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Pollutants emission scenarios for residential ventilation performance assessment. A review

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Abstract

Performance-based approaches for energy consumption in new buildings are increasingly used in codes and standards. Similarly, there is ongoing research on performance-based approaches for ventilation systems. The aim is to assess indoor air quality (IAQ) performance in low-energy houses at the design stage. In this context, the whole-building IAQ performance modelling process raises a very important question: What are the emission scenarios and occupancy schedules to be used as entry data to calculate the selected performance indicators? We focus on this issue through a literature review: firstly oriented toward the occupancy considerations so as to define the emission rates for CO₂, moisture, formaldehyde and PM_{2.5} to be use as input for ventilation performance assessment.

Based on this review, we propose daily schedules for the occupants and their associated moisture and CO₂ emissions. We completed them with emission rate values for the main pollutant sources from indoor activities regarding moisture emissions from laundry, showering and cooking; PM_{2.5} emissions from cooking and formaldehyde from building materials and furniture. Finally, from these values we built three emission rates classified for PM_{2.5} and formaldehyde: high, medium and low.

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

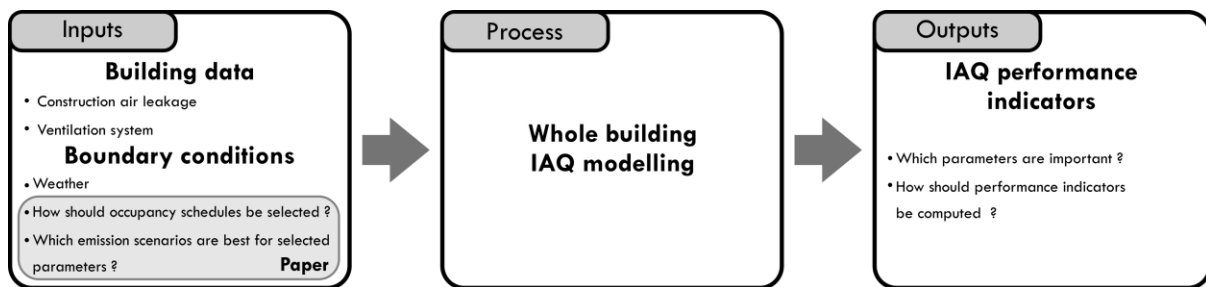
23 **1 Introduction**

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 (μ 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⁻¹.year⁻¹) and heart disease from all causes ($11,000 \mu$ DALY.(pers⁻¹.year⁻¹).
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, CO₂, formaldehyde and particle matter PM_{2.5} [10,11]. Indeed, formaldehyde and

69 PM_{2.5} 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_{2.5} and formaldehyde interesting for
75 their complementarity. Moisture and CO₂ 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. CO₂
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 CO₂, humidity, PM_{2.5} 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 "CO₂ "a", "moisture", "humidity", "formaldehyde", "fine particle matter",
95 "PM_{2.5}", "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 CO₂ 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. CO₂ 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_{2.5}), 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, CO₂ and HCHO, PM_{2.5} emissions were studied. CO₂ 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_{2.5} 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_{2.5} 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_{2.5} emission rates.
- 146 - *Lab kitchen*: PM_{2.5} 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_{2.5} emission rates.

151 For PM_{2.5} 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 CO₂ 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⁻¹ for a child and 16 L.h⁻¹ 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

	CO₂ emissions [L.h⁻¹.occupant⁻¹]	Water vapour [g.h⁻¹.occupant⁻¹]
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 ⁻¹	0.5 h	CCFAT [37]
- Lunch (weekend)	75 g.h ⁻¹ (150 g.h ⁻¹)	1 h	
- Dinner	300 g.h ⁻¹	1 h	
Shower ^(a) CCFAT / EN 15665	300 g	0.5 h / 6 min	EN 15665 [35]
Laundry ^(b)	100g.h ⁻¹	2 h	
Laundry drying ^(b)	50g.h ⁻¹	20 h	
Electric cooking device	2000 g.day ⁻¹ 3000		British standard, 1991 [48] & TR-14788 [34] (called A)
Gas cooking device	g.day ⁻¹		
Hand dish washing	400 g.day ⁻¹		
WC/shower/dish washing	200 g.day ⁻¹ .person ⁻¹		
Laundry	500 g.day ⁻¹		
Inside drying ^(c)	1500 g.day ⁻¹ .person ⁻¹		
<i>Cooking</i>			
- Breakfast	0.6 l.s ⁻¹	10 min	TR-14-88 [34]
- Lunch	1 l.s ⁻¹	10 min	(called B)

- Dinner	1.5 l.s ⁻¹	10 min	
Shower/person	0.5 l.s ⁻¹	10 min	
Laundry drying	0.06 l.s ⁻¹	12 h	
<i>Moisture generation rate</i>	Low/medium/high		
- 1 person	3.5/6/9 kg.day ⁻¹		British standard, 1991 [48] & TR-14-788 [34] (called C)
- 2 persons	4/8/11 kg.day ⁻¹		
- 3 persons	4/9/12 kg.day ⁻¹		
- 4 persons	5/10/14 kg.day ⁻¹		
- 5 persons	6/11/15 kg.day ⁻¹		
<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 ^(d)	1850 ± 670 g	11 ± 2 h	

(a) With 1 shower.day⁻¹.person⁻¹

(b) With x laundry.week⁻¹ (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⁻¹ 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 ⁻¹	ECA guidelines for	235	e 3:
- 14–16 years			50 g.h ⁻¹	ventilation requirements	236	Met
- Adult			50 g.h ⁻¹	in buildings [41]		
- <2 years	30 g.h ⁻¹	10 g.h ⁻¹			237	abol
- 10–13 years	45 g.h ⁻¹	15 g.h ⁻¹		[40]		
- >15 years	55 g.h ⁻¹	30 g.h ⁻¹			238	ism
- per person	55 g.h ⁻¹	38.5 g.h ⁻¹		[37] & [53]		
- per person	55 g.h ⁻¹	40 g.h ⁻¹		[35]	239	mois
<i>Recommended duration of emissions</i>	55 g.h ⁻¹ Living room 4 h	40 g.h ⁻¹ Bedroom 10 h		[34] & [48]	240	ture
					241	emis
- Active people	70 ± 5 g.h ⁻¹	30 ± 2 g.h ⁻¹	50 ± 5 g.h ⁻¹	<i>Experimental data</i> [49,50] cited in [52]	242	sion
- for 3 people		2.4 kg.day ⁻¹ (average 33 g.h ⁻¹ 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 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 ⁻¹]	Low 3.5 kg.day ⁻¹	Medium 6 kg.day ⁻¹	High 9 kg.day ⁻¹
1 occupant	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	-	-

264 Experimental Data [50] 2.0 X - -
 265 Table 4. Comparing calculated daily moisture emissions with thresholds given in TR 14-788-C (CEN,
 266 2006a), one occupant.

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 ⁻¹]	Low 6 kg.day ⁻¹	Medium 11 kg.day ⁻¹	High 15 kg.day ⁻¹
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⁻¹ for 10 min per shower;
- 275 - Cooking periods per day: 1512 g.h⁻¹ for breakfast for 15 min; 2268 g.h⁻¹ for lunch for 30 min;
 276 2844 g.h⁻¹ for dinner for 40 min;
- 277 - One laundry per person per week: 252 g.h⁻¹ for 2 h;
- 278 - One laundry drying per person per week (same days): 136.8 g.h⁻¹ for 11 h.

279 This results in an average production of 6 kg.day⁻¹ 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 CO₂ 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⁻¹ 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⁻¹.

288 Table 6: CO₂ metabolism emission rates

Emission rates	[L.(h.person)⁻¹]	Sources
<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⁻¹ and 15 L.h⁻¹ 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, 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 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.

Materials	Emission rates [$\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$] per m^2 of material surface area <i>unless specified otherwise</i>	Reference
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 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	
More than 8000 emission rates from consumer products and building materials		Pandora Database [71] EPEHCT project [65] NIST Database [72] <i>Chamber-tested loads</i>

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 m² 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 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 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 m^2 of floor surface area, defined by the
378 maximum calculated value.

379 **4.4 *PM_{2.5} particles***

380 **4.4.1 *PM_{2.5} 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-m³ 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_{2.5} 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-m² 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⁻¹ emitted with
433 minimum power (171°C ± 17°C) versus 13 mg.min⁻¹ with maximum power (242°C ± 5.2°C). Oil type
434 may also influence the emission rate (chips, sunflower oil, 1.20 mg.min⁻¹; chips, olive oil, 2.80
435 mg.min⁻¹) 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_{2.5} 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⁻¹.

443 Recently, [95] also measured the PM_{2.5} and PM₁₀ 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⁻¹) and grilling (meat broiling, 16.08 mg.min⁻¹)
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⁻¹] and steaming [0.05 mg.min⁻¹] produce fewer
456 emissions compared to other frying cooking methods (stir-frying [2.56 mg.min⁻¹], pan-frying[1.61
457 mg.min⁻¹].

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 PM₁₀ measurements were taken with personal exposure devices; at the same time the
461 PM_{2.5} 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 PM₁₀ filter behind an impactor plate.
463 The PM₁₀ emission rate of cooking activities was estimated at 4.1 ± 1.6 mg.min⁻¹ with 40% of the
464 particles smaller than 2.5 µm, with 1.7 ± 0.6 mg.min⁻¹ as the PM_{2.5} cooking emission rate. Other
465 sources excluding cooking and smoking were estimated to emit 0.093 mg.min⁻¹ for the PM₁₀ fraction,
466 with 20% smaller than 2.5 µm (approximately 0.018 mg.min⁻¹) as PM_{2.5}. 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_{2.5} 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 CO₂ 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⁻¹. The results confirm that cooking activities are the main PM_{2.5}
 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_{2.5} 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_{2.5} 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⁻¹ as the average value within the range of [10; 470] mg.min⁻¹.

487 Recently, an *in-situ* campaign was conducted on 30 residential buildings and one experimental
 488 building to characterise PM₁₀ and PM_{2.5} 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⁻¹; 20.54 mg.min⁻¹] (Table 8).

493 Table 8: Overview of PM_{2.5} emission rates

Cooking activities	Emission rate [mg.min ⁻¹]	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 & 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] <i>In-situ loads</i>
- Oven	10		
- 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_{2.5} emission cooking type.

Cooking type	Emission rate [mg.min ⁻¹]			
	<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⁻¹].
 509 Meal 3 with pasta bolognaise had an intermediary emission rate [1.9 mg.min⁻¹]. Meal 4 had the
 510 highest emissions with fried chicken and vegetable noodle wok cooking [3.2 mg.min⁻¹]. 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 ⁻¹]	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_{2.5} emission rate scenarios

522

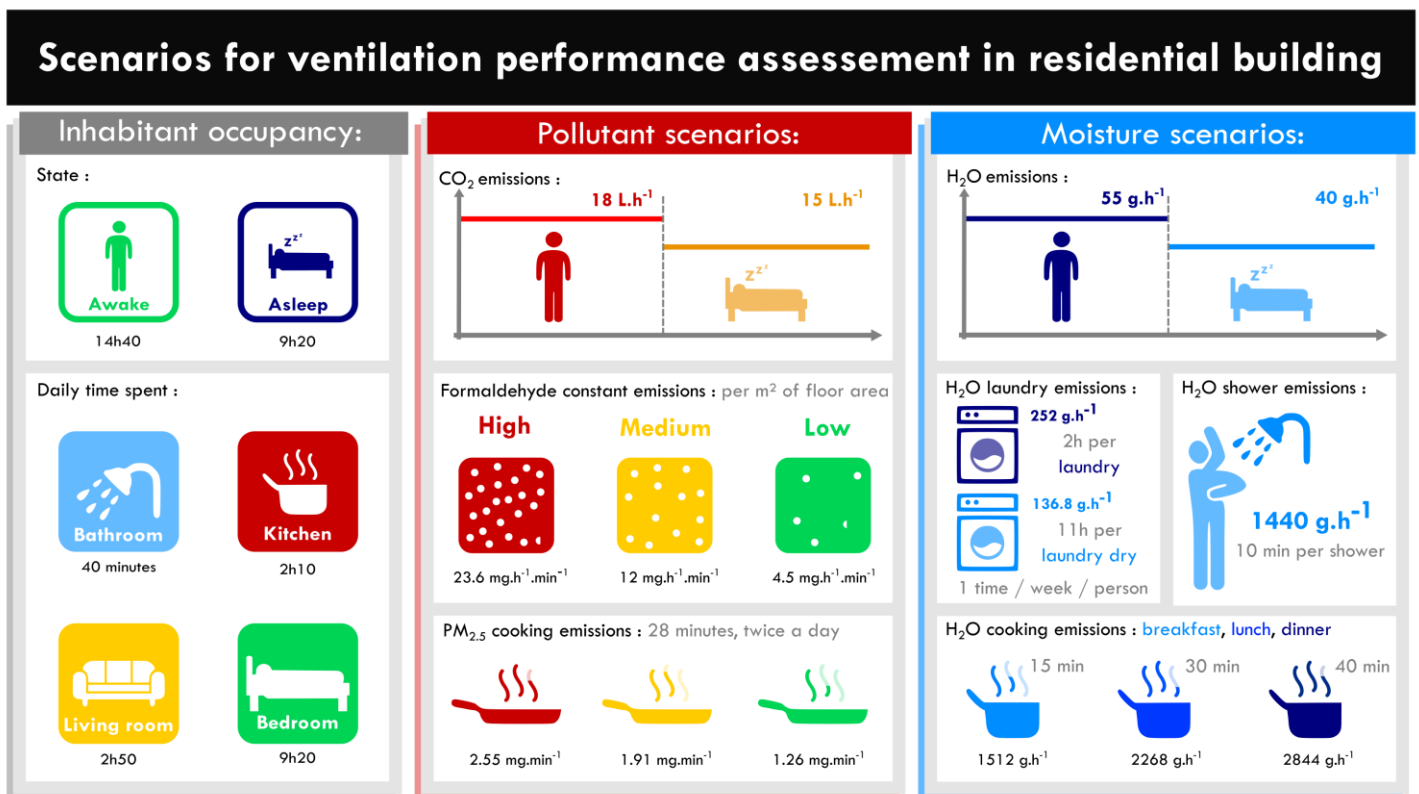
523 5 Synthesis of selected occupancy and emission input scenarios

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_{2.5} 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_{2.5}:
- 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_{2.5} rate can be used in the IAQ calculation.
- 542 - If no information is given, a high-emission PM_{2.5} 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_{2.5} 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 CO₂, moisture, as they are
552 commonly used, and on formaldehyde and PM_{2.5} 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 CO₂ 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_{2.5} 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⁻¹.m⁻²; the medium-emission rate:
565 12.0 µg.h⁻¹.m⁻²; and the high-emission rate: 23.6 µg.h⁻¹.m⁻². For PM_{2.5}, 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⁻¹; the medium-emission rate: 1.91 mg.min⁻¹; and the high-emission rate: 2.55
568 mg.min⁻¹.

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_{2.5} 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_{2.5}. 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.

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