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Authors

Leprince, Valérie
Casquero-Modrego, Núria
Ramalho, Olivier
[et al.](#)

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Towards healthy buildings: developing harm-metric frameworks to support design and decision-making

Valérie Leprince^a , Núria Casquero-Modrego^b , Olivier Ramalho^c ,
Max Sherman^d , Gaëlle Guyot^e , Iain Walker^f , Benjamin Jones^d ,
Jelle Laverge^g  and James A. McGrath^h 

^aCerema, Lyon, France; ^bBuilding Technology and Urban Systems, Lawrence Berkeley National Laboratory, Berkeley, USA; ^cHealth and comfort Department, Centre scientifique et technique du bâtiment Department, Marne-La-Vallée, France; ^dArchitecture and Built Environment, University of Nottingham, Nottingham, UK; ^eBPE research team, Cerema, l'Isle d'Abeau, France; ^fResidential Building Systems, Lawrence Berkeley National Laboratory, Berkeley, USA; ^gArchitecture and Urban Planning, University of Ghent, Ghent, Belgium; ^hDepartment of Physics, Maynooth University, Maynooth, Ireland

ABSTRACT

Current Indoor Air Quality (IAQ) regulations rely on concentration thresholds for individual pollutants, which limits their ability to capture cumulative health impacts and hinders the development of performance-based ventilation standards. Building on prior work, including Annexe D of ASHRAE 62.2, this study introduces a harm-based framework that shifts the reference from indoor concentrations to a standardised emission rate scenario. The proposed Harm Metric aggregates multiple contaminant exposures into a single health outcome expressed in DALYs·(10⁵ pers)⁻¹·year⁻¹, enabling an outcome-based evaluation of ventilation performance.

Applied to a representative sample of the French dwelling stock, the metric shows a median total harm of 994 DALYs·(10⁵ pers)⁻¹·year⁻¹. The main contributors are particulate matter, formaldehyde, nitrogen dioxide (NO₂), and radon. A ventilation sensitivity analysis demonstrates the metric's responsiveness, with total harm decreasing to around 800 DALYs·(10⁵ pers)⁻¹·year⁻¹ when airflow exceeds 350 m³·h⁻¹ in a 100 m² dwelling.

By linking emissions, ventilation, and health outcomes, this framework supports integrating chronic exposure impacts into building standards and codes. It offers policymakers a quantitative basis for transitioning towards performance-based regulation and highlights the need for improved emission scenarios using large-scale real-world data.

HIGHLIGHTS

- The Harm Metric is used to assess the cumulative health impact of indoor air contaminants based on default emission scenario.
- The metric provides a scientific tool to support performance-based IAQ regulation and the development of health standards.

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- The modelled case showed that total harm decreases as ventilation increases, converging above $350 \text{ m}^3/\text{h}^{-1}$ of airflow rate for a 100m^2 dwelling
- Particulate Matter (PM), Formaldehyde, NO_2 , and Radon were identified as the main contributors to the health impact in French existing dwellings.

1. Introduction

Indoor air quality (IAQ) is recognised as a key determinant of public health, with epidemiological and toxicological evidence linking exposure to indoor air contaminants and chronic health outcomes such as asthma and other respiratory diseases (Morantes et al., 2024). Regulatory frameworks in Europe have attempted to address these risks through indoor concentration thresholds defined for individual contaminants, primarily derived from World Health Organisation or national guidelines (ANSES, 2024; Dimitroulopoulou et al., 2023; WHO, 2018). Although conceptually simple and administratively robust, single-contaminant threshold approaches evaluate indoor contaminants independently and therefore provide limited capacity to assess cumulative health impacts, prioritise risk contributors, or account for variability in building operation and local conditions. When applied in isolation, threshold compliance may emphasise control of indoor contaminants with relatively small contributions to overall health impact, while offering limited guidance for optimising ventilation strategies as stressed in Jones et al. (2026).

In several European countries (such as France, Belgium, Denmark and Spain), there is a noticeable shift in IAQ regulations from prescriptive ventilation flow rate requirements towards performance-based metrics that directly assess IAQ outcomes. Performance-based regulations are necessary to support the implementation of energy and IAQ efficient systems such as smart ventilation (Guyot et al., 2018, 2019; Mortari et al., 2025). Achieving this transition requires quantitative metrics capable of integrating multiple indoor contaminants into a common health-based framework rather than relying on independent concentration thresholds. A growing body of research has therefore proposed the use of health-impacts metrics that aggregate indoor exposure to multiple indoor contaminants using population health indicators (Jones et al., 2026; Logue et al., 2010, 2011; Morantes et al., 2023, 2024), including several International Energy Agency EBC annexes (Annexes 5, Annexe 68 and 86). It has been included in the new Annexe D of ASHRAE 62.2 (ASHRAE, 2025). These efforts advocate for the transition from indoor concentration compliance towards evaluation of cumulative harm associated with chronic disease outcomes.

Building on these foundation, this study develops and applies a harm-based IAQ metric for indoor contaminants designed to support the evolution of IAQ standards and regulations in Europe (particularly EN 16798-1 currently under revision (CEN, 2019)). The proposed metric combines contaminants-specific concentration data (obtained either through onsite measurements or through modelling) with contaminant-specific harm intensities to estimate a median annual health impact in Disability-Adjusted Life Years (DALYs) per 10^5 person per year. By linking indoor contaminant exposure directly to health outcomes, the framework enables comparison of

ventilation strategies on the basis of their total health impacts rather than compliance with isolated contaminant thresholds.

This paper aims to answer the following questions:

- Which indoor air contaminants contribute most significantly to the cumulative health impact in typical French residential dwellings, based on national onsite measurement data on a representative set of dwellings?
- How does the proposed harm-based IAQ metric quantify individual and cumulative health impacts across a representative sample of dwellings in France?
- How can the harm metric be applied in a modelled case study of a typical French dwelling, using activity-based emission scenarios and default inputs?
- To what extent do different ventilation strategies, aligned with French regulation, ASHRAE 62.2 and EN 16798-1:2019, influence the total health impact as evaluated by the harm metric?

The final goal of the study is to introduce, to test and validate a harm-based framework for IAQ assessment, which we aim to propose for implementation in ventilation standards.

2. Methodology

This study builds on the Harm Intensity (HI) approach proposed by Logue et al. (2011). To answer the two first research questions, this study will first apply the proposed harm metric to a representative set of French residential dwellings using data from a national onsite measurement campaign by (Observatoire de la qualité des environnements intérieurs, 2025). This analysis will (1) demonstrate the applicability of the proposed harm metric; and (2) classify most harmful indoor contaminants on dwellings' occupants (3) quantify in DALY per 105 persons per year the cumulative health impact on dwellings' occupants.

In the second part of the study, a modelling framework based on standardised emission rates has been proposed based on an existing literature review primarily based on the Pandora database (Abadie et al., 2025a) and comparable modelling study (Poirier et al., 2021a). The harm metric calculation is then applied to a typical French dwelling, used as a case study, in which indoor contaminant concentrations are estimated based on activity-specific emission scenarios. In this case study, we evaluate different ventilation strategies in accordance with the French ventilation regulation, ASHRAE 62.2 and EN 16798-1 and their impact on the harm metric results is assessed.

This performance-based approach is similar to building energy regulations that assess performance through whole-building simulations rather than prescriptive component requirements (e.g., insulation thickness, boiler efficiency, etc.). In this case, energy performance is evaluated prior to construction using standardised assumptions for occupancy, heating, and operation; although these assumptions differ from actual use, they provide a consistent best-estimate reference for comparing buildings. We adopt the same performance-based logic for IAQ: standardised indoor contaminant

emission scenarios are defined, despite large real-world variability, to enable a consistent evaluation and comparison of IAQ management's performance at design stage (including ventilation, air cleaning, airing and mitigation strategies). The objective is not to precisely predict indoor contaminant concentration in a given building but to check the global IAQ performance with best-estimate default emission rate.

Some sections of the methodology below (Sections 2.3 and 2.5) are specifically intended for decision-makers involved in defining a new harm metric and its associated thresholds, while other parts (Sections 2.1, 2.2 and 2.4) are relevant to both building designers (who will use the harm metric to design a specific dwelling) and decision-makers.

2.1. Harm metric (framework for decision makers and designers)

2.1.1. General approach

Population harm associated with chronic exposure to an indoor contaminant i is defined as the product of its indoor contaminant concentration and its contaminant-specific harm intensity coefficient. Following (Morantes et al., 2024), annual harm H_i is expressed as:

$$H_i = HI_i \cdot C_i \quad (1)$$

where HI_i is the harm intensity ($\text{DALY} \cdot (\text{unit concentration})^{-1} \cdot 10^5 \text{ persons}^{-1} \cdot \text{year}^{-1}$) and C_i is the indoor concentration. This formulation assumes linear integration of chronic health impacts over the exposure range considered, consistent with exposure-response relationships adopted in previous population risk assessments.

(Morantes et al., 2024) defines a set of indoor contaminants of concern and reports chronic health impact intensities (HI), expressed in ($\text{DALY} \cdot (\text{unit concentration})^{-1} \cdot 10^5 \text{ persons}^{-1} \cdot \text{year}^{-1}$), building on earlier work conducted by Logue et al. (2011) (Table 1). The health impacts are derived for chronic exposure only. Indoor contaminant exclusions are driven primarily by limitation in data availability rather than by an assessment of negligible health relevance. Harm intensities, used in this method, may be revised as knowledge on the impact of existing and emerging indoor contaminants improves. As stressed in previously mentioned publications, a high harm intensity (HI) does not necessarily lead to a high harm impact if indoor concentrations of those contaminants in dwellings are low. In this context (Morantes et al., 2024) combined the median value of harm intensity with indoor contaminant concentrations to calculate the total Harm. Our study follows the same approach.

2.1.2. Adjustment for particulate matter

(Morantes et al., 2024) included an evaluation of the impact of $\text{PM}_{10-2.5}$ noting that $\text{PM}_{2.5}$ is a subset of PM_{10} and assuming that their indoor concentrations are proportional. In our study, since $\text{PM}_{2.5}$ is the metric most commonly measured, we propose adjusting its harm intensity (HI) to account for the additional impact of $\text{PM}_{10-2.5}$. It is important to note that this adjustment applies to harm intensity coefficients, not directly to measured indoor concentrations. To do this, we adjust the $\text{PM}_{2.5}$ harm intensity to account for the coarse fraction ($\text{PM}_{10-2.5}$) by assuming the coarse concentration is 1.3 times the $\text{PM}_{2.5}$ concentration.

Table 1. Harm intensities of individual indoor contaminants (Morantes et al., 2024) in (DALY · (unit concentration)⁻¹ · 10⁵ persons⁻¹ · year⁻¹).

Contaminant	Median Harm Intensity (HI)	Exposure-Response Approach
Acetaldehyde	0,053	toxicology
Acrolein	1,2	pooled
Acrylonitrile	1,2	toxicology
Benzene	0,067	pooled
benzyl chloride	0,062	toxicology
1,3-butadiene	0,27	toxicology
2-butoxyethanol	0,01	toxicology
Cadmium	5,3	toxicology
carbon disulphide	0,29	toxicology
carbon tetrachloride	0,52	toxicology
Chloromethane	0,00027	toxicology
Chromium	17	toxicology
crotonaldehyde(trans)	1,1	toxicology
1,2-dibromoethane	3,4	toxicology
1,4-dichlorobenzene	0,012	toxicology
1,2-dichloroethane	0,052	toxicology
1,1-dichloroethene	0,15	toxicology
Ethanol	0,0005	toxicology
2-ethylhexanol	0,0029	toxicology
Formaldehyde	4,3	pooled
Hexachlorobutadiene	0,03	toxicology
Hexane	0,0018	toxicology
Isoprene	0,0092	toxicology
Limonene	0,0093	toxicology
2-methoxyethanol	0,0028	toxicology
methyl methacrylate	0,051	toxicology
methyl tert-butyl ether	0,026	toxicology
methylene chloride	0,01	toxicology
Naphthalene	0,36	toxicology
nitrogen dioxide	5,7	epidemiology
Ozone	1,3	pooled
PM10	30	epidemiology
PM10 – 2,5	3,8	
PM2,5	60	epidemiology
Radon	0,44 ^a	pooled
Styrene	0,11	toxicology
sulfur dioxide	1,3	epidemiology
1,1,2,2-tetrachloroethane	0,13	toxicology
Tetrachloroethene	0,052	toxicology
Toluene	0,00087	toxicology
1,1,2-trichloroethane	0,15	toxicology
Trichloroethylene	0,0035	toxicology
vinyl chloride	0,98	toxicology
Xylenes	0,0034	toxicology

^a DALY/Bq/m³/10⁵ person/year

$$C_{PM_{10-2,5}} \approx 1,3 C_{PM_{2,5}} \quad (2)$$

This value is a modelling assumption taken from emission scenario reviews and used here to avoid ignoring coarse particles. While, mass distributions of PM₁₀, and therefore the coarse fraction, varies with the main source of emission as stressed by McGrath et al. (2014), the average value of 1,3 is consistent with the estimation made by Morantes et al. (2024) and with the result of McGrath et al. (2014) that obtained a fraction between 1,1 and 1,4 according to the emission source. Besides, the harm intensities for PM_{2,5} and PM₁₀ are derived from different epidemiological studies. The

adjusted $PM_{2,5}$ harm intensity should therefore be seen as a practical way to use available $PM_{2,5}$ data, not a definitive value. Future work should test the sensitivity of the method to other ratios (e.g. 1.0–2.0).

Therefore, to account for the contribution of ($PM_{10-2,5}$) when only $PM_{2,5}$ indoor concentrations are available, an adjusted harm intensity coefficient was defined by aggregating the health impacts associated with both fine and coarse particle fractions. The effective harm intensity for particulate matter ($HI_{PM_{2,5}}^*$) is therefore expressed as:

$$HI_{PM_{2,5}}^* = HI_{PM_{2,5}} + 1,3 * HI_{PM_{10-2,5}} \quad (3)$$

Substituting the harm intensity coefficients reported by Morantes et al. (2024) yields:

$$HI_{PM_{2,5}}^* = 60 + 1,3 * 3,8 \approx 65$$

The adjusted coefficient $HI_{PM_{2,5}}^*$ represents the combined harm intensity associated with total PM_{10} indoor exposure, expressed as a function of measured $PM_{2,5}$ indoor concentration. This formulation enables incorporation of coarse particle health impacts while maintaining compatibility with datasets in which $PM_{2,5}$ is the primary measured metric.

2.2. Estimating indoor contaminant concentrations (for decision makers and designers)

To apply the harm metric framework, indoor contaminant concentrations data must be measured or reasonably estimated either for: (1) a representative sample of dwellings if the objective is to estimate the harm associated with this dwelling stock (for decision makers aiming at determining thresholds values); or (2) a given dwelling, if the objective is to estimate the harm associated with the indoor air in this dwelling (for a design or an on-site assessment).

Indoor contaminant concentrations can be obtained either through: (1) direct measurement campaigns (on site assessment); (2) through simulation models based on pre-defined emissions and dwelling characteristics (design assessment); or (3) using default values through existing literature.

For a population-level assessment of a given dwelling stock, median indoor concentrations can be obtained through measurements in a representative sample of dwellings, as previously done in a French national campaign (Observatoire de la qualité des environnements intérieurs, 2025). When data are not available, literature-based default

Table 2. Default median concentration and geometric standard deviation (GSD) of main contaminants based on a literature review of measurements in dwellings (Morantes et al., 2024).

Contaminant	Median Concentration ($\mu\text{g} \cdot \text{m}^{-3}$)	GSD
$PM_{2,5}$	26	1.3
NO_2	22	1.3
Formaldehyde	28	1.2
Radon	78 ($\text{Bq} \cdot \text{m}^{-3}$)	1.4
Ozone (O_3)	7.3	2.2
Benzene	2.2	1.3

values such as those presented in, Table 2, can be used to ensure consistency across harm assessments as proposed by Morantes et al. (2024).

2.2.1. Simulation-based indoor concentration estimation

As an alternative to previous publications (ASHRAE, 2025; Morantes et al., 2024) which focused on using typical or predefined indoor contaminant concentrations, this study introduces a framework to obtain the relevant indoor concentrations through simulations by using a default emission scenario. This approach is conceptually equivalent to the standardised energy performance calculation used in building energy regulations.

For design-stage evaluations, in simulations, indoor concentrations are calculated using a dynamic mass-balance model and standardised emission scenarios from typical household activities such as appliances and products use patterns (e.g., cooking, cleaning, use of air fresheners, etc), along with assumptions about the dwelling and the ventilation system characteristics. Concentrations at each time step (h) are computed as:

$$C_{int;i}(h) = C_{int;i}(h - dt) + \left(\frac{Q(h)(C_{ext;c;i}(h - dt) - C_{int;i}(h - dt)) + E_{c;i}(h)}{V} - v_{k,i} \cdot C_{int;i}(h - dt) \right) \cdot dt \quad (4)$$

Where $C_{int;i}(h)$ expressed in ($\mu\text{g}\cdot\text{m}^{-3}$) is the indoor concentration of contaminant i within the dwelling at time step (h). The total airflow rate is $Q(h)$ in ($\text{m}^3\cdot\text{h}^{-1}$); $C_{ext;c;i}(h)$ in ($\mu\text{g}\cdot\text{m}^{-3}$) is the corrected outdoor concentration accounting for mitigation measures such as filtration. The corrected emission rate, $E_{c;i}(h)$ in ($\mu\text{g}\cdot\text{h}^{-1}$), represents the indoor emission rate of contaminant i ; $v_{k,i}$ in (h^{-1}) is the deposition factor into indoor surfaces; V in (m^3) is the total volume of the dwelling in which air is assumed to be uniformly mixed.

Assuming constant airflow, emissions, and outdoor concentration over a time interval dt , the differential equation becomes:

$$\frac{dC_{int;i}}{\left(\frac{C_{ext;c;i}(h-dt)}{\left(1 + \frac{V}{Q(h)}v_{k,i}\right)} + \frac{E_{c;i}(h)}{Q(h)(Q(h)+Vv_{k,i})} - C_{int;i} \right)} = \left(\frac{Q(h)}{V} + v_{k,i} \right) \frac{Q(h)}{V} dt \quad (5)$$

It leads to:

$$\int_{C_{int;i}(h-\Delta t)}^{C_{int;i}(h)} \frac{dC_{int;i}}{\left(\frac{C_{ext;c;i}(h-\Delta t)}{\left(1 + \frac{V}{Q(h)}v_{k,i}\right)} + \frac{E_{c;i}(h)}{Q(h)(Q(h)+Vv_{k,i})} - C_{int;i} \right)} = \int_{h-\Delta t}^h \left(\frac{Q(h)}{V} + v_{k,i} \right) dt \quad (6)$$

Leading to the analytical solution:

$$C_{int;i}(h) = \frac{Q(h) \cdot C_{ext;c;i}(h - \Delta t) + E_{c;i}(h)}{Q(h) + Vv_{k,i}} \left(1 - \exp\left(-\left(\frac{Q(h)}{V} + v_{k,i}\right)\Delta t\right) \right) + C_{int;i}(h - \Delta t) \cdot \exp\left(-\left(\frac{Q(h)}{V} + v_{k,i}\right)\Delta t\right) \quad (7)$$

2.2.2. Deposition assumptions

As stated by He et al. (2005; Thatcher et al., 2002) studies on particle deposition to indoor surfaces make it clear that the deposition rate varies broadly across conditions. Particle size is important and other factors can also influence the deposition rate significantly. Study from (Nazaroff, 2004) shows that PM with a diameter equal to 2.5 have a deposition factor of about 0,5 but it also shows that smaller particulates matters have a smaller deposition factor. This is confirmed by Long et al. (2001) that observed deposition range between 0.12 and 0,55 h⁻¹ for PM between 0,02 and 2,5). For this study a particle deposition coefficient of 0.3 h⁻¹ was used for PM_{2.5} (particulate matters with a diameter ≤2.5) and the resuspension was neglected.

2.2.3. Emission and outdoor concentration corrections

Table 3 provides default emission scenarios and outdoor concentrations are defined for optimistic (minimum value), average, and pessimistic (maximum value) conditions. The emission rate may be corrected with a mitigation factor according to installed IAQ management equipment (e.g., range hood or source control devices) in the dwelling that helps reduce the indoor contaminant concentration of a given contaminant. The corrected emission rate is defined as:

$$E_{c;i}(h) = E_i(h) \cdot Mit_{E;i} \quad (8)$$

Where, $E_i(h)$ in $\mu\text{g.m}^{-3}$ is the emission rate of contaminant “i” at time step “h” as provided in Table 3. $Mit_{E;i}$ represents the fraction of emission rate reduction efficiency associated with a mitigation strategy (as specified in Table 3). A value of 0 indicates complete removal, while 1 indicates no mitigation.

Similarly, the corrected outdoor concentration is:

$$C_{ext;c;i}(h) = C_{ext;i}(h) \cdot Mit_{C;i} \quad (9)$$

Where $C_{ext;i}(h)$, in $\mu\text{g.m}^{-3}$ is the external concentration of contaminant “i” at time step “h” as provided in Table 3. $Mit_{C;i}$ accounts for the fraction of the outdoor concentration reductions based on the mitigation strategies (e.g., filtration), as specified in Table 3. A value of 0 indicates complete removal, while 1 indicates no mitigation.

If an air cleaner is present, its effect on relevant contaminants should also be incorporated into Equation 8.

2.3. Proposed methodology for defining contaminants of concern for the total harm metric (For decision makers)

This section outlines a methodology for defining a harm metric, based on the median concentration of indoor contaminants across the dwelling stock of interest, within the context of a regulation, standard, or label. The proposed approach consists of two stages: (1) systematically including contaminants that are consistently identified in the literature as hazardous (i.e., contaminants of concern (CoC)), whether or not their concentration data are available for the dwelling stock; and (2) evaluating additional contaminants where concentration data is available, to determine their potential health impact and decide whether they warrant inclusion in the metric.

Table 3. Default outdoor concentration, emission scenario and mitigation strategy impact (to ease the reading, and to be in line with previous publications, most emission rates are provided in $(\text{mg}\cdot\text{h}^{-1})$) In following simulation, average scenarios are used.

Emissions E_i ($\text{mg}\cdot\text{h}^{-1}$)	Event	Default Duration	PM2.5		Average	Maximum	Mitigation (multiplying coef.) [Mit]
			Minimum	Maximum			
Cooking Aerosol production Vacuuming / cleaning Cooking appliance	Cooking	2*30 min /day	24,9 (25 th percentile of data)	82,1 (mean of cooking data)	166,8 (mostly grilling)	166,8 (mostly grilling)	Use of cooker hood: 0,5
	Aerosol production	1/10 h a day	0 (use of none)	56,2 (use of air freshener or candle)	156,8 (use of Incenses)	156,8 (use of Incenses)	
	Vacuuming / cleaning	1/2 hour per day	0,3 (reduced amount of cleaning)	1,6 (mostly vacuum cleaner)	3 (mostly sweeping)	3 (mostly sweeping)	
	Cooking appliance	2*30 min/day	4,6 (use of electric stove and oven)	9,3 (use of electric oven and gas stove)	13,9 (use of gas oven and stove)	13,9 (use of gas oven and stove)	
External: $C_{\text{ext},i}$	$\mu\text{g}\cdot\text{m}^{-3}$	24 h	7	12	20	20	Attenuation through the air renewal system (penetration factor), default value: 0,2 if filtration 0,8 for ventilation with thin air inlet and air leakage
Data sources and comments:							
- For Emission Pandora database, analysis perform in the context of Annexe 86 (Abadie et al., 2025a, 2025b) and consistency checked with (Poirier, 2023)							
- Other sources exist on a non-daily basis (e.g., pyrolysis of the oven) and are also available in above mention publications.							
- External conditions are based on the European Air Quality data (European Council, 2025).							
PM10-2.5							
By default, considered as 1.3 times $\text{PM}_{2,5}$ emissions.							
E_i ($\text{mg}\cdot\text{h}^{-1}$)	NO2						
	Cooking	2*1/2 hour per day	0 (Electrical appliance for cooking)	26 (State to the art gas appliance)	78 (Old gas appliance or high power)	78 (Old gas appliance or high power)	
External	$\mu\text{g}\cdot\text{m}^{-3}$	24 h	8	12	18	18	
Data sources and comments:							
- Unvented space heating by combustion is assumed to be forbidden and are therefore not considered in default emission scenario.							
- For cooking the "average" value assume one burner producing 8 ng/J at medium power ($800 \text{ W} = 800 \text{ J/s}$)							

(continued)

Table 3. Continued.

Event	Default Duration	Minimum	Average	Maximum	Mitigation (multiplying coef.) [Mit]
- Other field data from the 80's for stove and oven are also available but they are not state of the art products: 136,16mg/h – Stove 85.176 mg/h (Traynor et al., 1982)– 108mG/h 153.6 (Borrazzo et al., 1987) Oven - External data represents: 25%, median and 75% of values for France in 2023 presented in the European database, based on the European Air Quality Data (European Environment Agency, 2025)Values for other countries are also available in this reference, data for European cities are available here: https://ec.europa.eu/eurostat/databrowser/view/env_air_no2\$defaultview/default?table?lang=en					
HCHO (formaldehyde)					
E_i ($\text{mg.h}^{-1}.\text{m}^{-2}$ of floor area)	Material and furniture	24hr/day	0.0045 (Only low emission material and furniture)	0.012 (low emission material or furniture)	0.0236 (no constraint on material or furniture used)
External: $C_{\text{ext};i}$	$\mu\text{g.m}^{-3}$	24hr	0	2.8	5 (In dense urban / industrial area)
Data sources and comments:					
- Emissions are considered after 365 days of use.					
- Emission rates are based on average values calculated by Poirier (2023; Poirier et al., 2021b) based on Pandora database (Abadie et al., 2025).					
- External concentration are provided by the AURA regional agency (France) from measurement campaign between 2006 and 2007 (ATMO Rhône-Alpes, 2009)					
O3					
External: $C_{\text{ext};i}$	$\mu\text{g.m}^{-3}$	24 h	8	13	19
Data sources and comments:					
- External data from the European Air Quality data for the period 2019-2021 (European Environment Agency, 2023)					
- Values are given in SOMO35: 3000/5000/7000 $\mu\text{g}/\text{m}^3.\text{day}$ and are divided by 365 to provide an annual mean.					
- Additional data for the year 2018 (higher) are available here (Ozone indicator SOMO35 in 2018, 2018, 2024).					
Radon					
From soil (entry rate estimated from French dwelling concentration) $E_{\text{ext};i}$	$\text{Bq/h}/\text{m}^2$ of ground floor	24 h	31	119	349
Tight slab + radon barrier: 0.2 Ventilation of the basement/crawl space: 0,1 Dwelling not at ground floor: $1/2_{\text{nb_floor}}$ With $\text{nb}_{\text{ground floor}} = 0$					
Data sources and comments:					
119 Bq/h/m ² is the representative value proposed in p106 of UNSCEAR (2000), 47 and 470 are calculated using a rule of three, based on measurement of indoor concentration in France by IRSN in less exposed department (24 Bq/m ³ in Paris) and most exposed department (264 Bq/m ³ in Lozère) compare to the mean (90 Bq/m ³) that is assumed to receive the average amount of emission (IRSN, 2021).					

2.3.1. Contaminants systematically included

In the existing scientific literature, various studies highlight and quantify the health impacts of indoor air contaminants in dwellings using DALYs. (Logue et al., 2011, 2012) identified key contaminants and stressed the importance of ventilation to reduce exposure and then proposed a method to assess the chronic health impact of exposure to indoor contaminants in U.S. residential buildings based on DALY. (Morantes et al., 2024) extended this work and quantified chronic health impacts using DALYs and reported a list of six contaminants of concern which account for over 99% of the total harm in studied dwellings ($PM_{2.5}$, $PM_{10-2.5}$, NO_2 , Formaldehyde, Radon and Ozone).

Given these studies Particulate Matter (based on $PM_{2.5}$ concentration), Formaldehyde, NO_2 and Radon shall be systematically considered in IAQ regulatory assessment due to their health impacts and prevalence in indoor environments, regardless of whether their concentration data are available for the specific dwelling stock under assessment. As described in Section 2.1, we propose to use the corrected harm intensity of $PM_{2.5}$ to account for the health impact of PM_{10} .

Radon may be excluded from the assessment if it has been demonstrated that the regulatory requirements apply only to areas where radon indoor concentrations in buildings are systematically negligible. Radon concentrations are generally highest at ground level and decrease on upper floors due to greater distance from the soil gas source, and as such a lower risk, typically higher floors in multi-story dwellings. However, it is important to recognise that, for population assessment, even a low radon concentration still poses a risk. It is well documented that most radon-related lung cancer deaths arise from low-to-moderate exposure rather than from the smaller number of homes exceeding national action levels. This is because more of the population is exposed to low-to-moderate concentrations rather than to high concentrations (Kim et al., 2016, 2018)

Benzene and SO_2 should be considered if the targeted dwelling stock include areas known for high levels of ambient benzene or SO_2 , such as near industrial zones or heavy traffic areas.

Ozone (O_3) may also be included in the harm assessment when: (1) where there is no existing regulation limiting O_3 emissions from household equipment; or (2) when the targeted dwelling stock under assessment includes areas experiencing high ambient O_3 concentrations.

2.3.2. Inclusion of other contaminants through a health impact-based evaluation

Beyond the core list presented above, decision makers may require to include additional pollutant, in the harm metric framework to estimate DALYs, that are relevant in the targeted dwelling stock. Relevance is assessed based on harm calculations of the contaminant derived from available Harm Intensities and the median concentration of the indoor contaminants measured in a representative set of dwellings where the regulation would apply.

We propose to incorporate into the harm metric framework any contaminant whose median harm exceeds 1% of the highest individual harm value of selected

contaminants of concern (typically $H_{PM2.5}$). This threshold ensures that only indoor contaminants with a meaningful contribution to overall indoor air harm are incorporated into regulatory assessments.

2.4. Proposed methodology for calculating the total harm metric (for decision makers and designers)

For the total harm metric (H_m) calculation, the selected indoor contaminants are combined into a single value by summing the harm of individual indoor contaminants, resulting in the total harm (H_m). This approach assumes that the harm contributions from each contaminant are uncorrelated and simply additive. Some contaminants may originate from shared sources, or interact, possibly amplifying or reducing their combined health impact. Nevertheless, in the context of this study, given the lack of information available, it has been decided to consider this approximation acceptable as done in previous study (Morantes et al., 2024).

$$H_m = \sum_{i=1}^n H_i \quad (10)$$

H_m (DALY·(10⁵ person)⁻¹·year⁻¹): Total harm from all indoor contaminants in the dwelling; n : Number of contaminants of concern as defined in [section 2.3](#).

2.4.1. Proposed methodology for defining thresholds values (For decision makers)

The thresholds values for the harm metric represents the maximum acceptable annual chronic harm impact used as a performance criterion. Thresholds can be established using several complementary approaches, depending on the regulatory context and available data. It is recommended to ensure consistency between the method used to define the threshold and the method used during assessment. Specifically, if thresholds are derived from measured data in existing dwellings, the corresponding assessments should also rely on similar on-site measurements. Conversely, if thresholds are based on simulation scenarios, the assessments should be conducted using equivalent simulation models.

We propose three methods:

1. Comparison with Other Health Impacts: This approach establishes thresholds by comparing the health impact from indoor contaminants to other known sources of health impacts such as asbestos exposure, alcohol, etc. This comparison provides a broader context for understanding acceptable health impact levels. If this approach is chosen then the harm metric for IAQ shall include all relevant indoor contaminants.
2. Reference Dwellings: Thresholds can also be derived from measured time-averaged indoor contaminant concentrations in a representative sample of existing dwellings deemed to represent acceptable conditions. This method involves calculating the median or mean harm in those dwellings and using it as a benchmark. It is best suited for regulations applied to existing dwellings and when assessments are based on measurement.

3. Simulation-Based Approach: For regulations targeting the design of new dwellings or renovation, thresholds can be established from simulations using standardised emission scenarios and typical ventilation strategies. These scenarios should reflect typical indoor activities.

Applying multiple approaches (measurement-based and simulation-based), can be beneficial to: (1) ensure the consistency between the methods and therefore the relevance of the design methodology; and (2) determine the “minimum achievable” health impact (through simulation), providing guidance for optimised dwelling design.

3. Results

3.1. Definition of the harm metric and the corresponding threshold – application to the French context

The indoor contaminant concentration used in the case study for the French context are data collected during the second National Campaign on Housing (Campagne Nationale Logements 2 - CNL2) (Observatoire de la qualité des environnements intérieurs, 2025), conducted by the French Indoor Air Quality Observatory (OQAI now OQEI). This campaign included extensive measurements of more than 170 indoor air contaminants over a week in a representative sample of 571 dwellings across mainland France over three years (2020-2023). Dwellings were selected to reflect the diversity of the French housing stock in terms of occupation (i.e., number of occupants, gender, status of occupant, age), year of construction, dwelling type, geographic location (i.e., region, climatic zone, size of the city), and ventilation systems. Survey weights were applied for each dwelling in order to reflect the distribution of these criteria across the 30 million dwellings of the French housing stock. Contaminants were measured using standardised protocols previously described (Observatoire de la qualité des environnements intérieurs, 2025). The collected data provide geometric means, medians, and dispersion measures (such as GSDs) for key indoor air contaminants.

Table 4 lists the harm calculated for each contaminant for which both harm intensity and concentration data were available. It provides the harm values that correspond to the 25th, 50th and 75th percentiles as well as the mean concentrations measured in the French building stock. The second to last column represents the relative harm of the median concentration of a given contaminant compared to the harm due to PM_{2.5} (with $HI_{PM2.5}^*$ described in section 2.1). Contaminants underlined represent more than 1%. With France having a substantial radon-impacted zone, this contaminant is necessarily considered. The last column represents the proportion of the total harm due to this contaminant.

No concentration data were available in the database for Ozone, therefore, as proposed in the methodology, the default concentration listed in Table 2 has been used to assess its relevance in the harm metric.

The result is the total harm from relevant contaminants (underlined in orange) for the median concentration of contaminant in the French dwelling stock is $H_m = 994 \text{ DALY} \cdot (10^5 \text{ pers})^{-1} \cdot \text{year}^{-1}$ (and respectively 675, 1655 and 1150 $\text{DALY} \cdot (10^5 \text{ pers})^{-1} \cdot \text{year}^{-1}$ for the 25th and 75th percentiles and the mean concentrations).

Table 4. Harm impact (Morantes et al., 2024), concentration and harms of contaminants measured in the CNL2 and of ozone (default value).

CONTAMINANT	HARM INTENSITIES ¹		CONCENTRATIONS ²				HARM				PROPORTION OF TOTAL HARM	
	UNITS	P25	P50 (MEDIAN)	P75	MEAN VALUE	FOR P25	FOR P50	FOR P75	FOR MEAN VALUE	% OF HARM COMPARE TO PM2.53		
DATA AVAILABLE IN THE DATABASE												
PM2.53	65	G/M3	9,46	13,2	22,4	15,9	615,07	860,04	1458,61	1033,89	100%	87%
FORMALDEHYDE	4,3	G/M3	9,67	14,0	20,0	13,6	41,60	60,12	86,10	58,53	7%	6%
NO2	5,7	G/M3	2,19	8,01	13,0	6,75	12,48	45,65	74,10	38,48	5%	5%
RADON	0,44	Bq/M3	11,00	40	80	41,7	4,84	17,60	35,20	18,37	2%	2%
ACETALDEHYDE	0,053	G/M3	5,39	8,27	12,3	8,38	0,29	0,44	0,65	0,44	0%	0%
LIMONENE	0,0093	G/M3	7,38	18,2	33,1	15,3	0,07	0,17	0,31	0,14	0%	0%
BENZENE	0,067	G/M3	0,78	1,18	1,77	1,19	0,05	0,08	0,12	0,08	0%	0%
STYRENE	0,11	G/M3	0,39	0,54	0,85	0,59	0,04	0,06	0,09	0,06	0%	0%
TRICHLOROETHYLENE	0,15	G/M3	0,80	0,08	0,08	0,08	0,12	0,01	0,01	0,01	0%	0%
XYLENES (m + p)	0,0034	G/M3	1,12	1,88	6,04	2,77	0,00	0,01	0,02	0,01	0%	0%
2-BUTOXYETHANOL	0,01	G/M3	0,15	0,52	2,00	0,63	0,00	0,01	0,02	0,01	0%	0%
TETRACHLOROETHYLENE	0,052	G/M3	0,80	0,08	0,08	0,11	0,04	0,00	0,00	0,01	0%	0%
2-ETHYL-1-HEXANOL	0,0029	G/M3	0,72	1,31	2,88	1,29	0,00	0,00	0,01	0,00	0%	0%
TOLUENE	0,00087	G/M3	1,64	2,87	9,04	4,15	0,00	0,00	0,01	0,00	0%	0%
1,4-DICHLOROBENZENE	0,012	G/M3	0,09	0,09	0,09	0,14	0,00	0,00	0,00	0,00	0%	0%
DATA NOT AVAILABLE IN THE DATABASE (DEFAULT VALUE)												
OZONE	1,3 ¹	µG/m3		7,30			675	949	1655	1150	<1%	<1%
TOTAL HARM												

¹: From (Morantes et al., 2024)

² : From (Observatoire de la qualité des environnements intérieurs, 2025)

³: Corrected harm intensity to include the coarse fraction of particulates maters (see 2.1)

In the context of the French dwelling stock, the most significant contributors to health-related harm are particulate matter, formaldehyde, NO_2 , radon and Ozone. These findings are consistent with existing literature (Morantes et al., 2023, 2024), which has similarly identified these pollutants as key contaminants of concern.

3.2. Application to a case study: test dwelling simulation

A representative French single-family building was simulated to assess indoor contaminant concentrations and the resulting total harm. The building characteristics were as follows: single-family home (100 m² area, 300 m³ volume, 3 bedrooms, 1 living room, 1 kitchen, 1 bathroom, 1 toilet). It was simulated with various mechanical ventilation rates from EN 16798-1 (CEN, 2019), the French regulation “Arrêté de 1982” (Arrêté Du 24 Mars 1982 Relatif à l’aération Des Logements, 1983) and ASHRAE 62.2 (ASHRAE 62.2, 2022). The mean ventilation airflows over 24h are in the range [90–864 m³·h^{−1}], corresponding to a mean air change rate in the range [0.3–2.88 h^{−1}], see Table 5.

The simulation is based on the air mass balance through the building envelope, assumed to be one unique zone with the total ventilation airflow. No other air renewal is considered (no air leakage, no windows opening), the mixing was assumed to be perfect and a time step of one hour in the previous equations was used for the calculation. The duration of the simulation is 8760 h (repetition of 365 identical days).

For the French regulation and ASHRAE 62.2, the maximum flowrate is supposed to be used during the cooking event (30 min twice a day). As the time-step for the simulation was 1 h the average flowrate between minimum and maximum was used during the cooking events (at 11h and 19h).

Emission profiles from activities like cooking, cleaning, and the use of freshening products were used. Table 5 provides all the characteristics of the simulated dwelling (with French flowrates) and contaminant emissions. For other simulations (EN and ASHRAE standards), only the “minimum flowrate” and “maximum flowrate” were modified.

Results are given in Table 6, it provides the total harm calculated from the time-average concentration of the selected contaminants in the dwelling for different airflows of reference: EN 16798-1 Method 1, French regulation (Ministère de la Santé 1982) and ASHRAE 62.2. EN 16798-1 proposes various air flow rates according to the level of pollutants’ emissions in the buildings and the category of perceived air quality required by occupants.

Figure 1 plots the total harm according to the building ventilation mean air flow rate (values from Table 6). As expected, it shows that the total harm decreases as ventilation increases, but with diminishing returns beyond 350 m³·h^{−1}. This corresponds to the category II of the EN 16798-1 recommendations for low-polluting buildings (to ensure less than 20% of occupant dissatisfied). Regarding Ashrae 62.2, it shows the substantial benefit of applying a very high flowrate during cooking events as it gets a DALY of 969 with an average flowrate over the day of 122,5 m³/h which is equivalent to the DALY obtained with a constant flowrate of 185 m³/h (roughly 50% higher than the average flow used). This illustrates the efficiency of demand-controlled or event

Table 5. Input and output data for simulation: part A: Input regarding contaminant characteristics, part B: Input regarding building and ventilation characteristics, part C input regarding event characteristics, part D, output data for this test case.

A: Input, contaminant				
	Emission Source	Emission Rate	Mitigation Strategy	Mitigation Coefficient (1= no mitigation, 0= total removal)
Particulate Matters (PM2,5) (deposition factor $v_k = 0,3$)	Cooking	24.9 mg/h	No use of cooker hood	1
	Scented product	56.2 mg/h		1
	Vaccuming	1.6 mg/h		1
	Electrical oven	4.6 mg/h		1
	External	0.012 mg/m ³	Kind of ventilation: thin air inlet	0.8
Formaldehyde	All	0.012 mg/h/m ²		1
	External	0.0028 mg/m ³		1
NO2	Cooking	26 mg/h	No use of cooker hood	1
Radon	External	0.012 mg/m ³		1
	Infiltration	119 Bq/h/m ²	Floor lever = 0	1
			Mitigation due to radon membrane : none	1
			Mitigation due to basement ventilation = none	1
Ozone	Internal source	0 mg/h		1
	External	0.013 mg/m ³		1

B: Input, Building and Ventilation Characteristics				
Floor area	100 m ²			
Volume	300 m ³			
Description	3 Bedroom, 1 living room, 1 kitchen, 1 bathroom, 1 toilet			
Number of occupants	4			
Minimum ventilation flowrate	105 m ³ /h			
Average ventilation during cooking	142.5 m ³ /h			
Maximum ventilation flowrate	180 m ³ /h (30' during cooking event)			
PM deposition factor	0,3/h			

C: Input, events characteristics				
Event	Time of the event (hour)		Duration (hours)	
Cooking events	11		0.5	
	19		0.5	
Scented product	18		0.1	
Cleaning	17		1	

D: Results, Concentration and Total Harm of Contaminants				
Pollutant	Median Harm Intensity	Time-average concentration mg/m3	Median Harm (DALY)	Shared part of the total harm
PM*	65.00	0.013	823	77%
Formaldehyde	4.30	0.014	60	6%
NO ₂	5.70	0.022	126	12%
Radon	0.44	110 Bq/m ³	48	5%
Ozone	1.30	0,013	17	2%
Total Harm (Hm)			1074	DALY(10 ⁵ pers) ⁻¹ · year ⁻¹

*the calculation takes into account the harm of all PM₁₀.

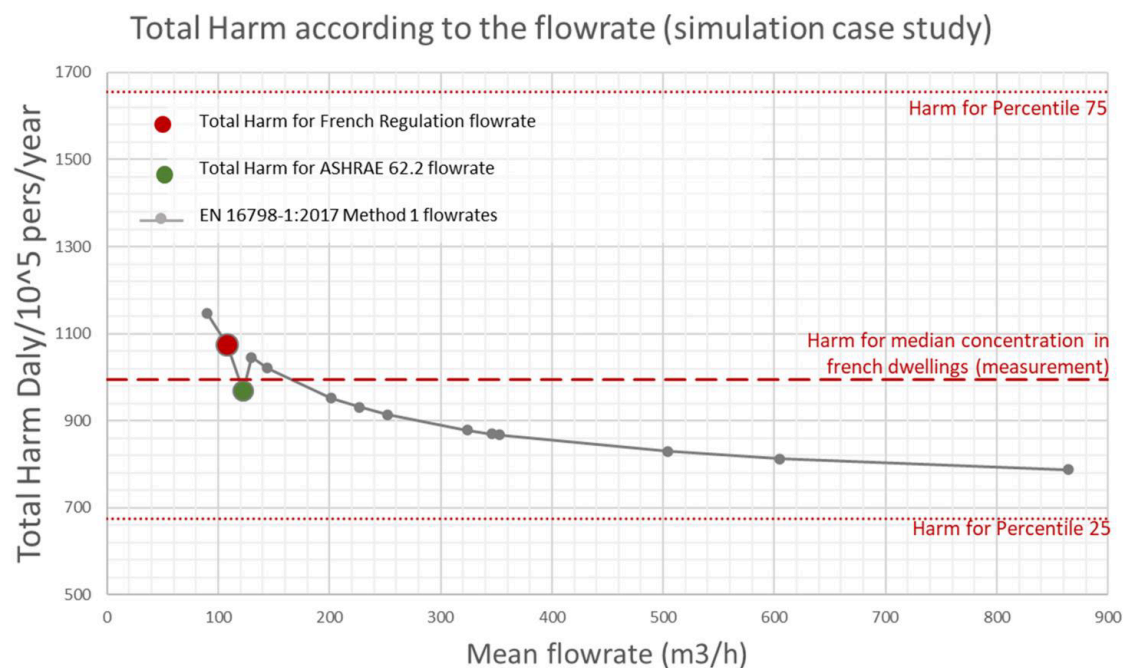
Table 6. Total harm for various flowrate in a single typical french dwelling.

		Category (as defined in EN 16798-1)	Minimum flowrate (m ³ ·h ⁻¹)	Maximum flowrate (m ³ ·h ⁻¹)	Mean flowrate over 24 h	Total Ham (H _m) (Daly/10 ⁵ pers/ year)
EN 16798-1 Method 1*	Very low- polluting building's product	I	324	324	324	878
		II	226,8	226,8	226,8	931
		III	129,6	129,6	129,6	1046
		IV	90	90	90	1146
	Low-polluting building's product	I	504	504	504	829
		II	352,8	352,8	352,8	867
		III	201,6	201,6	201,6	952
		IV	144	144	144	1021
	Non Low- Polluting building's product	I	864	864	864	787
		II	604,8	604,8	604,8	812
		III	345,6	345,6	345,6	870
		IV	252	252	252	914
French Regulation**			105	180	108,1	1074
ASHRAE 62.2***			104.4	540	122.5	969

* EN 16798-1 Method 1(minimum = maximum = average) (CEN, 2019)

** (Arrêté Du 24 Mars 1982 Relatif à l'aération Des Logements, 1983)

*** (ASHRAE 62.2, 62.2, 2022)

**Figure 1.** Total harm according to the flowrate.

ventilation strategies. The French regulation also imposes larger flowrate during cooking events but not large enough to induce noticeable benefice.

Figure 1 also shows the harm for 25th percentile, median and 75th percentile of concentrations in the French dwelling stocks. The harm in the simulated case study is very close from the harm for the median. The factors influencing this result are explained in the discussion below.

4. Discussion

This study demonstrates the applicability, feasibility and relevance of a harm-based metric for evaluating IAQ in dwellings. By applying the harm metric to a representative set of French dwellings and a modelled case study, we present insights based both on real-world measurement data and simulations, to better understand the impact of the main IAQ contaminants on health.

The results confirm that, for the French dwelling stock, particulate matter is the dominant contributor to health impact, followed by formaldehyde, NO_2 , and radon. This finding is consistent with previous studies (Logue et al., 2010; Morantes et al., 2024), reinforcing the validity of the proposed metric and its underlying assumption.

In this study, we focused on the harm from the median concentration of contaminants in the observed stock, as it represents a typical estimate of harm for an individual dwelling, rather than the average harm across the entire dwelling stock. This approach is usually chosen when defining realistic thresholds for metrics in building regulation (such as airtightness values etc.). However, estimating the harm on a population would require computing mean values for contaminant concentrations across the building stock rather than median values.

The typical total harm for the French dwelling stock was estimated at $994 \text{ DALY} \cdot (10^5 \text{ pers})^{-1} \cdot \text{year}^{-1}$, with Particulate Matter accounting for 87% of the total health impact. This distribution was expected and reflects both the high harm intensity of particulate matter and its relatively elevated indoor concentrations in dwellings. However, it should be noticed that the relative dominance of PM may potentially lead to unacceptable exposure to other pollutants, if additional exposure limits for acute effects are not taken into account in design optimisation (Laverge et al., 2024).

In the modelled case study, the total harm metric effectively captured the sensitivity of IAQ to different design ventilation rates. As ventilation rates increased, total harm decreased, though with diminishing returns beyond $350 \text{ m}^3 \cdot \text{h}^{-1}$. This threshold corresponds well with Category II of the EN 16798-1 standard for low-polluting buildings, which reinforces the validity of the current version of the standard. These findings highlight the value of the proposed harm metric in informing ventilation standards and supporting evidence-based policy decisions. It also shows the relevance of imposing an adequate ventilation flowrate during main emission events (cooking), as it is done in Ashrae 62.2, it can be done either with a cooker hood or with an additional flowrate.

We observe a good consistency between the total harm calculated from modelled scenarios using regulatory flowrates ($1074 \text{ DALY} \cdot (10^5 \text{ pers})^{-1} \cdot \text{year}^{-1}$) and that derived from measured data (median value: $994 \text{ DALY} \cdot (10^5 \text{ pers})^{-1} \cdot \text{year}^{-1}$). Nevertheless, multiple factors may induce difference between simulation and measurement. On one hand, simulation scenarios likely overestimate emissions, as they assume frequent contaminant-generating activities and underestimate air renewal as they do not include air flow rate due to window opening or infiltration. On the other hand, some other sources of pollution are not taken into account (smoking occurs in 25% of dwellings) and the measured data may reflect dwellings with insufficient ventilation (only 50% of dwellings in the database have a centralised ventilation system and only 47% air

Table 7. Proportion (%) of the total harm for the 6 main contaminants for simulated values and measured concentration.

	For simulated concentration ($H_m=1074$ DALY/ 10^5 suppl person/ year)	For measured concentration ($H_m=994$ DALY/ 10^5 person/year)
PM _{2.5}	77%	87%
Formaldehyde	6%	6%
NO ₂	12%	5%
Radon	5%	2%
Ozone	2%	1%

terminal actually extract the required flowrate), moreover the additional flowrate during cooking is very scarcely used. These two effects seem to offset each other to some degree but highlight the importance of validating simulation assumptions using field data. Alternate explanations for differences between measured and modelled harm values could include underestimation of real-life mitigation behaviours (e.g., use of range hoods or cleaning products with lower emissions) or the natural variability in dwelling geometry and occupant behaviour. Further investigation is warranted to explore these effects in more detail.

Nevertheless, the harm associated with the 25th and the 75th percentile of measured data in the French dwelling stock are 675 and 1655 DALYs/ 10^5 person/year, which are significantly lower and higher (respectively) than all simulated value. This indicates that the simulation, and the emissions scenario used, provides a reasonable order of magnitude given the magnitude of difference in dwellings.

Table 7 shows that simulation tends to underestimate the impact of PM compared to measurements, however the simulated concentration is less than 5% below the measured one but this difference on H_m is due to the predominant impact of PM.

Future efforts should prioritise the refinement of default emission scenarios and deposition factor, incorporating real-life behavioural data, and leveraging the OQEI database to characterise actual ventilation rates in dwellings. These enhancements would improve the accuracy and realism of harm estimates and further support the adoption of the harm metric in regulatory frameworks.

5. Conclusion

This study builds upon an existing harm-based metric for IAQ assessment expressed in (DALY·(10^5 pers)⁻¹·year⁻¹), while introducing a new methodology for estimating indoor contaminant concentrations through modelling. This approach allows cumulative health impacts of multiple indoor air contaminants to be quantified using either measured data or simulated emission scenarios.

Applied to French residential data, the metric consistently identified PM, formaldehyde, NO₂ and radon as the key contributors to health harm, aligning with prior research. Application to a case study dwelling further confirmed the metric's responsiveness to changes in ventilation air flow rate, with diminishing benefits observed beyond 350 m³·h⁻¹ and the important benefice of increasing drastically the flowrate

during emission events. This threshold aligns with the EN 16798-1 standard, reinforcing its scientific basis.

Three priorities should guide future work. First, emission input data should be refined using large-scale real-world monitoring datasets and occupant behavioural observations. Second, future research should also explore the integration of occupant behaviour, infiltration, and contaminant interactions to refine harm estimates. Third, sensitivity analyses on key assumptions, including the PM coarse fraction ratio and deposition coefficients, would strengthen the robustness of harm estimates and support adoption across regulatory contexts.

The harm metric provides a transparent, scalable, and health-grounded basis for performance-based IAQ regulation, offering policymakers a tool to move beyond prescriptive airflow requirements towards outcome-oriented standards for both new construction and existing dwellings.

Use of generative artificial intelligence

This manuscript was prepared with the assistance of artificial intelligence (AI) tools (ChatGPT 4) to support the writing process, particularly in drafting and language refinement. However, all scientific content, analysis, interpretations, and conclusions were conceived, validated, and authored by the human contributors.

Author contributions

CRedit: **Valérie Leprince**: Writing – original draft; **Olivier Ramalho**: Resources; **Núria Casquero-Modrego**: Writing – review & editing; **Max Sherman**: Writing – review & editing; **Gaëlle Guyot**: Writing – review & editing; **Iain Walker**: Writing – review & editing; **Benjamin Jones**: Writing – review & editing; **Jelle Laverge**: Writing – review & editing; **James A. McGrath**: Writing – review & editing .

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Notes on contributors

Valérie Leprince, Project Director, IEQ and Ventilation, Cerema.

Núria Casquero Modrego, Research Scientist, Lawrence Berkeley National Laboratory.

Olivier Ramalho, Research Engineer, CSTB.

Max Sherman, Professor/Researcher, University of Nottingham.

Gaëlle Guyot, Project Director / Researcher, Cerema.

Iain Walker, deputy department head for the Whole Building Systems Department of the Building and Industrial Systems Division, Lawrence Berkeley National Laboratory.

Benjamin Jones, Associate Professor, University of Nottingham.

Jelle Laverge, Associate Professor, Ghent University.

James A. McGrath, Assistant Professor, Maynooth University.

ORCID

Valérie Leprince  <http://orcid.org/0000-0002-5919-6699>

Núria Casquero-Modrego  <http://orcid.org/0000-0001-5677-4142>

Olivier Ramalho  <http://orcid.org/0000-0001-8848-3788>

Max Sherman  <http://orcid.org/0000-0002-5251-8763>

Gaëlle Guyot  <http://orcid.org/0000-0001-6112-9295>

Iain Walker  <http://orcid.org/0000-0001-9667-1797>

Benjamin Jones  <http://orcid.org/0000-0002-5606-9379>

Jelle Laverge  <http://orcid.org/0000-0002-5334-1314>

James A. McGrath  <http://orcid.org/0000-0002-9832-370X>

Data availability statement

The data that support the findings of this study are available from the corresponding author, Valerie Leprince, upon reasonable request.

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