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Development of an assessment methodology for IAQ ventilation performance in residential buildings: An investigation of relevant performance indicators

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Abstract

Ventilation of residential buildings is an important area of research, since it addresses crucial issues: providing healthy indoor air to occupants, avoiding condensation risk and damage of the building, as well as ensuring energy efficiency. With regard to regulatory or labeling requirements, performance-based approaches for ventilation should be developed. These must ensure that a ventilation system is designed not only to save energy but also to avoid risks to occupants' health. In order to formulate a performance-based approach, a crucial question has to be addressed: What are the relevant indoor air quality (IAQ) performance indicators to be calculated? In this paper, we present an extensive investigation of the literature on IAQ performance in order to identify a reduced set of relevant indicators. We identified five relevant IAQ performance indicators to be used as output data: maximum cumulative exceeding carbon dioxide (CO₂) exposure over 1,000 ppm, maximum cumulative occupant formaldehyde (HCHO) and fine particulate matter (PM_{2.5}) exposure, maximum percentage of time with relative humidity (RH) higher than 70%

24 (condensation risk), and maximum percentage of time with RH outside a range of 30–70%
25 (health risk). Importantly, we demonstrate that a performance-based method using these
26 five IAQ indicators is relevant, applying it to a low-energy house.

27 **Keywords** Ventilation, indoor air quality, performance, residential buildings, indicator,
28 review

29 **Introduction**

30 Since people spend 60–90% of their life in indoor environments (e.g., homes, offices,
31 schools), and because indoor air is generally more polluted than outdoor air, indoor air
32 quality (IAQ) is a major factor affecting public health [1–4]. For example, Logue et al. [5]
33 estimated that the current harm to public health in disability-adjusted life years (DALYs) per
34 person-year from all sources attributable to IAQ, excluding second-hand smoke (SHS) and
35 radon, was somewhere in the range between the health effects of road traffic accidents
36 (4,000 μ DALYs/person-year) and all-cause heart disease (11,000 μ DALYs/person-year).
37 According to the World Health Organization (WHO) [6], 99,000 deaths in Europe and 81,000
38 in the Americas were attributable to household (indoor) air pollution in 2012. Health gains
39 in the European Union (EU-26) due to effective implementation of IAQ requirements are
40 very important: these have been estimated at more than 300,000 DALYs per year [6].

41 The main role of building ventilation is to ensure correct IAQ. The different regulations and
42 standards throughout the world are mainly based on “prescriptive” approaches, using
43 airflows or air change rate requirements as performance indicators [7–11]. For example, the
44 French building code for residential ventilation imposes air renewal rates adapted to the
45 house size and the type of ventilation system (different airflow rates are required for
46 constant airflow ventilation and for humidity-controlled ventilation) [12].

47 However, with the same ventilation rates, we could achieve a wide range of IAQ levels. As a
48 result, standards and regulations generally set ventilation rates on the basis of comfort
49 considerations and not on health criteria, as suggested in the Healthvent project [16,17].
50 These are all based on the assumption that airflows evacuating human bioeffluents,
51 including odors, are sufficient means of controlling other contaminants [18,19], which,
52 however, cannot be guaranteed.

53 The European standard 15665 [13] proposed IAQ performance indicators for assessing
54 ventilation performance, but the long list of criteria, as well as the lack of selection of
55 parameters used to calculate these criteria, has made it inapplicable to date [9,14].

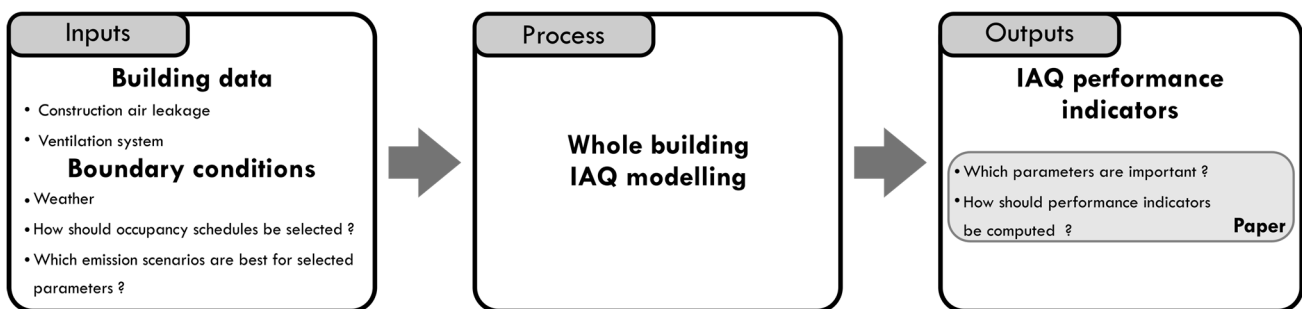
56 A “performance-based” approach, where achieved IAQ is checked at the design stage of a
57 building, is still lacking in regulations and standards and needs to be developed for building
58 ventilation [15]. The main purpose would be to evaluate IAQ performance level by
59 considering the ventilation systems globally, rather than checking ventilation rates only.

60 From a review of performance-based approaches applied to residential ventilation [16], we
61 learned that such methods were rare and almost always use IAQ indicators based on carbon
62 dioxide (CO₂) and humidity (condensation risk) only.

63 Choosing relevant pollutants and relevant indicators to assess IAQ levels in residential
64 buildings is a challenging task; indeed, the list of identified indoor pollutants is long and may
65 still grow [17]. Several reviews devoted to measurement studies of concentration levels in
66 buildings have been conducted, discussing acceptable values and proposing metrics to
67 assess IAQ performance and health impact [5,18,19]. However, there is still no consensus in
68 the literature on which pollutants are the most important to be considered, which precise
69 indicators should be used, and how to compute them at the design stage of a building. The

70 answers to these questions are a necessary step for performance-based assessment and
71 represent the research gap addressed in our paper.

72 Moreover, the choice of IAQ performance indicators, being the main output of a
73 performance-based method, also impacts the other steps of performance assessment:
74 inputs and process, as shown in Figure 1.



75

76

77 *Figure 1. Schematic diagram illustrating a performance-based approach for ventilation at the design stage of a*
78 *residential building.*

79

80 In this paper, we propose an extensive review and analysis of the literature dealing with IAQ
81 performance indicators in order to identify a reduced set of relevant indicators to be used in
82 performance-based approaches, going beyond the only two historical indicators used today
83 based on CO₂ and humidity. We then demonstrate that the proposed set of IAQ indicators
84 can be applied in a performance-based approach to ventilation system assessment,
85 illustrating this based on a case study.

86 **Methodology for the literature investigation**

87 There is no consensus on a reduced set of IAQ performance indicators to be used in a
88 performance-based method for ventilation, as illustrated by the long list of performance
89 indicators proposed in the European EN 15665 standard "*Ventilation for buildings.*
90 *Determining performance criteria for residential ventilation systems*" [13] and by the on-
91 going research for its revision. The recent International Energy Agency's Energy in Buildings
92 (IEA-EBC) Annex 68 "*Indoor air quality design and control in low energy residential buildings*"
93 proposed metrics to evaluate the IAQ of low-energy residential buildings based on 14
94 pollutants of concern [20].

95 In this paper, we used three important definitions given in the EN 15665 standard:

- 96 - **Parameter:** pollutant or marker that is used in the expression of a requirement
- 97 - **Criteria/performance indicator:** way (method) to express the required performance
- 98 - **Requirement/threshold:** level of required performance.

99 The first part of the paper addresses the first issue: the analysis and selection of the relevant
100 parameters in residential dwellings. The second part of the paper goes on to analyze the
101 corresponding IAQ performance indicators based on the selected parameters and the
102 corresponding requirements (or thresholds). Then, the third part of the paper proposes a
103 selection of five IAQ performance indicators and the corresponding requirements (or
104 thresholds) to which they should be compared in a performance-based approach. Lastly,
105 this paper presents the results of an application on a low energy house, using the selected
106 IAQ indicators to compare the performances of three ventilation systems.

107 We reviewed standards (European Committee for Standardization [CEN] and American
108 Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE]), published

109 literature, regulations from European countries, as well as resources from the Air Infiltration
110 and Ventilation Center (AIVC, IEA-EBC Annex 5) related to residential building ventilation
111 IAQ performance, using the keywords: ventilation performance, IAQ performance indicator,
112 ventilation IAQ performance, ventilation IAQ criteria, IAQ criteria, performance-based
113 ventilation. We selected only the literature relevant for the assessment of ventilation
114 systems performance. As a result, 82 documents from 1983 to 2020 were analyzed in this
115 paper.

116 **Review of parameters of concern for ventilation performance assessment**

117 In order to select the most relevant parameters for the evaluation of ventilation
118 performance, this study was motivated by a number of points: parameters already used for
119 the evaluation of ventilation systems performance; pollutants presenting a major health
120 issue because they are commonly observed and have a strong health impact; and pollutants
121 relevant for ventilation performance assessment because they are impossible to reduce at
122 source, such as those related to human metabolism or kitchen activities. We started from
123 the two commonly used parameters, CO₂ and humidity, and extended our research
124 framework to identify other pollutants that could complement them.

125 *General studies on pollutants of concern*

126 A starting point for our investigation was the AIVC technical note “TN 68: Residential
127 Ventilation and Health” [17]. Authors considered existing guidelines and standards, hazard
128 assessment, cumulative risk assessment, as well as impact assessment exposure studies,
129 and proposed a selection of high-priority pollutants for residential ventilation standards
130 (Table 1). They confirmed the importance of considering fine particulate matter (PM_{2.5}),
131 formaldehyde (HCHO) and acrolein, as pointed out elsewhere [5]. In that particular paper

132 [5], the authors estimated the population-averaged annual cost in DALYs lost due to chronic
 133 air pollutant inhalation in U.S. residential dwellings. The paper presents the results in DALYs
 134 lost per year per 100,000 persons for the 12 pollutants with the highest median DALY losses
 135 (PM_{2.5}, HCHO, acrolein, ozone, nitrogen dioxide [NO₂], ammonia, acetaldehyde,
 136 crotonaldehyde, 1,1-dichloroethene, styrene, carbon tetrachloride, 1,4-dichlorobenzene,
 137 chromium, + acute carbon monoxide [CO] deaths, radon and SHS for comparison).
 138 CO, radon and SHS were excluded in Table 1. Indeed, in the context of ventilation standards,
 139 it is important to consider ventilation as a way to dilute remaining pollutants once their
 140 sources have been reduced. From this perspective, Borsboom et al. [17] propose that
 141 tobacco smoke and radon should not be considered when establishing ventilation
 142 standards. Although these pollutants were clearly identified in a cumulative risk assessment
 143 study [5] and an impact assessment of chronic residential exposure [19], they are more
 144 impacted by home characteristics (such as the depressurization of subfloors for radon) and
 145 occupant behavior than by ventilation strategies [17]. We can assume that CO is, likewise,
 146 not a pollutant suitable for assessing ventilation performance, as shown by the results of a
 147 study [21] in which adjusting the stove had a greater impact than changes in airflows.

148 *Table 1. Selection of pollutants in residential ventilation standards [13]*

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

149 PM_{2.5} are defined as particles with an aerodynamic diameter equal or inferior to 2.5 μm,
 150 also known as fine particles. They are emitted inside and outside mainly during combustion
 151 (natural and anthropic). They can become the main contributor to the indoor pollutant
 152 concentration [22]. Furthermore, due to their small dimension, these particles can
 153

154 penetrate the human airways to varying depths and may even infiltrate the blood [23]. The
155 inhalation of these particles has a wide range of effects, from eye, nose, or throat irritation
156 to respiratory or cardiovascular dysfunction (such as myocardial infarction or stroke)
157 depending on the time and intensity of exposure [24]. As a result, several studies identified
158 PM_{2.5} as one of the pollutants of concern in dwellings [25,26,5,17]. Moreover, Logue et al.
159 [5] estimated that PM_{2.5} have a huge impact in terms of the total health damage due to
160 indoor air pollutants in the DALY calculation. The French Agency for Food, Environmental
161 and Occupational Health and Safety (ANSES) concluded that the socioeconomic cost of
162 indoor air pollutants, calculated on the basis of early mortality alone, was €19.5 billion per
163 year, of which €14.5 billion was directly attributable to suspended particulate matter [27].
164 Therefore, we decided to retain PM_{2.5}.

165 HCHO is a common volatile organic compound (VOC) that is interesting to survey in
166 dwellings for many reasons, as proposed in [5,17]. Firstly, this substance is recognized as
167 having wide-ranging health impacts, depending on the concentration as well as acute and
168 chronic exposure. Effects are known to range from eye irritation to nasopharyngeal cancer
169 (deemed to be unattributable to confounding factors), and are suspected to include other
170 neurologic, reprotoxic, and carcinogenic effects [28–30]. Secondly, this pollutant is nearly
171 always present in homes, and it is also produced almost exclusively indoors (up to 10 times
172 more than outside) due to the huge quantity of indoor emitting materials, furniture, and
173 products [31]. It can also result from the oxidation or reaction of other VOCs into alkene and
174 ozone [32]. As a result, several studies identified HCHO as one of the pollutants of concern
175 in dwellings [25,33,26,19,5,17], and we consequently decided to retain it.

176 In addition, humidity is one of the prioritized pollutants of concern identified in Table 1.
177 Indeed, the WHO shows the relationships between adverse health effects such as

178 respiratory and allergic symptoms and damp or moldy indoor environments [34]. The risk of
 179 mold has been clearly linked to the lack of performance of ventilation systems and the
 180 energy efficiency programs that tend to decrease the indoor air temperature [35].

Criteria	Pollutant	PM _{2.5}	SHS	Radon	HCHO	Acrolein	CO (acute)	NO ₂	Chloroform	CO ₂	H ₂ O
Parameters already used as indicators										x	x
Health issue based on [5] ranking		1	2	3-6	4	5	7	8	9		x
Adapted to ventilation performance evaluation		x			x	x		x	x	x	x
Total		1x	2	3-6	4x	5x	7	8x	9x	xx	xxx
Selected parameters		x			x					x	x

Table 1. Criteria and identified pollutants for the selection of parameters for ventilation performance assessment

181 Moreover, a review of performance-based approaches used in standards and regulations
 182 dedicated to smart ventilation showed that the performance indicators most widely used
 183 included criteria based on humidity to avoid condensation risk, as in France and Belgium
 184 [16].

185 Finally, in Table 2, we cross-tabulated the main pollutants previously discussed in the
 186 literature analysis with the three criteria we defined to characterize a relevant parameter
 187 for IAQ performance indicators. When deciding between the pollutants with health issues
 188 and also suited to ventilation performance evolution, such as HCHO, acrolein and NO₂, we
 189 gave priority to those with a greater impact on health. Therefore, using IAQ performance
 190 indicators based on at least the pollutants HCHO, humidity, and PM_{2.5} to assess ventilation
 191 performance appears important for risk avoidance. Moreover, CO₂ has already been used as

192 an IAQ indicator, even if its role as a pollutant is not yet clearly established, as will be
193 discussed in the following section.

194 *A focus on CO₂*

195 There is debate in the literature regarding whether CO₂ should be considered a pollutant,
196 despite the fact that it has no health consequences at concentrations observed in residential
197 dwellings, or whether it could be considered as a relevant marker in ventilation standards.

198 Indeed, several studies have shown that health effects directly attributable to CO₂ are
199 minimal at concentrations observed in indoor environments, which are commonly in the
200 range of 350–2000 ppm, and sometimes up to 6000 ppm in bedrooms during night periods
201 [36]. The American Conference of Governmental Industrial Hygienists considers 5000 ppm
202 to be the threshold for 8-h exposure in indoor environments [37]. In 2013, the ANSES
203 published results of an analysis of available CO₂ epidemiological and toxicological studies, as
204 well as of studies on the effects of CO₂ on health, performance, and comfort [38]. On the
205 basis of the results, it was concluded that the only health threshold on which several studies
206 converge is exposure of 10,000 ppm for 30 min, corresponding to respiratory acidosis for a
207 healthy adult at a modest level of physical exertion. The analysis mentions an experimental
208 study [39] of 22 human subjects, suggesting an effect on psychomotricity performance
209 above 1000 ppm attributable to CO₂ but which, according to the authors, still requires
210 further investigation. In addition, 1000 ppm is the old threshold proposed by Von
211 Pettenkofer in 1858 to prevent odors from bioeffluents, assuming an outside concentration
212 of 500 ppm [40]. Other studies of specific applications such as bomb shelters, submarines
213 [41], and high-risk industrial facilities and homes [42] have used higher threshold values for

214 CO₂. They confirm that CO₂ is not dangerous by itself at the levels measured in residential
 215 buildings.

216 The recent study by [43] shows different results. A total of 25 individuals were exposed for
 217 4 h 15 min, first to pure CO₂ (at either 1000 ppm or 3000 ppm) and then, by decreasing the
 218 ventilation rate, to all emissions from occupants (called “human bioeffluents”), including
 219 CO₂, and corresponding CO₂ levels (of either 1000 ppm or 3000 ppm). No statistically
 220 significant effects were observed in the first case; the second showed an increase in
 221 reported headaches, fatigue, sleepiness, and difficulty in thinking clearly. The authors
 222 conclude that moderate concentrations of bioeffluents, but not pure CO₂, will affect
 223 occupants at typical indoor exposure levels. This can also be seen as a study of dose–
 224 response relationships between human bioeffluents, including CO₂, and indicators of health,
 225 wellbeing, and performance.

226 From the threshold values summarized in Table 3, we highlight that, despite the consensus
 227 that pure CO₂ has no effect on human health at concentrations observed in residential
 228 settings, moderate concentrations of human bioeffluents, including CO₂, will affect
 229 occupants at typical indoor exposure levels.

230 *Table 3. CO₂ concentration levels and their associated health effect found in the literature: no effect linked to*
 231 *pure CO₂ exposition; an effect but an effect for human bioeffluents at typical indoor exposure levels*

Effects	CO ₂ threshold [ppm]	Comments	References
<i>Comfort</i>	1000	To prevent odors from bioeffluents	(Von Pettenkofer, 1858) [40]
<i>No effect</i>	1000 or 3000 for 4 h 15 min	Pure CO ₂	(Zhang, et al., 2016) [43]
<i>Increasing intensity of reported headache, fatigue, sleepiness, and difficulty thinking clearly</i>	1000 or 3000 for 4 h 15 min	Metabolic CO ₂ + human bio-effluents	(Zhang, et al., 2016) [43]
<i>Hygienic threshold in indoor environments</i>	5000	For 8-h exposure	(ACGIH, 2011) [37]

<i>Respiratory acidosis for a healthy adult at a modest level of physical exertion</i>	10,000	For 0.5 h	Several studies reviewed in (ANSES 2013) [38]
<i>Bomb shelters</i>	20,000		(de Gids and Heijnen, 2011) [41]
<i>Submarine</i>	30,000		(de Gids and Heijnen, 2011) [41]
<i>Irreversible effects</i>	50,000		(French Ministry for Ecology, 2007) [42]
<i>Mortality level</i>			(de Gids and Heijnen, 2011) [41]
<i>- 1% lethal effects threshold</i>	100,000		(French Ministry for Ecology, 2007) [42]
<i>- 5% lethal effects threshold</i>	200,000		(French Ministry for Ecology, 2007) [42]

232

233 Moreover, several authors agree that CO₂ is a good marker of occupant emissions, including
234 bio-emissions and odors [40,44–46,43], as well as some VOC and particle emissions from
235 office equipment used by occupants [47–49]. Emmerich and Persily, 2011 [48] justify the use
236 of CO₂ as an indicator of ventilation rate per person based on regulations or standards, since
237 the relationship between indoor CO₂ concentration and ventilation rates is well understood
238 and described in [50–52]. It has also been recommended that CO₂ be monitored to mitigate
239 the risk of virus transmission during the COVID-19 pandemic and used, for example, as a
240 traffic light indicator based on CO₂ level (yellow/orange light is set to 800 ppm and the red
241 light up to 1000 ppm) [53]. Other slightly different values have been applied in specific
242 countries such as France [54] and Belgium [55]. All analyzed performance-based approaches
243 used in regulations and standards for smart ventilation have used performance indicators
244 based on CO₂ [16], as have most of the analyzed literature on smart ventilation performance
245 [56].

246 In summary, the analyzed literature shows that using CO₂ is relevant as a parameter for
247 performance-based approaches for ventilation. Indeed, it is at least correlated with
248 bioeffluents, which affect occupant health at CO₂ concentrations widely measured in
249 dwellings. Therefore, CO₂ is relevant, but needs to be used with other parameters.

250 **Review of IAQ ventilation performance indicators and thresholds based on** 251 **the selected parameters of concern**

252 Once the parameters have been identified, relevant IAQ performance indicators also need
253 to be determined. However, qualifying and quantifying IAQ is a complex issue. For each
254 parameter, there are several ways of using measured or calculated data related to the
255 individual parameter. Performance indicators could be related to background or peak
256 exposures, or may be calculated over different time periods (whole year/heating period/one
257 standardized week in the winter, etc.). Depending on the information we are looking for, it
258 can be relevant to calculate the indicators per occupant (dose or exposure) or per zone
259 (condensation risk), including either the whole building, specific zones, or all zones, etc.

260 *Pollutants with dose–response law-based indicators*

261 Most of the performance indicators based on pollutants in the literature come from
262 measurement campaigns and are related to comparisons with a given threshold, set to
263 different levels depending on guides and regulations in different countries and referred to
264 as “IAQ metrics.” The IEA-EBC Annex 68 “*Indoor air quality design and control in low energy*
265 *residential buildings*” [18] proposed using three IAQ metrics:

- 266 - *For long-term exposure:* the maximum value, among the pollutants of concern, of
267 the ratio between the mean concentration and the reference exposure limit value

268 (ELV) set to the minimal value used worldwide, i.e., 9 µg/m³ for HCHO [57] and 10
269 µg/m³ for PM_{2.5} [26]

270 - *For short-term exposure:* the maximum value among the pollutants of concern of the
271 ratio between the mean concentration, over the reference period for the reference
272 acute ELV, and the related acute ELV set to the minimum value used worldwide, i.e.,
273 for HCHO, 123 µg/m³ for HCHO over 1 h (Canada) and 25 µg/m³ for PM_{2.5} over 24 h
274 (WHO)

275 - *The DALY metric* described elsewhere [5].

276 Other studies use a different approach based on the dose–response law approach [58–60].

277 The dose depends on the cumulative exposure, which is an indicator calculated per person
278 as shown by Equation 1 [61]. This indicator is rarely used in an in situ measurement context,
279 as it would need to be calculated to know exactly where occupants are in the house at each
280 time step and to measure the concentrations in each of the rooms, as well as at each time
281 step. At the design stage of a building, it can be calculated starting from occupancy
282 schedules used as input data.

283
$$CumExp_i = \sum_{t=0}^d C(t) \cdot \Delta t$$

284 *(Equation 1)*

285 where the cumulative exposure $CumExp_i$ (kg.m⁻³.h) for an occupant i , is the sum of $C(t)$
286 pollutant concentration level (in kg.m⁻³) to which the occupant is exposed at the instant t ,
287 multiplied by the time step Δt (depending on the measurement or the simulation time step)
288 and d the total duration (of the measurement or the simulation).

289 The average occupant exposure, $AvgExp$, is another performance indicator proposed by
290 the EN 15665 [13]. It is defined as the average concentration to which an occupant is

291 exposed. It can be obtained by dividing the cumulative exposure by the total duration of the
 292 simulation (Equation 2).

$$293 \quad \text{AvgExp}_i = \frac{\sum_{t=0}^d C(t) \cdot \Delta t}{d} = \frac{\text{CumExp}_i}{d}$$

294 (Equation 2)

295 where AvgExp_i (in $\text{kg} \cdot \text{m}^{-3}$) is the ratio between CumExp_i (in $\text{kg} \cdot \text{m}^{-3}$) and the total duration d .

296 In a more general way, the EN 15665 standard [13] also proposes using the following IAQ
 297 performance indicators depending on whether they are related to specific activities or
 298 background pollution:

- 299 - For specific activities: maximum threshold, average and weighted concentration,
 300 average exceeding concentration over a threshold value, dose above a given value,
 301 decay criteria, time to obtain a percentage of the maximum value, and value after a
 302 certain time
- 303 - For background pollutants: maximum threshold, average and weighted
 304 concentration, average exceeding concentration over a threshold value, and dose
 305 above a given value

306 Table 4 provides an overview of the pollutants with dose–response law-based performance
 307 indicators.

308 *Table 4. Pollutant-based performance indicators in the reviewed literature*

Performance indicators	Thresholds	References
<i>Three IAQ metrics</i>		
- $C_{\text{long-term}}/\text{ELV}_{\text{long-term}}$	$\text{ELV}_{\text{long-term}} = 9 \mu\text{g}/\text{m}^3$ for HCHO and $10 \mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$	[18]
- $C_{\text{short-term}}/\text{ELV}_{\text{acute}}$	$\text{ELV}_{\text{acute}} = 123 \mu\text{g}/\text{m}^3$ over 1 h for HCHO and $25 \mu\text{g}/\text{m}^3$ over 24 h for particulate matter $\text{PM}_{2.5}$	
- DALY	No threshold	
Cumulative exposure CumExp_i or	Depending on pollutant; $\text{ELV} \cdot d (\mu\text{g} \cdot \text{m}^{-3} \cdot \text{h})$	[62]

309

310 *Humidity-based indicators*

311 We also reviewed IAQ performance indicators related to humidity. Variables associated with
312 humidity are relative humidity (RH) and absolute humidity. RH is the ratio of water vapor
313 pressure in the air at a given temperature to the saturation water vapor pressure at the
314 same temperature. Absolute humidity is the mass of water vapor in the air per unit mass of
315 air. It is rarely used as an IAQ performance indicator (EN 16798-1 [11]). RH is the parameter
316 most commonly measured and used, as shown in Table 5.

317 Performance indicators related to humidity can be divided into two categories:

- 318 1. To assess occupant comfort and health: indicators related to an acceptable range
319 and number of hours out of this range, as proposed in the standard EN 15665[13].
320 For example, some authors [65,66] note that the minimum thresholds for RH vary
321 within the range of 20–30%, while the maximum thresholds vary in the range of 65–
322 80%. Very rarely, only the number of hours when RH is lower than a threshold
323 should be calculated. Mansson et al. [67] propose that the number of hours with RH
324 lower than 30% should not exceed 800 h.
- 325 2. To assess the condensation risk in a building: the number of hours during a given
326 period with humidity higher than a given threshold, set to 75% in the French
327 regulation for demand-controlled ventilation (DCV) [68] or to 80% in the former
328 Belgium regulation for DCV [69]. In Nordic countries, however, strongly varying
329 thresholds could be set, with [70] proposing 45%.

330 Some authors, such as Woloszyn et al. [71], propose more detailed indicators as boxplots,
 331 which are also relevant for scientific analysis. However, they are less appropriate for use in a
 332 regulatory context.

333 This part of the literature is summarized in Table 5.

334 *Table 5. Humidity-based performance indicators in the reviewed literature*

Performance indicators	Thresholds	References
Absolute humidity	< 12 g/kg	EN 16798-1 [11]
Number of hours with RH < 30%	< 800 h	
4-Week period with water vapor content < 7g/kg during the heating season	< 0	[67]
RH	<i>Usual range</i> [min; max] Min [20–40%] Max [60–80%]	[65]
RH	<i>Acceptable range</i> [30; 70%]	[72] and TR 14788 [73]
Number of hours with RH under or over the range Time ratio when the value of RH is over the range during a selected period	Not given	EN 15665 [13]
RH boxplot	[40; 50%]	Inspired by EN 15251 [71,74]
Number of hours with RH >75% Over the heating period	WC and main room < 100 h Kitchen < 600 h Bathroom < 1000 h	French regulation for DCV [68]
Time per month during which critical thermal bridges are exposed to RH > 80% from December 1 to March 1	No absolute threshold	Former Belgian regulation for DCV [69]
Number of hours with RH > 45% (in Nordic countries)	Not given	[70]

335

336 *CO₂-based indicators*

337 We reviewed IAQ performance indicators related to CO₂. The EN 15655 (CEN, 2009)
 338 standard proposes using four different indicators for a background pollutant: the average
 339 concentration, the weighted concentration, the average exceeding concentration above a
 340 threshold value, and the dose above a threshold value. Concentrations can be compared
 341 with four classes in order to assess the IAQ level, as proposed by several standards such as
 342 EN 16798-1 [11], the Finnish Society of Indoor Air Quality and Climate (FISIAQ) [75], and EN

343 13779 [76], assuming an outdoor concentration of 400 ppm: CO₂ lower than 750 or
344 800 ppm, between 750/800 ppm and 900/1000 ppm, between 900/1000 ppm and
345 1200/1400 ppm, and higher.

346 Based on this approach, Ribéron et al. proposed using the air stuffiness index for homes
347 (ICONE) [77]. This index is given in (Equation 3) as a log function of the percentage of time
348 when the measured CO₂ concentration at night is higher than 1000 ppm (f_1), and 1700 ppm
349 (f_2), in the main bedroom and the living room:

$$350 \quad I_{ICONE} = 8.3 \log(1 + f_1 + 3f_2)$$

351 *(Equation 3)*

352 Recent studies on ventilation performance [9,78] used a large set of indicators (six):
 353 cumulative exposure over 1000 ppm (ppm.h), standardized by the duration of the heating
 354 period or by the exceeding period; average exceeding concentration above 1000 ppm;
 355 average concentration; percentage of time spent in four classes based on the three
 356 thresholds (400, 600, and 1000 ppm) above outdoor concentration; exposure cumulative
 357 frequency plot; and standard deviation of concentrations.

358 Most of the performance-based approaches for ventilation reviewed in [16] (from France,
 359 Spain, The Netherlands, and Belgium), as well as some references such as the IEA (Mansson,
 360 [67], p. 27) and several papers [9,79–81], propose adapting the “dose” concept initially used
 361 for pollutants and calculating a cumulative exceeding exposure over thresholds varying
 362 between 950 ppm and 2000 ppm. These are sometimes calculated per room or per person,
 363 and the calculation period can also vary (whole year, several definitions of heating period,
 364 etc.), as described in the last lines of Table 6.

365 Table 6 summarizes CO₂-based performance indicators and associated thresholds in the
 366 reviewed literature.

367 *Table 6. CO₂-based performance indicators and thresholds in the reviewed literature*

CO ₂ -based performance indicators	Thresholds	References
Average concentration, weighted concentration, average exceeding concentration above a threshold value, dose above a threshold value	Four classes based on 750; 900; 1200 (ppm)	EN 15655 (background pollutant) [13]
	800; 1000; 1400 (ppm)	EN 16798-1 [11] + [75]
	above C _{outdoor}	EN 13779 [76]
The air stuffiness index for homes, ICONÉ $I_{ICONE} = 8.3 \log(1 + f_1 + 3f_2)$	Not given (relative comparison)	[77]
- Cumulative exposure over 1000 ppm (ppm.h): standardized by the heating period duration or by the exceeding period	Not given (relative comparison)	[9,78]
- Average exceeding concentration above 1000 ppm		
- Average concentration		
- Percentage of time spent in four classes based on the		

three thresholds (400, 600, 1000 ppm) (outdoor=0)		
- Exposure cumulative frequency plot		
- Standard deviation of concentrations		
Cumulative exposure over 1050 ppm (ppm.h)	Not given (relative comparison)	<i>Annex 27 IEA [67]</i>
Cumulative exposure indicator over 2000 ppm (ppm.h) in each room	400,000 ppm.h	<i>French regulation for DCV [68]</i>
Yearly averaged concentration in each room	900 ppm	<i>Spanish regulation for ventilation [82]</i>
Yearly cumulative exposure over 1600 ppm in each room	500,000 ppm.h	
Per-person cumulative exposure over 950 ppm	Not given (relative comparison)	<i>Former Belgian regulation for DCV [69]</i>
Per-person exposure index over 1200 ppm (LKI_{1200})		
$LKI_{1200} = \sum_{t=0}^T \left(\frac{C_{CO_2 > 1200}(t) - 1200}{1000} \right) * t$	30,000 ppm.h	<i>Dutch regulation for DCV [83]</i>

368 **Proposal for a reduced set of performance indicators and associated**
369 **thresholds**

370 The challenge in our investigation consists in identifying and selecting, from the long lists of
371 indicators described in Tables 4–6, a reduced set of performance indicators to assess the
372 IAQ performance of ventilation at the design stage of a building. Indeed, if we compare our
373 approach with the ones developed for energy performance, usually only two or three
374 performance indicators are used (total primary energy consumption, summer comfort
375 indicator, renewables integration indicator, etc.).

376 Since we identified four relevant parameters: HCHO, humidity, CO₂, and PM_{2.5}, to assess
377 ventilation performance, we wanted at least one performance indicator per parameter. We
378 proposed two indicators for humidity, since we wanted to assess two separate risks: the
379 condensation risk (building damage risk and indirect health risk to occupants) and the direct
380 health risk.

381 For pollutants with dose–response laws, HCHO and PM_{2.5}, our investigation considered the
382 cumulative exposure indicator as important at the design stage of a building. Indeed, it is
383 directly related to the response on health, and dose thresholds have been proposed in the
384 literature from dose–response studies [62]. In our work, we focused on long-term exposure.
385 We also considered the maximum cumulative exposure among the occupants of a home as
386 the most relevant performance indicator related to pollutants at the dwelling scale:
387 *MaxExp* (Equation 4).

388 This could be compared with the cumulative exposure corresponding to the reference ELV
389 set to the minimum value used worldwide, as proposed by Cony Renaud Salis et al. [18].

$$390 \quad \text{MaxExp} = \max_i \left(\sum_{t=0}^d C(t) \cdot \Delta t \right) = \max_i (\text{CumExp}_i)$$

391 (Equation 4)

392 where *i* is related to the building occupants.

393 Therefore, we proposed a reduced set of five IAQ performance indicators based on health
394 and building preservation, including one indicator based on the bedrooms where occupants
395 spent most of their time[1,3], one indicator based on all rooms, and three indicators based
396 on occupants:

- 397 - **I_{CO2}** = Cumulative CO₂ exposure exceeding the reference value (for instance: over
398 1000 ppm) – maximum of all bedrooms
- 399 - **I_{HCHO}** = Cumulative HCHO exposure of occupants – maximum of all occupants (health
400 risk)
- 401 - **I_{PM2.5}** = Cumulative PM_{2.5} exposure of occupants – maximum of all occupants (health
402 risk)

- 403 - I_{RH70} = Percentage of time with RH higher than a threshold (for instance: 70%) –
404 maximum of all rooms (condensation risk)
- 405 - I_{RH30_70} = Percentage of time spent by an occupant with RH outside of a given range
406 (for instance: 30%–70%) – maximum of all occupants (health risk)

407 The time intervals to be calculated over a total duration time d correspond to the heating
408 period for mild climates where air conditioning is rare (as in France).

409 These performance indicators could then be compared with selected thresholds. In order to
410 illustrate this proposal, we selected published thresholds presented in Table 7 and adapted
411 them to a simulation duration d in hours. For CO₂, HCHO, and PM_{2.5}, we propose comparing
412 the calculated cumulative exposure to the threshold exposure corresponding to a constant
413 threshold concentration (1000 ppm, 9 µg.m⁻³, and 10 µg.m⁻³, respectively) during the entire
414 simulation. For the maximum time spent with RH >70% in all the rooms, we propose
415 comparing it to the ratio between the number of hours thresholds and the duration d used
416 in technical agreements for French DCV [68]. In this reference, the thresholds for number of
417 hours with RH >75% are 1000 h in bathrooms, 600 h in the kitchen, and 100 h in all other
418 rooms. With a simulation duration equal to 5568 h (during the heating period from 1 Oct to
419 20 May), we obtain the thresholds expressed in percentages equal to 18%, 10.8%, and 1.8%,
420 respectively. We propose keeping the distinction made between rooms, calculating local
421 indicators ($I_{RH70,r}$) for each of the three types of rooms.

422 For the maximum time spent indoors by an occupant with RH out of the range 30–70%, we
423 propose comparing it to the ratio between a threshold and the duration d . Mansson [84]
424 proposes the threshold of 800 h for time spent with RH <30%, but using three different
425 heating period durations d depending on the location (Nice 13 Nov–27 Apr; London 27

426 Sept–20 May ; Ottawa 2 Oct–20 May). We calculated the ratio as a percentage threshold
 427 with the Ottawa duration equal to 5544 h, in order to have a duration d close to the one
 428 used for the I_{RH70} thresholds and to keep the same order of magnitude.

429 *Table 7. Selected IAQ performance indicators and corresponding thresholds calculated for a simulation duration*
 430 *d (hours).*

IAQ performance indicators		Thresholds	Reference used to calculate the indicator
I_{CO_2}	Maximum cumulative exceeding CO ₂ exposure over 1000 ppm in the bedrooms (BR) (ppm.h)	1000 d (ppm.h)	[43] 1000 ppm combined with occupants' bioeffluents
I_{HCHO}	Maximum cumulative occupant HCHO exposure ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}$)	9 d ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}$)	[18] 9 $\mu\text{g}\cdot\text{m}^{-3}$ proposed as the ELV for HCHO
$I_{PM_{2.5}}$	Maximum cumulative occupant PM _{2.5} exposure ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}$)	10 d ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}$)	[18] 10 $\mu\text{g}\cdot\text{m}^{-3}$ proposed as the ELV for PM _{2.5}
$I_{RH70,r}$	Maximum time spent with RH >70%	Bathrooms: 18%	[68] 1000 h/600 h/100 h are the thresholds for RH >75% in bathrooms/kitchen/other
	By room r (%)	Kitchen: 10.8%	
		Other rooms: 1.8%	We keep these values in a conservative approach
I_{RH30_70}	Maximum time spent by the occupant with RH out of 30–70% (%)	14.4%	[67] 800 h is the threshold for RH <30%. We select the value of 800 h in a conservative approach

431
 432 Results could be given with the radar approach as proposed in Figure 2, plotting each
 433 normalized indicator (Equations 5 & 6), which must be lower than 1 for a regulatory
 434 approach requiring compliance with thresholds values, as illustrated in black line on the
 435 radar.

436
$$I^n = \frac{I}{\text{Threshold}}; \text{ for } I^n_{CO_2}, I^n_{HCHO}, I^n_{PM_{2.5}}, I^n_{30_70}$$

437 (Equation 5)

438

$$I^n = \max\left(\frac{I_r}{\text{Threshold}(r)}\right); \text{ for } I^n_{RH70}$$

439

(Equation 6)

440

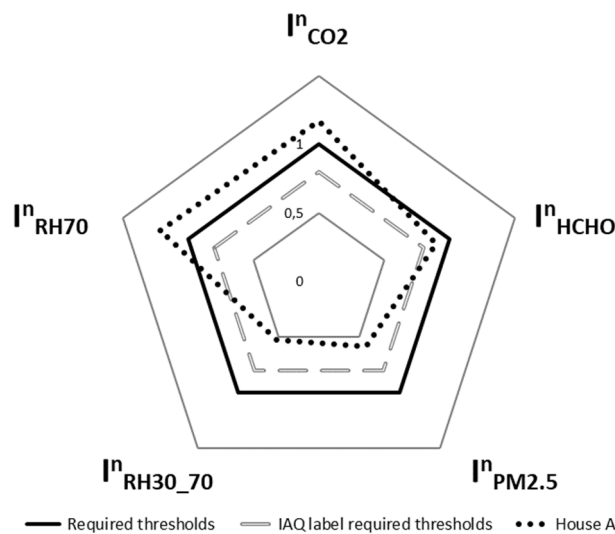
These could also be required to be lower than 80% to claim an IAQ label, as illustrated by

441

the gray dotted line on the radar. In the given case for a completely hypothetical “House A,”

442

changes must be made to the ventilation design (and/or also to occupant behavior to



443

reduce emissions levels) in order to allow the ratios I^n_{CO2} and $I^n_{PM2.5}$, to be lower than 1.

444

Figure 2. Visualization proposal: calculated IAQ indicator ratios with their thresholds at the design stage of “House A.” The black pentagon illustrates the required thresholds by the regulations (ratio=1). The dotted gray pentagon could illustrate a better performance results expected for an IAQ label (ratio=0.8).

447

448 Application to a case study: a low-energy house

449 Case study

450

The case study is a low-energy, two-storey detached brick house, as shown in Figure 3 and

451

described in [85]. We assume being at the design stage of this house, which must comply

452

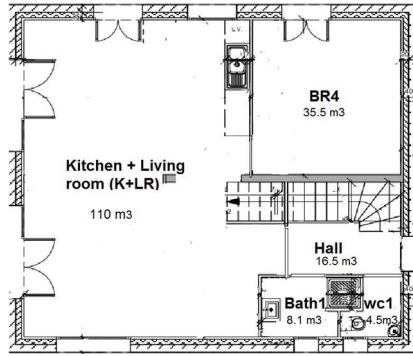
with a hypothetical regulation, code, or label, requiring the proposed IAQ ventilation

453

performance indicators to be calculated according to the proposed method.

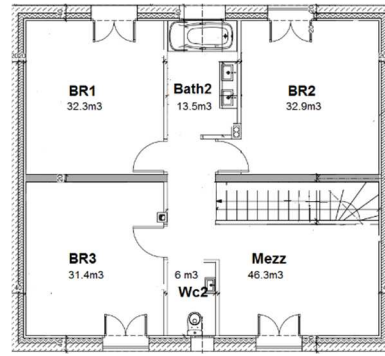
454

a)



455

b)

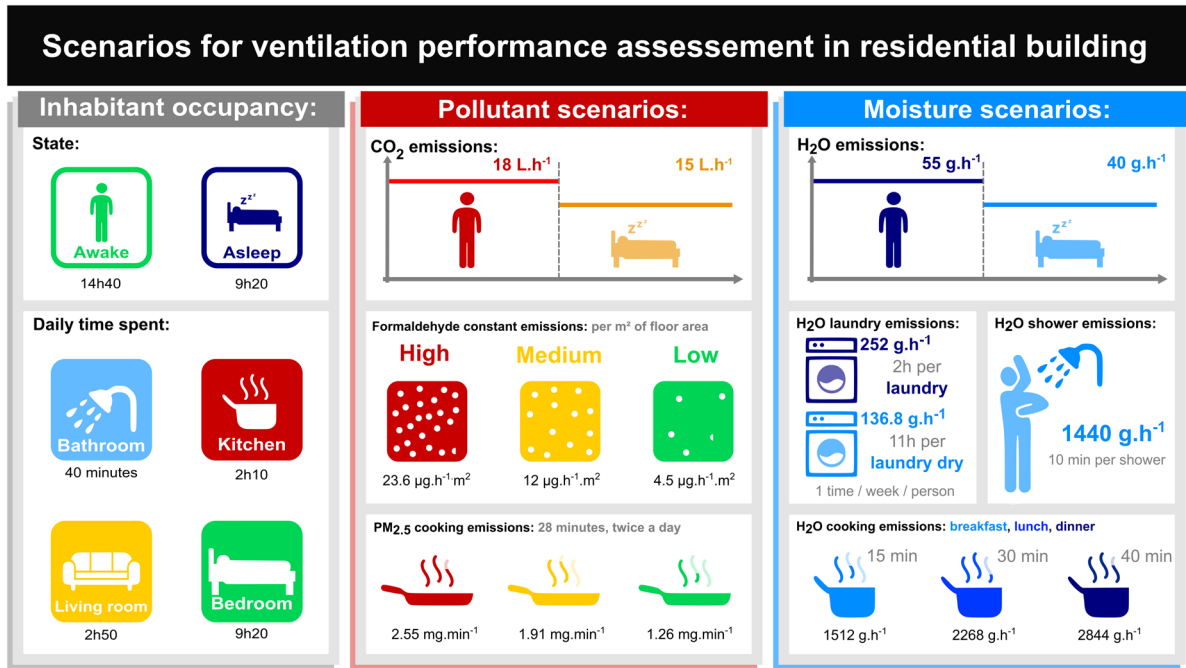


456

Figure 3. Plan of the house studied: (a) ground floor (b) first floor.

457 Airflows, RH, PM_{2.5}, CO₂, and HCHO concentrations were computed using numerical
458 modeling with CONTAM software [86]. The house was modeled using 11 zones, each room
459 represented by one zone. A 10-min time step was selected with weather data for a typical
460 year in Lyon, France (ASHRAE IWECC Weather file, 2001). The calculation was performed over
461 the heating period from October 15, 00:00 AM, to April 14, 12:00 PM, accounting for 4366
462 simulated hours. The inside temperature was set to 20°C during this period. The wind at the
463 building was calculated from the weather data using a 0.3287 modifier factor, resulting from
464 a power law used with factors from a suburban area and the house being 8.5 m in elevation.
465 The pressure coefficients from the EN 15242 were used, assuming no barrier, i.e., +0.5 on
466 the upwind facades and -0.7 on the downwind facades.

467 The moisture buffering effect was represented using the boundary layer diffusion model in
468 CONTAM. The simplified particles phenomena implemented in CONTAM were used with a
469 default penetration rate of 1, a deposition velocity using 0.65 m.h⁻¹, and 9.90 .10⁻⁷ h⁻¹ as
470 indoor particle resuspension rate based on measured median values in a four-resident
471 dwelling given in [87]. We used the pollutant emission data and occupancy schedules
472 proposed in an extensive review [88], as summarized in Figure 4. Only three indoor emission
473 scenarios (low/medium/high) for HCHO and PM_{2.5} were simulated.



474

475

Figure 4. Scenarios of pollutant emission and occupancy schedules used (from [88])

476

Description of the three ventilation systems

477

Several options for the ventilation system were assessed, complying with French airing

478

regulations [89]:

479

1. **An exhaust-only** constant airflow ventilation system (EV)

480

2. **A balanced** constant airflow ventilation system (BV) (extracted airflows at each exhaust

481

component are the same for 1 and 2)

482

3. **A humidity-based** demand-controlled ventilation (DCV) system, considered to be one of

483

the references in France.

484

According to French regulations, for a seven-room house with two bathrooms and two

485

toilets, a constant-airflow ventilation system must provide the following extracted flows: 30

486

$\text{m}^3 \cdot \text{h}^{-1}$ in each bathroom, $15 \text{ m}^3 \cdot \text{h}^{-1}$ in each toilet, and $45 \text{ m}^3 \cdot \text{h}^{-1}$ in the kitchen. A high-speed

487

ventilation system must also be able to provide $135 \text{ m}^3 \cdot \text{h}^{-1}$ in the kitchen during peak

488

periods. As a result, the total extracted airflow in the whole house is $135 \text{ m}^3 \cdot \text{h}^{-1}$ during basic

489 mode and $225 \text{ m}^3 \cdot \text{h}^{-1}$ during peak mode. The basic mode accounts for an average dwelling
490 air change rate of 0.4 h^{-1} .

491 The humidity DCV system adjusts the airflows according to the direct RH measurement
492 through the extensions and retractions of a hygroscopic fabric modifying the cross-section
493 of inlets and outlets [90]. In our case study, this system includes:

- 494 • A kitchen exhaust Air Terminal Device (ATD) providing an airflow of between 15 and
495 $55 \text{ m}^3 \cdot \text{h}^{-1}$, and a peak airflow of $135 \text{ m}^3 \cdot \text{h}^{-1}$ for 30 min if activated by the user
- 496 • Bathroom exhaust ATD providing an airflow of between 5 and $45 \text{ m}^3 \cdot \text{h}^{-1}$
- 497 • Toilet exhaust ATD providing a constant airflow of $5 \text{ m}^3 \cdot \text{h}^{-1}$, which could be switched
498 to $30 \text{ m}^3 \cdot \text{h}^{-1}$ for 20 min thanks to an occupancy sensor
- 499 • One trickle ventilator in each bedroom and two in the living room, with an operating
500 rate of between $4 \text{ m}^3 \cdot \text{h}^{-1}$ and $31 \text{ m}^3 \cdot \text{h}^{-1}$ (reference pressure of 10 Pa).

501

502 *Results and discussion*

503 The main results of this case study are detailed in Table 8 for each of the three emission
504 scenarios (low/medium/high for HCHO and PM_{2.5}). Figure 5 focuses on the medium emission
505 scenarios as an example. It shows the IAQ performance of the three ventilation systems,

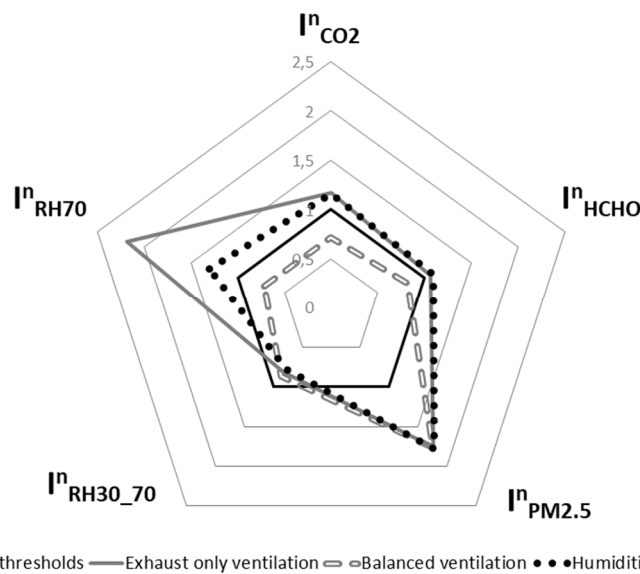


Figure 1. Normalized performance indicators for all three ventilation systems (medium emission scenarios)

506 assessed according to the five selected IAQ indicators for this case study.

507

508 With this performance-based approach applied to this study case, we can first observe that
509 none of these three ventilation systems either reaches all the IAQ targets or provides
510 complying IAQ performance results. For example, the balanced ventilation system (BV)
511 provides the best IAQ in terms of CO₂, HCHO, and condensation risk. However, the DCV
512 system provides slightly better IAQ if one looks at the occupant-based humidity indicator,
513 with a Iⁿ_{RH30_70} result 10% lower. The EV system shows almost the same performances as
514 the DCV, except for the Iⁿ_{RH70} (condensation risk), for which this system is 67% less efficient
515 than the DCV system. Indeed, this condensation risk score is reached in bedrooms: for the

516 EV and DCV systems, the uncontrolled infiltration airflows are higher than for the BV
 517 systems. As a consequence, the air inlet flows in bedrooms vary more, and can be lower for
 518 EV and DCV than for BV systems. With the BV, the entering airflows in the bedrooms are
 519 therefore higher compared to EV, leading to higher air change rates and, as a result, a lower
 520 level of humidity in the bedrooms. In addition, DCV outperforms EV. This result confirms
 521 that the DCV strategy provides a clear benefit over EV, despite lower airflows during low
 522 humidity periods. Finally, the three system responses are close in terms of $I_{PM_{2.5}}^n$ indicators,
 523 and none reaches the acceptable threshold. Indeed, the airflow provided at high speed
 524 during cooking periods is the same in the three systems, and seems to not be efficient
 525 enough to remove $PM_{2.5}$ during peak emission.

526 *Table 8. Ventilation system performance results based on the five normalized IAQ indicators with input scenario*
 527 *variations for HCHO and $PM_{2.5}$*

Ventilation system	Normalized indicator (with associated scenario)								
	$I_{CO_2}^n$	$I_{RH_{30-70}}^n$	$I_{RH_{70}}^n$	I_{HCHO}^n			$I_{PM_{2.5}}^n$		
				Low	Medium	High	Low	Medium	High
EV	1.17	0.82	2.18	0.52	1.06	1.88	1.21	1.76	2.31
DCV	1.16	0.78	1.3	0.53	1.09	1.94	1.3	1.78	2.33
BV	0.72	0.87	0.72	0.43	0.82	1.41	1.24	1.76	2.29

528

529 The performances are far from acceptable for the $I_{PM_{2.5}}^n$ and I_{HCHO}^n indicators, except for the
 530 low and medium HCHO emission scenarios. These results highlight the interest of this
 531 performance-based method, taking into account IAQ parameters other than the traditional
 532 CO_2 and humidity, for a better consideration of IAQ in the choice and design of ventilation
 533 strategy.

534 Conclusion and perspectives

535 In order to improve IAQ in buildings, we suggest that performance-based approaches should
 536 be used to choose and design the ventilation strategy at the design stage of a given

537 residential building. The first challenge was to identify a reduced set of relevant IAQ
538 performance indicators. As shown by the published literature, most of the IAQ performance
539 indicators already considered for the assessment of ventilation performance are based on
540 humidity and CO₂ only, and neglect other parameters.

541 In this paper, we first analyzed and selected the relevant parameters for the assessment of
542 IAQ ventilation performance in residential settings. We then analyzed and selected the
543 corresponding IAQ performance indicators based on the selected parameters and identified
544 the corresponding requirements (or thresholds). We reviewed standards, the published
545 literature, regulations in European countries, as well as resources from the AIVC.

546 As a result, based on four relevant parameters (HCHO, humidity, CO₂, and PM_{2.5}), we
547 identified at least five relevant IAQ performance indicators (I_{CO_2} , I_{HCHO} , $I_{PM_{2.5}}$, $I_{RH_{30-70}}$, $I_{RH_{70}}$) to
548 be used as output data of a ventilation performance assessment approach of this kind.

549 Applying such a performance-based method using these five indicators, we demonstrated in
550 this paper how this could make it possible to compare the performance of three different
551 ventilation strategies in a low-energy house. In this case, we observed a small advantage for
552 the studied BV system on global IAQ performance and showed that humidity-based DCV,
553 despite lower airflows during low-humidity periods, provides almost the same IAQ
554 performance as EV-only ventilation, while clearly reducing condensation risk.

555 We also observed poor performances for indicators based on HCHO and PM_{2.5}, highlighting
556 the importance of taking into account IAQ parameters other than the traditional CO₂ and
557 humidity, for a better consideration of IAQ in performance-based approaches.

558 This list of performance indicators is intended to be improved as new knowledge in the field
559 becomes available, and can be expanded as soon as new pollutants of concern are

560 identified. Moreover, within a broader overall performance framework, these IAQ indicators
561 should be expanded to include energy performance indicators such as the energy losses or
562 electricity consumption of systems, virus transmission prevention, and acoustic comfort,
563 among others.

564 At present, this paper proposes a clear contribution to the development of performance-
565 based approaches for ventilation in residential buildings and the improvement of IAQ for
566 future occupants. Furthermore, the proposed IAQ indicators can also be used to process
567 data collected during IAQ measurement campaigns.

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