017.02.088>.
- 876 [89] C. O'Leary, Y. de Kluizenaar, P. Jacobs, W. Borsboom, I. Hall, B. Jones, Investigating  
877 measurements of fine particle (PM<sub>2.5</sub>) emissions from the cooking of meals and  
878 mitigating exposure using a cooker hood, *Indoor Air.* 29 (2019) 423–438.  
879 <https://doi.org/10.1111/ina.12542>.
- 880 [90] D.A. Olson, J.M. Burke, Distributions of PM<sub>2.5</sub> Source Strengths for Cooking from the  
881 Research Triangle Park Particulate Matter Panel Study, *Environ. Sci. Technol.* 40  
882 (2006) 163–169. <https://doi.org/10.1021/es050359t>.
- 883 [91] C. Chen, Y. Zhao, B. Zhao, Emission Rates of Multiple Air Pollutants Generated from  
884 Chinese Residential Cooking, *Environ. Sci. Technol.* 52 (2018) 1081–1087.  
885 <https://doi.org/10.1021/acs.est.7b05600>.
- 886 [92] Y. Zhao, C. Chen, B. Zhao, Emission characteristics of PM<sub>2.5</sub>-bound chemicals from  
887 residential Chinese cooking, *Build. Environ.* 149 (2019) 623–629.  
888 <https://doi.org/10.1016/j.buildenv.2018.12.060>.
- 889 [93] G. Buonanno, L. Morawska, L. Stabile, Particle emission factors during cooking  
890 activities, *Atmos. Environ.* 43 (2009) 3235–3242.  
891 <https://doi.org/10.1016/j.atmosenv.2009.03.044>.
- 892 [94] M.A. Torkmahalleh, S. Gorjinezhad, M. Keles, H.S. Unluevcek, C. Azgin, E. Cihan, B.  
893 Tanis, N. Soy, N. Ozaslan, F. Ozturk, P.K. Hopke, A controlled study for the  
894 characterization of PM<sub>2.5</sub> emitted during grilling ground beef meat, *J. Aerosol Sci.* 103  
895 (2017) 132–140. <https://doi.org/10.1016/j.jaerosci.2016.10.011>.

- 896 [95] K. Kang, H. Kim, D.D. Kim, Y.G. Lee, T. Kim, Characteristics of cooking-generated  
897 PM10 and PM2.5 in residential buildings with different cooking and ventilation types,  
898 Sci. Total Environ. 668 (2019) 56–66. <https://doi.org/10.1016/j.scitotenv.2019.02.316>.
- 899 [96] H. Ozkaynak, J. Xue, J. Spengler, L. Wallace, P. Jenkins, PERSONAL EXPOSURE TO  
900 AIRBORNE PARTICLES AND METALS: RESULTS FROM THE PARTICLE  
901 TEAM STUDY IN RIVERSIDE, CALIFORNIA, (n.d.) 23.
- 902 [97] French Ministry for Ecology, Compulsory labeling of VOC emission of all construction  
903 products and decorative products installed indoors, 2011.
- 904 [98] S. Déoux, C.-S. Coeudevez, S. Berlin, Guide Grand Air, (2016).  
905 [https://www.cerema.fr/system/files/documents/2018/03/MEDIECO\\_GUIDE\\_GRAND\\_](https://www.cerema.fr/system/files/documents/2018/03/MEDIECO_GUIDE_GRAND_)  
906 [AIR-Avril\\_2016.pdf](https://www.cerema.fr/system/files/documents/2018/03/MEDIECO_GUIDE_GRAND_).  
907