A framework for integrating indoor air quality into the life cycle assessment of buildings: application to the sizing of ventilation rates

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Abstract

Purpose

Life cycle assessment (LCA) methods are used in building ecodesign, but do not currently consider indoor air quality (IAQ). Since we spend about 85% of our time indoors, and are exposed to potentially hazardous substances, IAQ is of particular importance to human health. Its consideration in LCA could help make adequate design choices (e.g. materials, window layouts or ventilation rates) and reduce the building's impacts, while avoiding their transfer to other life cycle stages.

Methods

To address this gap, we propose a methodology combining building LCA and models that encompass the whole pollutant pathway, from emission to quantified impacts on human health using the disability-adjusted life years (DALYs) indicator. We account for volatile organic compounds (VOCs) and fine particulate matter ($PM_{2.5}$), emitted from materials and indoor activities. An optimal ventilation rate allowing to reduce overall IAQ and LCA impacts (namely from energy for space heating and ventilation fans) is identified. The framework's applicability is demonstrated on a case study: different rooms having distinct uses, occupancy and activity patterns, lead to different emission rates, impacts and optimal ventilation rates. The influence of heat sources (gas, electricity, wood) on optimal rates is assessed and different window layouts for natural ventilation are tested.

Results and discussion

$PM_{2.5}$ and heating are the main sources of impacts, respectively ranging from 40–94%, and 1–31% of total impacts of each room, which range from 2500 µDALY/year to 14200 µDALY/year. Rooms with higher indoor emissions have higher optimal ventilation rates: 1.2 ACH (air changes per hour), 2.9 ACH and 13.2 ACH in the meeting room, office and kitchen respectively. These rates also vary for different heat sources due to their different IAQ and LCA impacts: 2.7 ACH, 5 ACH and 15 ACH for coal (still a common fuel in rural Asian countries), gas and electric fan heating respectively in the living room. The combined use of double-flow ventilation to lower heating needs and filters that reduce $PM_{2.5}$ concentrations leads to a 56% decrease in total impacts of the meeting room.

Conclusions

This study shows the applicability of the framework to building ecodesign. For instance, distinct optimal ventilation strategies can be devised, depending on the room or building use. The framework can also have a regulatory application in public health, through representative archetypes, by providing general recommendations in the tertiary and residential sectors.

1. Introduction

Indoor air quality (IAQ) is of particular importance to human health since we spend about up to 90% of our time in indoor environments (U.S. Environmental Protection Agency 1989) and it bears a significant share of global burden of diseases. For instance, 92 million Disability-Adjusted Life Years (DALYs), i.e. 3.6% of total global DALYs, were associated with household fine particulate matter ($PM_{2.5}$) in 2019 (Murray et al. 2020, 87). $PM_{2.5}$ can be emitted indoor by occupant activities, which may lead to high indoor concentrations that exceed the World Health Organisation's recommended limits (WHO 2021; Slezakova et al. 2018; Mainka and Fantke 2022; Aquilina and Camilleri 2022). $PM_{2.5}$ emitted outdoors can penetrate through unfiltered ventilation, and also contribute to indoor concentrations, with particular importance in highly polluted cities, especially in India, Bangladesh and China (WHO 2023).

Besides $PM_{2.5}$, exposure to gaseous substances in indoor air can result in adverse health effects. These substances include some volatile organic compounds (VOCs) which are highly toxic, and even carcinogenic. They can be emitted by construction materials, identified as important sources of chemicals in indoor environments (Huang et al. 2022). A framework modelling their emission, indoor concentration, intake and health impacts expressed in DALYs was developed by Bhoonah et al. (2013a). Other indoor gaseous pollutants include carbon dioxide (CO_2) and ozone (O_3), but the direct consequence of their intake on human health has not yet been quantified. For CO_2, the recommended exposure concentration is 1000 ppm (ANSES 2013; Canada Health 2021), beyond which occupants can start to feel drowsiness or sleepiness. In the case of O_3 and other precursors such as hydroxyl radicals, nitrate radicals, different studies highlight its importance on IAQ, since it is a precursor to indoor chemical reactions with organic substances (e.g. isoprene, monoterpenes and oxygenated compounds). These reactions can lead to the production of highly toxic substances, in particular VOCs such as formaldehyde or acetaldehyde (Salthammer, Mentese, and Marutzky 2010; Mendez et al. 2015; Weschler and Carslaw 2018).

In order to reduce the impacts of pollutants emitted indoors on human health, air can be renewed, allowing for the evacuation of pollutants. Though high ventilation rates during activities can lead to important decreases, by up to 100% in indoor pollutant concentrations (Bhoonah et al. 2023b), if outdoor temperatures are low, occupant comfort could be affected. This can also cause an increase in energy consumption for heating to maintain comfort temperatures. If mechanical ventilation is used, higher ventilation rates also lead to higher electricity consumption by fans. Since IAQ impacts decrease, but impacts of heating and electrical fans increase, an optimal ventilation rate should yield the lowest impacts when accounting for all sources. To identify this rate, impacts of IAQ and energy consumption have to be evaluated using a common unit. For energy consumption, impacts are currently considered in building ecodesign through the life cycle assessment (LCA) of buildings. LCA allows to evaluate a building's impacts throughout all *stages* of its lifespan (*construction*, *operation* – energy and water consumption, waste production, occupant transportation, *renovation* and *end-of-life* – incineration, landfill, recycling or reuse) on different impact indicators. These can be separated into three main areas of protection: biodiversity, resources and human health as suggested in e.g. ImpactWorld + (Bulle et al. 2019). LCA is now widely used in the construction sector and at the building level for various study objectives (Cabeza et al. 2014; Anand and Amor 2017; Ortiz, Castells, and Sonnemann 2009). However, IAQ is mainly assessed through monitoring (after the building's construction) or simulation of pollutants' indoor air concentrations, and not treated by current LCA methods and ecodesign tools.

To integrate IAQ impacts into the LCA of buildings, modelling the entire pollutant pathway is required, linking materials and indoor activities to human health impacts considering the same endpoint human health damage indicator as the one used in LCA: Disability-Adjusted Life Years (DALYs). A framework for the calculation of health impacts of VOCs emitted by materials was developed by Bhoonah et al. (2023a), and for $PM_{2.5}$ emitted by occupant activities by Bhoonah et al. 2023b. It was concluded that parametric models based on average scenarios could lead to substantial uncertainties on indoor air concentrations. For instance, at high ventilation rates, air concentrations could vary up to a factor 100 between scenarios when windows were open before as compared to during the activity. Ventilation and emission dynamics can be captured by dynamic models, such as INCA-Indoor (Octopus Lab 2017), to obtain time-dependent pollutant air concentrations.

The aim of this study is to develop a methodology integrating IAQ into building LCA, in order to determine optimal building design parameters. Its applicability is demonstrated on a case study to identify optimal ventilation rates for different rooms and scenarios. More specifically, the different steps are to:

- calculate LCA impacts of the case study building on all life cycle stages.
- calculate health impacts linked to IAQ, accounting for VOCs and $PM_{2.5}$ emitted by materials and occupant activities.
- add IAQ and LCA impacts for a range of ventilation rates in order to determine optimal values allowing to reduce total health impacts for different rooms.

Using different variants of a case study, we aim at demonstrating the applicability of the methodology developed to decision-making in building construction.

2. Materials and methods

2.1. Overall followed approach

The general approach followed to integrate IAQ impacts to building LCA is presented in Fig. 1. The different parts of the method (for a given ventilation rate) are shown with main influential factors at each step and the method is described with fuller details in the next sections. As an example, the methodology is applied using existing software: Pleiades modeller allowing to create a building model, Pleiades STD to perform dynamic thermal simulation (Peuportier and Blanc Sommereux 1990), Pleiades LCA for life cycle assessment (Polster et al. 1996), and INCA Indoor for IAQ calculations (Mendez et al., 2015).

We model the building under study using Pleiades Modeller (IZUBA ÉNERGIES 2001a) which allows to define building characteristics: design, layout, materials, mechanical ventilation rates, openings (windows and doors), location and occupancy. Heating needs are calculated with Pleiades STD (Peuportier and Blanc-Sommereux 1990) based on outdoor climate, thermal properties of building materials and use characteristics (e.g. occupancy, internal heat gains, temperature set point). For the building's LCA, we use Pleiades LCA (Polster et al. 1996; Thiers and Peuportier 2012), considering all *stages* of its life cycle: *construction*, *operation* (heat and electricity consumption based on calculated heating needs and hot/cold water consumption based user inputs), *renovation* and *deconstruction*. The LCA database ecoinvent v3.4 cutoff (Frischknecht et al., 2004) is used.

Material VOC emissions are calculated considering a material age of one year, after which emissions are stabilised (see Supporting information 2 section S.3.). Activity VOC and $PM_{2.5}$ emissions (µg/h) are obtained from literature, and summarised in Supporting Information 3 (SI 3). The heating system $PM_{2.5}$ emissions also depend on the calculated heating energy needed, since more fuel is burnt for higher consumption, leading to higher emissions. Using the INCA-Indoor model (Octopus Lab 2017), which considers the building specifications obtained from Pleiades Modeller (room geometry, mechanical ventilation rates, opening of windows and doors), and pollutant emission rates based on materials and activity scenarios, indoor air concentration of pollutant x $C_{\mathrm{in},x}$ (µg/m^3) are calculated. These are coupled with occupant exposure (µg$_{\mathrm{intake}}$/µg$_{\mathrm{indoors}}$) through different pathways according to dynamic occupancy. Using the effect factors (µDALY/µg$_{\mathrm{intake}}$) of each pollutant, a total IAQ-related health damage is calculated and added to LCA impacts in µDALYs.

Variations in ventilation rates are tested on a case study in order to identify optimal trade-offs that allow to reduce overall health impacts. In order to demonstrate possible applications of the developed methodology in the tertiary and residential sector, we study virtual variants of a case study, with particular attention to different heat sources and window layouts.

2.1. Building characteristics

The case study used to illustrate the methodology corresponds to the office building of Octopus Lab (developer of INCA-Indoor) situated at La Madeleine in the north of France (see SI 1 S.1.). Three out of ten rooms are selected for the case study: a) meeting room, b) kitchen and c) office. They represent distinct uses, which not only lead to different choices of materials (in particular flooring: bamboo flooring for the meeting room, PVC flooring for the kitchen and carpet for the office), but also room-specific occupant activities. The meeting room is occupied by five persons from 9:30 to 11:00 and from 14:00 to 17:00. The kitchen is occupied by six persons from 8:30 to 9:00, 12:30 to 13:30 and from 16:00 to 16:30. The office is occupied by three persons for longer periods: from 9:00 to 12:30 and from 13:30 to 18:00. The building is heated by a collective gas boiler (located in a different compartment than those studied), but two alternatives are also studied: a portable electrical fan heater, and a coal stove. Coal heat stoves are still a common practice in rural India or China (Shen et al. 2020; Li et al. 2022).

All rooms are subject to a normalised infiltration rate I_4 of 1.7 m^3/h/m² under 4 Pa, which is on the low-end of infiltration rates in tertiary buildings (Carrié et al. 2006). The normalised infiltration rate defines the airflow rate at a pressure difference of 4 Pa between the inner and outer sides of the envelope. The rooms are fitted with mechanical ventilation. The air renewal rate considers both infiltrations and mechanical ventilation. It is expressed in air changes per hour (ACH)

– the number of times the room's air volume is renewed in an hour. Ranges within which the air renewal rate is varied are based on values reported in literature: from 0.2 ACH for closed, airtight buildings (Persily et al. 2010) to 15 ACH for non-OECD countries (Rosenbaum et al. 2015). The average for houses in OECD countries is 0.64 ACH (Rosenbaum et al. 2015).

The minimum air renewal rate for offices and residences is 18 m^3/h per occupant according to the French regulation on health in indoor environments (decree of 20 November 1979). It can be converted into ACH using the room's volume and occupancy rate. This results in a minimum air renewal rate of 90 m^3/h (2 ACH) for the meeting room, 108 m^3/h (3 ACH) in the kitchen and 54 m^3/h (1.3 ACH) in the office.

2.2. IAQ input parameters

Material VOC emissions were calculated using the multilayered emission model described by Micolier (2019), with mass fractions obtained from Pharos (Healthy Building Network 2000) and diffusion and material-air partition coefficients obtained from Huang et al. (2017; 2019). For two materials, namely bamboo flooring and gypsum board, optimal parameters calculated by Bhoonah et al. (2023a) are used. The multilayered model considers the buffer effect of material layers, which affects the emission profile. The age of materials is set to one year and most material thicknesses are estimated according to usual professional practice. Sources of uncertainty lie in these parameters, since they affect emission rates. However, after one year, material emission rates are stabilised, except for isopentane from expanded polystyrene (see SI 2 S.3.). Model data (emitted substances, mass fractions, diffusion coefficients and material-air partition coefficients) are given in SI 3. VOCs emitted by activities and their emission rates are given in SI 3. In the case of $PM_{2.5}$, emission data are obtained from Bhoonah et al. (2023b) and resuspension rates are presented in SI 3. Activity scenarios for one day are summarised in SI 1.

2.3. IAQ impact assessment method

Indoor air concentrations of $PM_{2.5}$ and VOCs are calculated using the INCA-Indoor multizone model for different ventilation rates through the mass balance of pollutants in each room under study. Influential parameters include the building's characteristics (location, dimensions and openings), occupancy rates, meteorological conditions and outdoor pollution (determined by the building's geographical location), and indoor activities and their emission rates in each room. Airflows are simulated using CONTAM (Dols and Polidoro 2020), considering infiltration, exfiltration and flows between rooms based on outdoor and indoor pressures and temperatures. A constant indoor temperature of 20°C is considered in all rooms by INCA-Indoor for the calculation of airflows and indoor pollutant concentrations. $PM_{2.5}$ concentrations also depend on their deposition rates (K. Lai and Nazaroff 2000) and VOC concentrations depend on their sorption to material surfaces and chemical reactions between indoor substances (Mendez et al. 2015). Air is treated as an ideal gas, obeying to the ideal gas law.

2.3.1. Intake of pollutants

The intake of pollutant x, $M_{\mathrm{intake},path,x}$ (μg_{intake}), through each pathway (inhalation for VOCs and $PM_{2.5}$ and ingestion, direct dermal contact and gaseous dermal uptake for VOCs) is calculated using Eq. (1), according to concentrations and occupant exposure during their presence in the room.

$$M_{\mathrm{intake},path,x} = V_{\mathrm{room}} \int_{t=0}^{T} XF_{path} \times C_{\mathrm{in},x} dt$$

1

V_{room} (m^3) is the room's volume. Indoor concentration of pollutant x $C_{\mathrm{in},x}$ ($\mu g/m^3$) and exposure factors XF ($kg_{\mathrm{intake}}/kg_{\mathrm{in\ compartment}}/s$) are dynamic (see SI 1 S.6.).

The presence of occupants varies according to the day of the week: there is no presence during weekends in offices, while the presence of occupants is more important during these two days in residential buildings. The total intake of occupants through inhalation (m^3/s) is shown in SI 1 S.6. The intake of VOCs by the four pathways (inhalation, ingestion, dermal contact and gaseous dermal uptake) are considered, while only inhalation is considered for $PM_{2.5}$ since it is mainly absorbed through the respiratory system (Thangavel, Park, and Lee 2022) and current effect factor models consider only inhalation as intake pathway (Burnett et al. 2014; Fantke et al. 2019).

2.3.2. VOC effect factors

Effect factors EF ($\mu DALY/\mu g_{\mathrm{intake}}$) are calculated based on ED_{10} or ED_{50} (the lifetime doses per person that causes a disease probability of 10% and 50% after intake) obtained from USEtox (Fantke et al. 2017) and the ToxVal database (US EPA and Richard 2018), for cancer diseases, reproductive/developmental non-cancer diseases and general non-cancer diseases.

2.3.3. $PM_{2.5}$ effect factors

The effect factor (EF) is based on the Global Burden of Disease (GBD) integrated exposure-response (IER) model, adapted from Fantke et al. (2019) by Bhoonah et al. (2023b) for indoor contexts, as given in Eq. (2).

$$EF\left(\bar{C}_{\mathrm{in,PM_{2.5}}}\right) == \frac{\left(RR_i\left(\bar{C}_{\mathrm{in,PM_{2.5}}} + \Delta C_{\mathrm{in,PM_{2.5}}}\right) - RR_i\left(\bar{C}_{\mathrm{in,PM_{2.5}}}\right)\right) \times \frac{M_{i,r}}{RR_i\left(\bar{C}_{\mathrm{out,PM_{2.5}},r}\right) \times POP_r} \times SF_{i,r}}{\Delta \bar{C}_{\mathrm{in,PM_{2.5}}} \times BR_{yr}}$$

2

Where RR_i (-) is the relative risk of developing disease i from exposure to average indoor PM$_{2.5}$ concentration $\bar{C}_{\mathrm{in,PM_{2.5}}}$ (µg/m^3) (see Fantke et al. 2019), $\bar{C}_{\mathrm{out,PM_{2.5},r}}$ (µg/m^3) the ambient PM$_{2.5}$ concentration of the city, $\Delta\bar{C}_{\mathrm{in,PM_{2.5}}}$ (µg/m^3) the increment on the exposure-response curve, $M_{i,r}$ (deaths/year) the annual mortality in region r due to disease i, obtained from the GBD Collaborative Network for 2019 (Burnett et al. 2014; GBD Global Burden of Disease Collaborative Network 2019). POP_r (cap) is the population of the region, obtained from the national population prospects (United Nations 2019), $SF_{i,r}$ (DALY/death) is the severity factor specific to the region and disease and BR_{yr} (m^3/year) is the breathing rate. In this study, EF corresponds to exposure to ambient (background) and activity-related PM$_{2.5}$ concentrations, considering possible contributions of multiple activities to indoor concentrations $C_{\mathrm{in,PM_{2.5}}}$ at a given point in time.

2.3.4. Health impacts

Health impacts HI_x (µDALY) linked to each substance x are calculated as the product of the total mass intake $M_{\mathrm{intake},x}$ (µg$_{\mathrm{intake}}$) and its effect factor EF_x (µDALY/µg$_{\mathrm{intake}}$), expressed in Eq. (3).

$$HI_x = EF_x \times M_{\mathrm{intake},x}$$

3

In the case of VOCs, we distinguish between the different intake pathways and related effect factors. For PM$_{2.5}$, we calculate the total impacts as a product of the total intake by inhalation and the effect factor linked to average indoor concentrations in the room, $EF\left(\bar{C}_{\mathrm{room}}\right)$. The total health impacts is the sum of HI_x of all substances considered.

2.4. LCA input parameters and method

The functional unit is given for each room in SI S.4. The materials and equipment used in the building (illustrated in SI 1 S.1.) and their respective masses, obtained from Pleiades LCA based on the building model on Pleiades Modeleur, are given in SI 3 A1. The building's lifespan is 100 years, and indoor temperatures are maintained at above 19°C in all rooms. We do not consider the effect of ventilation on active cooling in summer (air conditioning). The heating power (W) and energy (kWh) needed to achieve a minimum of 19°C temperature in all rooms during working hours are calculated using Pleiades STD, based on outdoor temperatures, airflow rates, insulation, and occupancy. An electricity consumption of 0.02 Wh/m^3 is considered for ventilation fans. A prospective attributional hourly mix based on Frapin et al. (2022) was considered to evaluate impacts of electricity consumption. Concerning electric heating, it finally comes to a mix of 57% nuclear, 21% hydro and renewable energies, 20% gas and 2% coal. Detailed hypotheses and other relevant parameters including the functional unit, heater efficiency and waste treatments are presented in SI 1 S.4. Variations in ventilation rates are applied without compromising occupant comfort in winter (indoor temperatures), potentially leading to increased energy consumption for heating.

We use Pleiades LCA for the building life cycle assessment and health impacts are calculated using ReCiPe 2016 (Huijbregts et al. 2017; Johan Lammerant et al. 2019), which is one of the most recent and updated endpoint methods, with the ecoinvent v3.4 cutoff database (ecoinvent 2017). Impacts are given for each room under study. Those linked to construction (material fabrication and transport), heating, IAQ, renovation and deconstruction are specific to the room. Impacts linked to the building's foundation, equipment (cables, pipes and furnace), electricity and water consumption are allocated according to the room's floor area (see SI 1 – A6). Water consumption impacts are regionalised for France (see SI 2 S.1.).

2.5. Optimal ventilation rates

IAQ and LCA results (hierarchist health impacts) are added for each ventilation rate. The rate that yields the lowest total impact is identified for each room. We compare the ventilation speeds to reference comfort air speeds v_{air} (m²/s). The comfort air speed for the kitchen is $Q_{\mathrm{air,window}}$ = 179 ACH and $Q_{\mathrm{air,vent}}$ = 8 ACH for mechanical ventilation (see SI 1 S.5.). We note that these rates are based on air speeds at the window or vent, but that air reaches a larger cross-section area in the room where its speed decreases. We note that INCA-Indoor and Pleiades STD are simulation-based, and that the models can run for one ventilation rate at a time. Thus, due to time constraints, a limited number of simulations (one for each ventilation rate) is run.

3. Results

3.1. Indoor pollutant concentrations

Materials emit VOCs continuously, while activities emit VOCs or PM$_{2.5}$ at specific points in time. The concentration curves of PM$_{2.5}$ over a winter week (thus including electrical fan heating that increases particle concentrations in air through their emission by the friction of moving rotors and through their resuspension due to blown air) are presented in Fig. 2 for the three rooms: a) meeting room, b) kitchen and c) office. For an average mechanical ventilation rate of 0.6 ACH, the contribution from outdoor sources are represented by blue curves and that of indoor activities in orange.

In the case of the office, concentration increments occur during working days, with peaks around activity periods. The highest peak concentrations over the week in the three rooms are different due to the different activities: 80 µg/m^3 in the meeting room, 2240 µg/m^3 in the kitchen and 130 µg/m^3 in the office. Kitchen PM$_{2.5}$ concentrations are very high, especially due to grilling, as compared to the other rooms where vacuuming and electrical fan heating have the highest emissions. We note that the electrical fan heater considered is portable, and not representative of fixed electrical heaters. In the absence of activities, outdoor concentrations are higher than indoors, and vary throughout the week between 8 μg/m^3 and 50 μg/m^3, with an average of 22 μg/m^3. While higher ventilation rates allow to decrease $PM_{2.5}$ from indoor sources, there is an increase in penetration from outdoor sources (see SI 2 S.4.) if no additional measures are taken (e.g. filter).

3.2. Health impacts according to LCA damage indicator coupled with IAQ

Results of the life cycle assessment are presented in Fig. 3 for each room and for all life cycle stages (including IAQ impacts), corresponding to a ventilation rate of 0.6 ACH and the use of gas heating.

We note from Fig. 7 that the *operation* stage, including IAQ, heating and specific electricity use, has the highest impacts on human health, representing 85 to 98% of total impacts in the three rooms for the given ventilation rate, especially due to IAQ, which represents over 77% of the total impacts. However, with higher ventilation rates, IAQ impacts are lowered and heat impacts increased, as seen in the next section. Reference values for total LCA impacts of buildings on human health are scarce but the few values found in the literature indicate a range of around 80 to 1000 μDALY/m²/year which fit the order of magnitude found in this study and highlight the significance of IAQ impacts in buildings (Wurtz and Peuportier 2021; Saadé et al. 2022).

3.3. Optimal ventilation rates

Impacts of relevant life cycle stages for different ventilation rates are presented in Fig. 4, together with optimal ventilation rates for gas and electrical heating. We only consider IAQ, heating and electricity consumption of ventilation fans, since they are affected by changes in ventilation rates.

Highest impacts are induced by the inhalation of $PM_{2.5}$ (56 to 98% of impacts considered in this section: IAQ, heating and ventilation fans) and heating (gas or electric: 1 to 44%). $PM_{2.5}$ impacts are both related to indoor sources and outdoor penetration (see Fig. 2). Impacts of electricity use from ventilation fans (2–9% of total energy consumption) and VOCs emitted by activities or materials are lower: <0.001% for ventilation fans, < 0.4% for activities, < 10% for materials. In the meeting room and office, $PM_{2.5}$ impacts are mainly due to outdoor sources while impacts from indoor sources are lower. In the kitchen, indoor sources are dominant.

We note that the rate inducing the lowest overall impacts in each room is different mainly due to the differences in volume, occupancy (exposure) and activities (emissions). The optimal rate can also be different in the same room but for different heat sources, because 1) LCA impacts of each heat source are different and 2) the electrical fan heater causes the resuspension of particles, leading to additional IAQ impacts. In the meeting room, the optimal ventilation rate is 1.2 ACH for gas heating and 2.3 ACH for electrical heating due to increased IAQ impacts related to the heater. For the same reasons, the optimal ventilation rate for gas heating is also lower than that for electrical heating in the office (2.9 ACH v/s 5 ACH). We note that these results consider only VOCs and $PM_{2.5}$, but not other potentially harmful substances such as CO_2, which can be above recommended limits at rates below 5 ACH (see Fig. 5).

In the kitchen, impacts from $PM_{2.5}$ and heating decrease with increasing ventilation to an optimal rate of 13.2 ACH, beyond which they increase again. The rate is much higher as compared to the other two rooms because indoor $PM_{2.5}$ emissions are much higher, and because of the larger number of persons present (6 persons in the kitchen, 5 in the meeting room and 3 in the office). The high ventilation rate can be difficult to attain without causing occupants' discomfort due to draught and lowered indoor temperatures, especially in winter. While the optimal ventilation rates remain within $Q_{\mathrm{air,vent}}$for the office and meeting room, it is exceeded in the kitchen. The calculated air speed corresponds to the inlet and would be lower inside the room. The actual room air speeds could be evaluated using CFD (computational fluid dynamics).

Impacts presented are related to heat consumption, electricity consumption for ventilation fans, and IAQ. Compared to total impacts (IAQ and all stages of the room's LCA), $PM_{2.5}$ represents a share of 57–96% in the kitchen, with lowest impacts related to highest ventilation rates. Heating impacts range from 1–33%, with lowest impacts related to lowest ventilation rates. For the other two rooms, $PM_{2.5}$ impacts range between 54% and 91%, while heat consumption represents 1–42% of impacts.

3.3.1. Carbon dioxide concentrations

Figure 5 shows the maximum CO_2 concentration in the meeting room, with a red line indicating the recommended limit and yellow markers representing the duration for which this limit is exceeded.

At the calculated optimal ventilation rate of 1.2 ACH, which does not account for CO_2 concentrations, the limit of 1000 ppm is exceeded for 22 h/week. For the recommended flow rate of 18 m3/h/person (2 ACH for five occupants in this room), the CO_2 concentration limit is exceeded for an estimated 16 hours per week. This suggests that the calculation of optimal ventilation rates should not only consider VOCs, $PM_{2.5}$ and heating needs, but also CO_2 concentrations.

3.4. Strategies further limiting health impacts

Besides finding an optimal ventilation rate, other ventilation strategies can be devised to reduce overall impacts. We identified two main sources of impacts linked to IAQ: indoor $PM_{2.5}$ (both penetrating from outdoors and emitted by indoor sources) and energy consumption for heating. To address each of them respectively, the effect of filters and a double-flow ventilation system with heat exchanger are tested in the meeting room heated with gas and ventilated at 1.2 ACH (optimal ventilation rate identified).

A filter type F9 is considered (equivalent to MERV 16 (ASHRAE 52.2 2017)), capturing more than 99% of particles with diameters over 1 μm and 45–95% of particles with smaller diameters from penetrating air. As illustrated in Fig. 4, impacts in the meeting room are mainly due to outdoor penetration. Thus, the filter leads to a three-fold decrease in intake: 26460 μg_{intake}/year with filter and 83890 μg_{intake}/year without. The average air concentration is below C_0, the theoretical minimum risk exposure level (TMREL) being 5.8 μg/m^3 (see SI 2 S.4.). It is the safe limit under which effects have not been observed (Burnett et al. 2014). In this case, no impacts related to $PM_{2.5}$ inhalation were considered. This assumption is based on the absence of evidence from epidemiological studies supporting effects at concentrations below this limit and should be updated if correlations between $PM_{2.5}$ exposure and diseases at lower concentrations are recorded. For this first assessment, no additional material where included in the LCA to represent filter manufacture, renewal and end-of-life, nor additional electricity consumption that could be induced by the filter.

With double-flow ventilation, fresh air enters through vents and flows into ducts before entering the room. Air is also extracted from the room, flowing into separate ducts. A heat exchanger allows the preheating of fresh external air entering the room by the warmer air being extracted from the room, resulting in lower need for additional heating: 34% decrease, leading to a proportional decrease in heating impacts. We consider a double electricity consumption by the ventilation system for the double-flow due to the presence of a second fan.

Figure 6 summarises the calculated impacts, $PM_{2.5}$ intake quantities and heating needs for different scenarios: no filter and single-flow ventilation, no filter and double-flow ventilation, filter and single-flow ventilation, filter and double-flow ventilation at 1.2 ACH (identified optimal ventilation rate for the meeting room).

The combination of double-flow ventilation and filter decreases total IAQ and heating impacts by 89% as compared to a single-flow ventilation without filters. Impacts presented are linked to heat consumption (up to 10% of total LCA + IAQ impacts), electricity consumption for ventilation fans (< 0.001% of total impacts) and IAQ (74% of total impacts). Considering the whole life cycle of the building, the double-flow/filter combination leads to 75% decrease in impacts: from 2235 μDALY/year (20 hours$_{\text{lost}}$/year) to 504 μDALY/year (5 hours$_{\text{lost}}$/year).

Other solutions include, for instance in the kitchen, a hood which can have a $PM_{2.5}$ capture efficiency of 0.6 to 1 (Eom et al. 2023). An efficiency of 0.6 results in an optimal ventilation rate of 5.8 ACH, at which impacts of $PM_{2.5}$ emitted by cooking indoors are reduced by 60% and total IAQ + LCA impacts by 10% as compared to cooking with no hood at the same ventilation rate. An efficiency of 100% leads to an optimal ventilation rate of 0.6 ACH, with 75% decrease in total IAQ + LCA impacts. The decrease in impacts between a scenario with and without hood for a 60% efficiency is lower since the optimal ventilation rate is high, hence leading to the partial evacuation of particles even without the use of a hood.

3.5. Residential variants

The case study that has been discussed is specific to the given use: office building, occupied only during working days and work hours, with related activities. We choose to explore a variant of the meeting room, used as a residential living room, and that of a residential kitchen with natural ventilation. Since the occupancy scenarios and activities (given in SI 1 S.6.) are different, optimal ventilation rates are also expected to change. $PM_{2.5}$ concentrations in each room are given in SI 2 S.5.

3.5.1. Living room

LCA impacts of heating with gas, electricity or coal, and indoor impacts related to resuspension from activities (dusting, walking, vacuuming and folding clothes) and emission from electric fan heater and coal heater are presented in Fig. 7.

VOC impacts are negligible, representing < 0.2% of all impacts for activities and < 5% for materials. Optimal ventilation rates are 5 ACH for gas heating, 15 ACH for portable electrical heating and 2.7 ACH for coal heating. In the case of electrical heating, the duration of heating and indoor $PM_{2.5}$ emissions are considered to be equal for all ventilation rates and heating needs (He et al. 2004). We consider a collective gas boiler installed outside the room, which in this case does not affect the room's air quality, unlike a boiler situated inside the occupied zone. For the heating stove situated in the living room, indoor emissions depend on the heating needs. Thus, higher ventilation leads to higher evacuation of $PM_{2.5}$, but also increased emissions from coal combustion. Since the effect factor model used is non-linear, effect factors decrease with increasing average indoor concentrations. The combined effect of both leads to lower health impacts at 0.2 ACH than at 0.6 ACH (see SI 2 S.5.).

Electric heating leads to the lowest LCA impacts (i.e. IAQ impacts excluded) for equivalent heating needs: 93% of gas and 12% of coal heating impacts. The total $PM_{2.5}$ impacts with stove heating are up to 4 times higher than with electrical fan heating. The contribution of outdoor $PM_{2.5}$ has less relative importance in the case of coal stove and electric fan heater (except at 15 ACH for electric fan heater). However, modern heating stoves making use of dry wood or pellets might substantially decrease both LCA and IAQ impacts depending on their location in the building, their efficiency, their design and occupant habits. LCA end-point health impacts of wood are over 7 times lower than coal. According to the Stove Industry Alliance, modern heat stoves could represent only 2.7% of indoor $PM_{2.5}$ emissions, while the coal stove considered in this study represent 48 to 91% of emissions from activities.

Though electrical heating has the lowest LCA impacts, if it contains a fan, indoor IAQ impacts could be non-negligible due to $PM_{2.5}$ resuspension and emission. Gas heating, at a ventilation rate of 5 ACH, can yield lower IAQ and heating related impact: 2350 μDALY/year. At 15 ACH (optimal rate for electrical heating) impacts amount to 3110 μDALY/year. For the scenario with a heat stove, impacts are of 12400 μDALY/year for an optimal ventilation rate of 2.7 ACH (IAQ + heating). If the living room is fitted with an electrical heater without fan, there might be different $PM_{2.5}$ emissions (or resuspension) from heating and the same LCA impacts as electrical fan heater. Considering no additional $PM_{2.5}$ emissions would lead to up to 2% decrease in impacts (heating, ventilation fan and IAQ) as compared to collective gas heating for a ventilation rate of 5 ACH.

The ideal ventilation rates are higher than the recommended value of 18 m^3/h per person (2 ACH for the living room with 5 occupants). Furthermore, CO_2 concentrations, already above recommended limits for ventilation rates below 5 ACH (see Fig. 5), do not include potential fugitive CO_2 emissions from the burning of coal. Optimal ventilation rates do not exceed $Q_{\text{air,vent}}$, except for electrical heating.

3.5.2. Kitchen

We test the different window layouts from SI 1 S.2. for the home kitchen (on the ground floor of an apartment in La Madeleine, in the north of France, considering an average wind speed of 16.7 km/h). Figure 8 illustrates impacts related to heating and indoor $PM_{2.5}$, average air change rates ACH, and average $PM_{2.5}$ concentrations (µg/m^3) for each scenario.

Average and dynamic air renewal rates do not exceed $Q_{\mathrm{air,window}}$ = 179 ACH (see SI 2 S.2.). The lowest health impacts (3580 µDALY/year, i.e. 31 $\text{hours}_{\text{lost}}$/year from heating and IAQ), linked to the highest ventilation rate, is achieved by scenario 5 with cross-ventilation. Scenario 3 and 4 present similar health impacts (4964 µDALY/year and 4762 µDALY/year) due to perpendicular windows.

This study shows that the kitchen should be placed, if possible, in a room either with the presence of cross-ventilation or with perpendicular windows. A kitchen hood should also be installed if possible, since 60–100% of particles can be extracted (Eom et al. 2023), leading to 1% – 85% decrease in heating and IAQ impacts altogether. However, the electricity consumption of the hood should then also be included in the study.

4. Discussion

This methodology presents several strengths. First, it is a comprehensive framework evaluating the total impacts of a building, considering a global scale through LCA and a local (indoor) scale through IAQ impact assessment. It can help in decision-making early at the design phase in order to avoid additional health impacts on occupants. Some limitations and linked perspectives have been identified, and the possible applications are discussed in the following sections.

4.1. Limitations and perspectives linked to LCA modelling

We note that optimal ventilation rates are dependent on the calculated impacts, and are potentially not similar for different impact assessment methods (see SI 2 S.1. for results using Impact World+). This is because impacts can be different for different methods, and the ventilation rate yielding lowest LCA + IAQ impacts is also likely to change. Further research is needed to investigate those discrepancies. In the case of electrical heating, we considered an average electricity mix according to a prospective attributional LCA approach. However, considering a marginal mix corresponding to consequential LCA (the consequence of adding an electricity demand is an additional electricity production fulfilled by marginal technologies), coal or gas thermal plants would be the main electricity production techniques (in France), thus increasing generated impacts (Roux, Schalbart, and Peuportier 2016). The effect of different LCA methods or electricity mix on the optimal ventilation rate could be assessed in order to evaluate the uncertainties of the results. Regarding the use of filters, their LCA impacts were not considered, and their efficiency relies on their regular maintenance and replacement. Actual filter efficiency can vary if users do not ensure replacement at adequate times.

4.2. Limitations and perspectives linked to IAQ modelling

For rooms with low indoor $PM_{2.5}$ emissions, such as the meeting room, outdoor $PM_{2.5}$ has the highest contribution to indoor concentrations. Thus, calculated optimal ventilation rates are also low in order to avoid the penetration of particles. However, very high CO_2 concentrations are observed at ventilation rates below 5 ACH in the meeting room, but no health effect factor is available. A consideration of the presence of pollutants whose effects on human health have not yet been quantified would improve the robustness of this methodology. Moreover, several activities such as cooking or lighting of candles can release other pollutants than $PM_{2.5}$, namely VOCs. Their concentrations and effects should be considered when possible. In the case of a heating stove, the only fugitive emission rates were obtained from a study in rural China for coal fuel. Further study on recent heat stove technologies and wood fuel (e.g. Flamme Verte in France, for which no fugitive emission rate was obtained) can be made for more representativeness. As a more general perspective, a wider range of heating devices should be assessed using this integrated framework, including other types of electrical heating and the effect of heat power on emission rates (e.g. radiant heaters, electric oil filled heater, heat pump), wood heating (e.g. pellet or log stove, boiler) or gas heating (condensing and or modulating, possibly inside the occupied zone).

In the case of dust, resuspension depends on dust coverage and type of flooring. For instance, carpets can trap more particles than hard floorings. Furthermore, vacuum cleaners both trap and release particles (decrease in dust coverage and thus future resuspension, for e.g. due to walking, but emission/resuspension while vacuuming). Thus, a thorough study on resuspension values for different building uses and flooring types can be realised, considering dust coverage and the net gain of vacuuming.

A thorough focus on uncertainties of IAQ modelling and resulting impacts can be realised. A main source of uncertainty lies in the activity scenario, as different activities and durations can lead to large differences in pollutant concentrations and resulting impacts. Through a sensitivity analysis, main parameters of influence can be identified in order to simplify the model. Uncertainties related to LCA (fabrication of elements, use and end of life stages) could also be addressed.

Finally, the framework is based upon a total damage on human health obtained by adding the LCA result and the IAQ contribution. The equivalence of LCA and IAQ related DALYs could be discussed, as could the addition of different environmental indicators into a unique LCA damage indicator (for e.g. DALYs corresponding to toxic substances are treated as equivalent to DALYs corresponding to climate change). In this study, we treat the DALY as a single unit and assume that they can be added together.

4.3. Applications of the integrated IAQ and LCA framework

We have demonstrated that the methodology enables the identification of optimal mechanical ventilation rates for different case studies according to the building/room’s characteristics, location (which determines outdoor pollution and meteorological conditions), and function (which determine indoor activities and occupancy). In addition, optimal natural ventilation strategies can be devised, such as window layouts or the organisation of rooms based on indoor activities. For instance, we concluded that a kitchen should be placed in a room with cross-ventilation or perpendicular windows if possible. Solutions such as double-flow ventilation, filters or kitchen hoods can be assessed using this method.

Additional solutions to reduce the impacts of IAQ can also be explored, since very high ventilation rates are not always realistic. For example, the effect of the frequency of cleaning surfaces (through sweeping, vacuuming or mopping) on PM resuspension rates or cooking habits (e.g. types of oil used, type of food cooked, and presence of lids) on kitchen emissions can be studied to recommend best practices. The increase in ventilation rates are particularly inconvenient when outdoor temperatures are lower or higher than comfort levels (e.g. in winter or during heat waves). Thus, intelligent ventilation systems could be devised, such as increased ventilation rates when outdoor temperatures are within a comfort range, or the adaptation of these rates according to the presence of certain pollutants in indoor air ($PM_{2.5}$, CO_2 or VOCs).

The methodology can also be used to update existing regulations on ventilation in different sectors. For instance, in some cases, optimal ventilation rates exceeded both the French regulatory value (decree of 20 November 1979) and the maximum recommendation of 5 ACH by the International Energy Conservation Code (International Energy Conservation Code (IECC), ICC Digital Codes 2021). Using representative archetypes for different building categories, associated with reference activity and occupancy scenarios, optimal ventilation rates can be identified. Activity scenarios can be obtained from surveys, or stochastic models (Vorger et al. 2014) and the building stock can be simulated based on national statistics.

5. Conclusions

In this paper, we developed a methodology allowing to link IAQ and building LCA. We saw that impacts of IAQ are very important at the building’s scale, especially at low ventilation rates, and that they should not be neglected in building ecodesign. Two main pollutant categories were studied: VOCs and $PM_{2.5}$, emitted from materials or indoor activities. We showed the applicability of this framework to decision-making in building design, construction or planning through a case study. Material and activity VOC emissions were responsible for lower health damages than energy use for heating and $PM_{2.5}$. Particles are emitted by indoor activities (especially cooking and heating stove), penetrate from outdoors or resuspend from surfaces. For different variants of the case study, optimal ventilation rates or window layouts yielding lowest total impacts (of heating and $PM_{2.5}$) were identified. We noted that optimal ventilation rates were highest for rooms with high $PM_{2.5}$ emissions, namely, the kitchen: 13.2 ACH (without hood above the cooking stove). Natural ventilation through perpendicular or opposite windows can also result in considerable decrease of impacts if open during kitchen activities. The use of a coal stove, still used in Asian rural areas, had high impacts on occupants due to fugitive emissions. Additional solutions were proposed to reduce impacts from increased ventilation rates: double-flow ventilation with heat exchanger and the use of filters, led to a decrease by 56% of overall impacts (LCA + IAQ).

Main perspectives of this study include detailed sensitivity analysis, first on impact assessment methodology, including the LCA hypotheses (e.g. marginal vs attributional electricity mix), and second on the IAQ impact assessment developed. A wider range of heating devices should also be included since they influence both LCA and IAQ impacts. Finally, building archetypes can be developed in order to facilitate the integration of the framework into building ecodesign tools.

Declarations

Acknowledgements

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Data availability statement

The data used to support the findings of this study are included within the supplementary information files 1 and 3.

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Figures

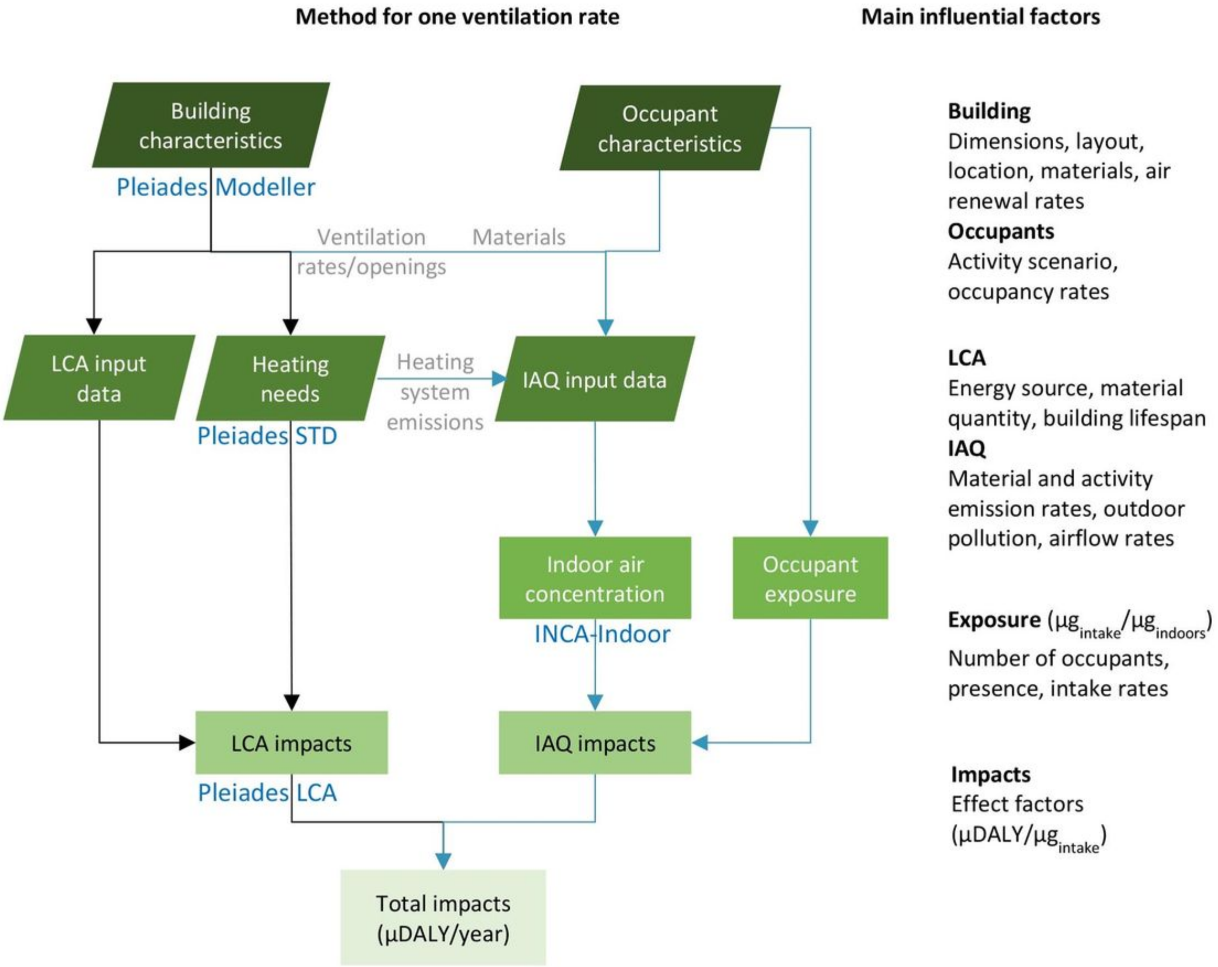

Figure 1

General approach followed to integrate IAQ impacts into building LCA for a given ventilation rate

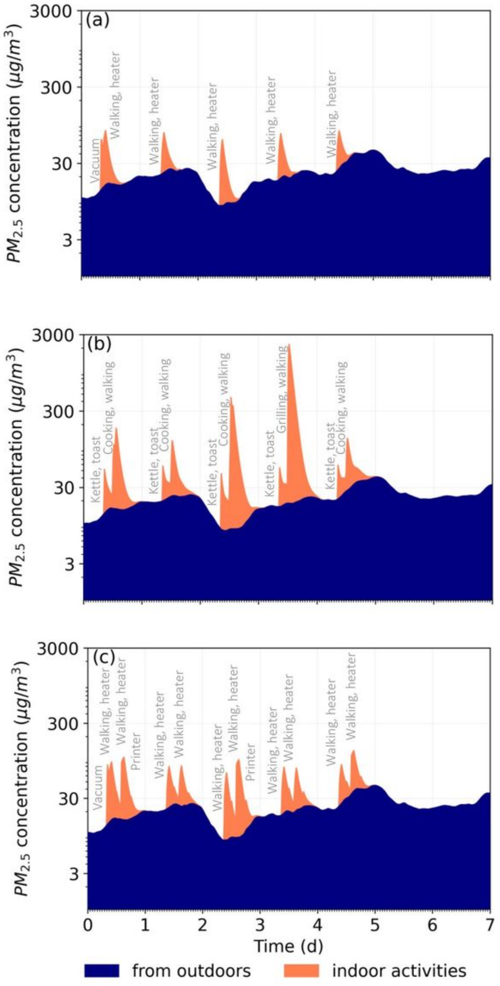

Figure 2

$PM_{2.5}$ concentration in the (a) meeting room, (b) kitchen and (c) office over one winter week due to outdoor penetration (navy) and indoor activities (orange) at 0.6 ACH

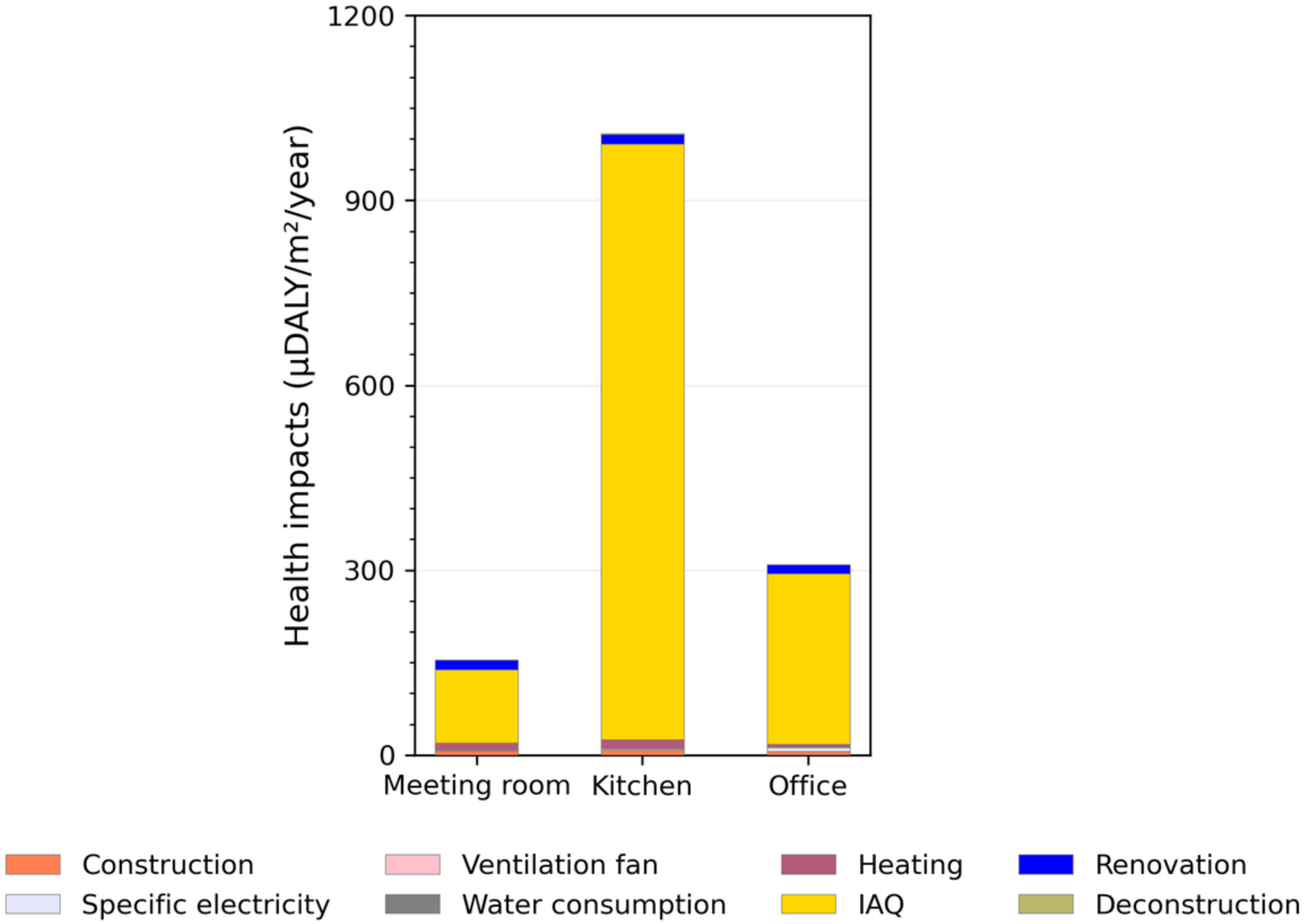

Figure 3

Health impacts per net floor area for the meeting room, kitchen and office separated into life cycle stages: *construction*, *operation* (electricity consumption – specific and from ventilation fans, water, heating and IAQ), *renovation* and *deconstruction* – ReCiPe 2016 – Hierarchist

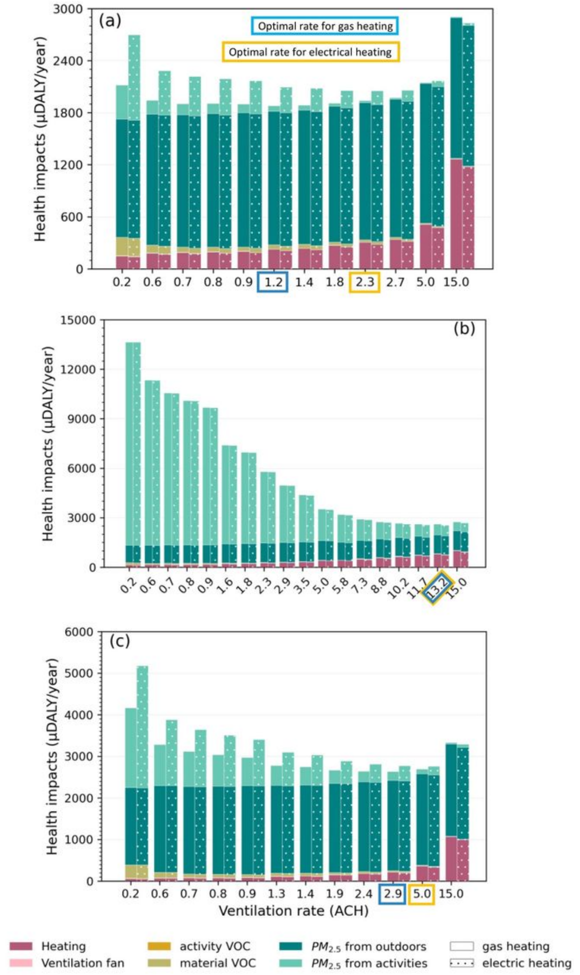

Figure 4

Impacts for different ventilation rates, related to heating, ventilation fan, VOCs from activities and materials and $PM_{2.5}$ from outdoor and indoor sources in the a) meeting room, b) kitchen and c) office

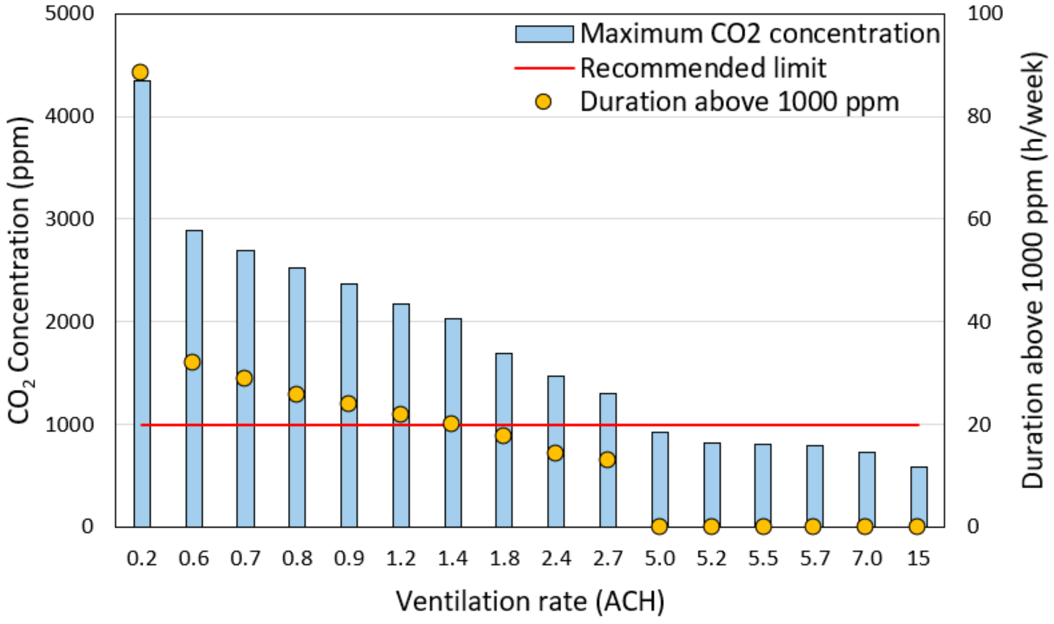

Figure 5

Maximum CO_2 concentrations in the meeting room represented by bars, recommended limit represented by a red line and the duration for which concentrations exceed this limit are represented by yellow markers for different ventilation rates

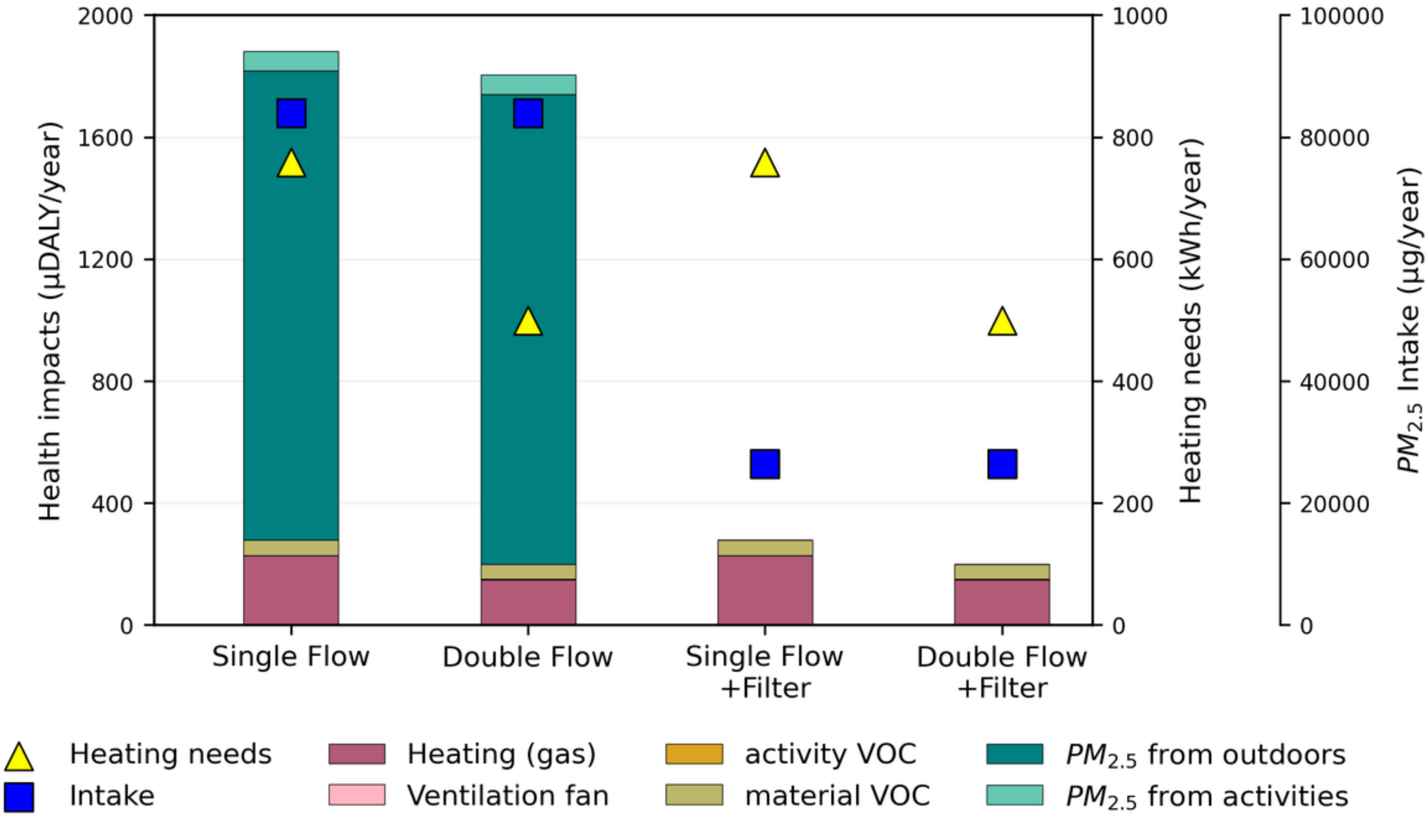

Figure 6

Yearly heating needs (kWh), $PM_{2.5}$ intake (µg) and health impacts (µDALY) for a single-flow ventilation, double-flow, single flow with filter, and double flow with filter at 1.2 ACH

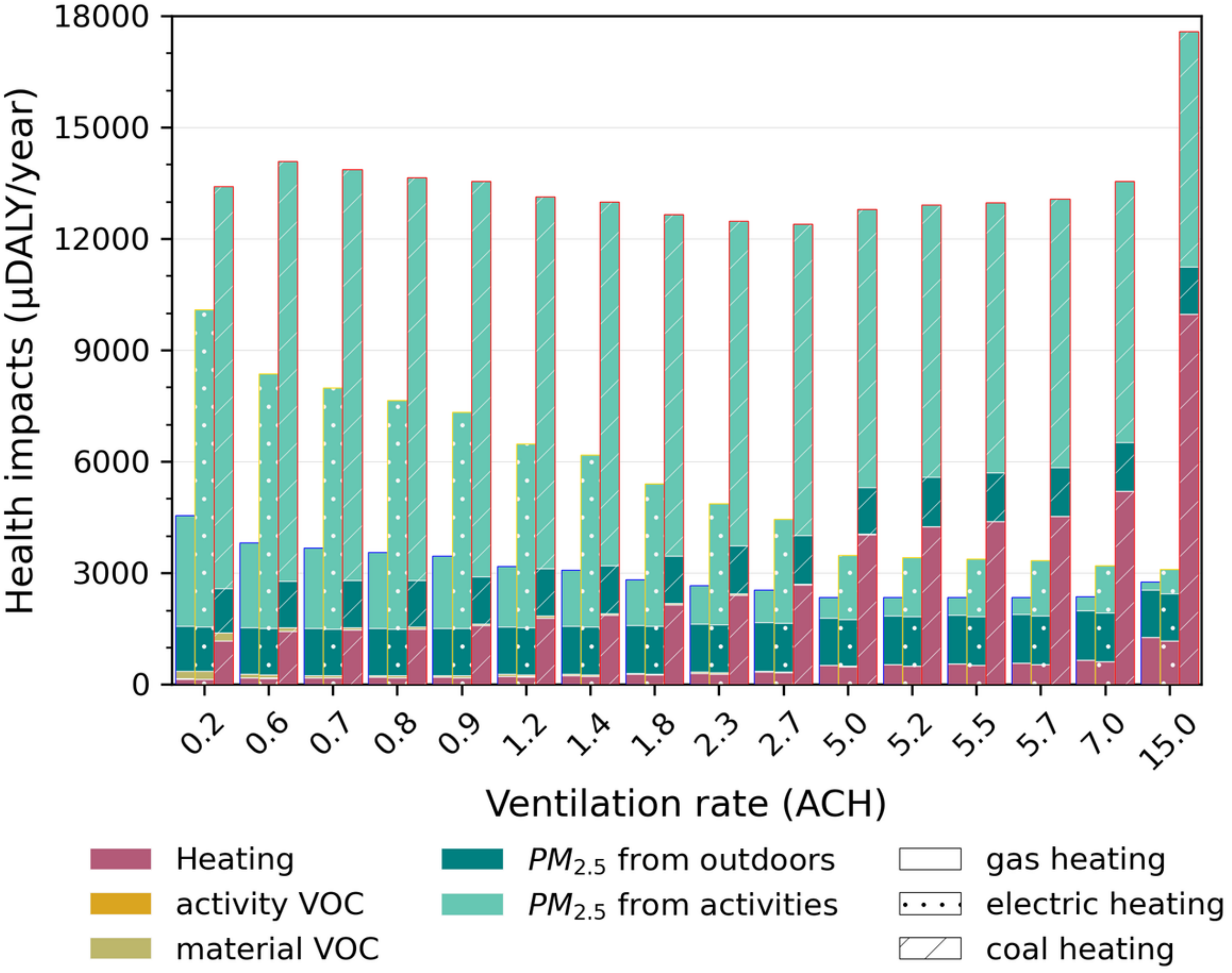

Figure 7

Influence of the air change rate on the health impacts of a residential living room for three heat sources: gas, electricity and coal

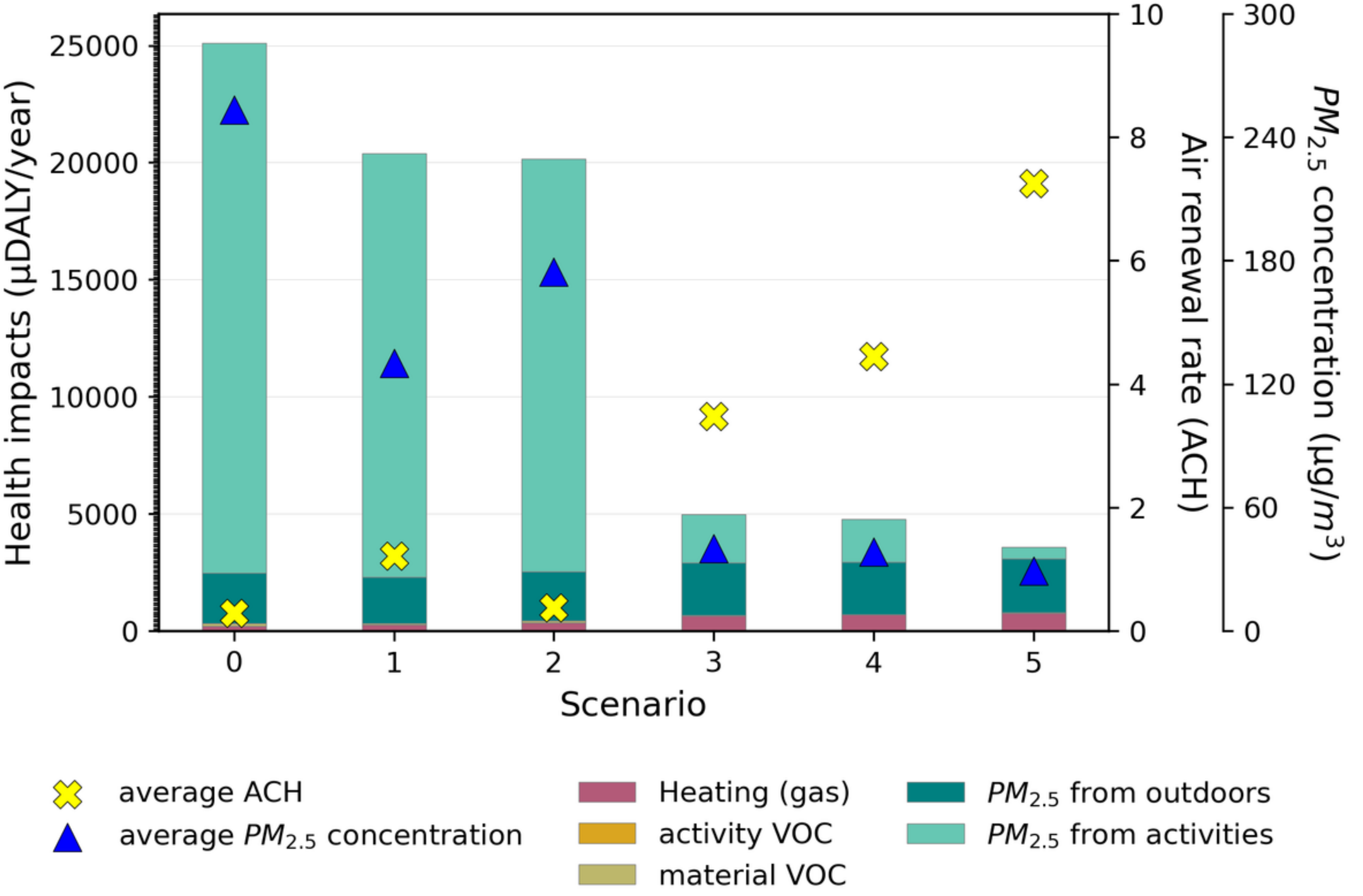

Figure 8

Health impacts related to heating and $PM_{2.5}$ indicated by bars, average ACH indicated with yellow square markers and average $PM_{2.5}$ concentrations (µg/m^3) indicated with triangle blue markers for a residential kitchen with window opening scenarios 0: infiltration only, 1: extractor, 2: one window open, 3: two perpendicular windows open, 4: three windows open (2 perpendicular) and 5: cross-ventilation