IAQ SIMULATION – GOING BEYOND CO_2 CONCENTRATION FOR THE ASSESSMENT OF TWO INNOVATIVE VENTILATION CONCEPTS

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ABSTRACT

This simulation study was performed within the framework of IEA EBC Annex 68 and assesses two innovative ventilation concepts in terms Indoor Air Quality (IAQ), namely the extended cascade ventilation and the active overflow ventilation concept. Both aim at reducing costs and spatial requirements for mechanical ventilation with heat recovery (MVHR) in low-energy housing. In a simple co-simulation approach CO_2, formaldehyde and particulate matter (PM) concentration is evaluated for a representative Austrian dwelling. Besides sources and sinks for CO_2, humidity and particulate matter (size resolved), the temperature and humidity dependent emission rate of formaldehyde from building materials is modelled.

INTRODUCTION

As a consequence to today's airtight building construction, ventilation measures have to be considered and appropriately designed. Building simulation can help to identify a sensible ventilation concept and allows for optimizations in terms of indoor air quality (IAQ), energy-use and cost-effectiveness. However, typically building energy simulations do not address IAQ and if so, only in a very simplified form, e.g. CO_2 concentration arising from human occupancy. However, other pollutants sources should be considered when designing building ventilation. Within the framework of IEA EBC Annex 68 the most relevant pollutants in low-energy housing were identified, sources characterized and simulation methods tested.

This work builds upon the results of this IEA project to assess two innovative ventilation concepts in terms IAQ and energy performance, namely the extended cascade ventilation and the active overflow ventilation concept. The first is based on the simple idea of not directly supplying air into the living room, provided that the floor plan permits. The latter provides a possible solution for refurbishment projects were it is not possible to route air ducting into each bedroom.

VENTILATION CONCEPTS

There is no uniform strategy on how to ensure sufficient ventilation in residential buildings within the European Union (EU). Within a survey, national building codes and guidelines regarding residential ventilation have been reviewed (Zukowska et al. 2020). Therein, stakeholder interviews reveal that, while mechanical ventilation with heat recovery (MVHR) is well accepted in some countries, a number of barriers impede a more widespread implementation. Costs and spatial requirements, including duct routing, were identified as specific challenges for the the implementation of MVHR, in particular in refurbishment projects. Various innovative solutions have been proposed to address these barriers (Kolarik (Ed.) and Rojas (Ed.) 2020).

This simulation study assesses two concepts that aim to reduce the required ducting within a dwelling and compares them with a conventional MVHR implementation and an extract air system. The two innovative concepts are suitable for centralized (one unit for several dwellings) and decentralized (one unit per dwelling) MVHR systems alike.

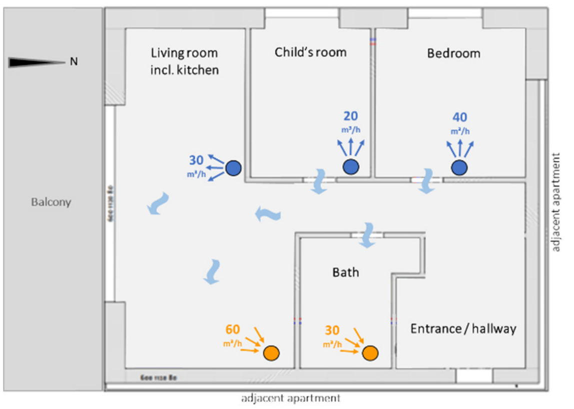

Figure 1: Floor plan of the simulated dwelling with a conventional MVHR ventilation concept: air is supplied into living room, child's room and bedroom and air is extracted from kitchen area and bath.

A conventional residential MVHR system requires supply and extract air ducting to each room of the dwelling. Fresh air is supplied into living room, bedrooms, workrooms, etc. while "used" air is

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extracted from wet rooms, i.e. kitchen, bath and toilet (if needed also from the storerooms). Hallways act as overflow zones, where the air can flow from supply air rooms to extract air rooms. That way, the hallway are also sufficiently ventilated. Figure 1 shows this standard implementation of a MVHR system for the simulated dwelling.

Extended cascade ventilation

The so-called "extended cascade ventilation" principle was first documented in Swiss projects (Fraefel 1999) and systematically investigated in an Austrian research project (Sibille et al. 2013). It is based on the conventional MVHR concept but omits, provided that the floor plan permits, the supply air opening in the living room. In this research project it was concluded that many modern floor plans are such, that the overflowing air from the bedrooms will have to pass the living room zone on the way to the extract air rooms. Besides saving ducting, a silencer and an outlet, the air is most effectively used and the total air exchange rate can be reduced compared to the standard layout with supply air for the living room. Figure 2 shows the implementation of this extended cascade principle for the simulated floor plan. Note that the total supply air for the entire dwelling is reduced to 60 m³/h compared to 90 m³/h for the conventional MVHR concept.

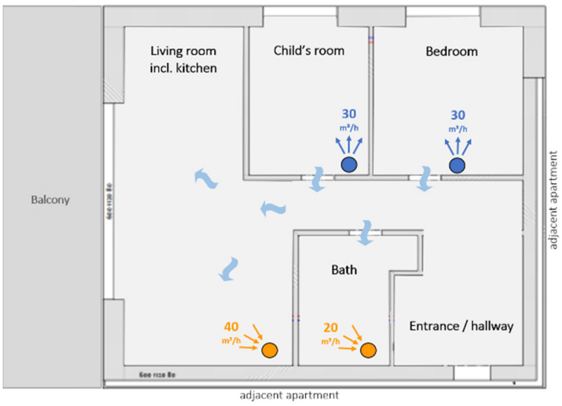

Figure 2: Floor plan of the simulated dwelling with an extended cascade ventilation concept: the living room is only supplied indirectly via overflowing air from the bedrooms.

Active overflow concept

The so-called "active overflow" ventilation principle provides a possible solution for refurbishment projects were it is not possible to route air ducting into each supply air room, i.e. bedrooms. Instead, one active overflow element (AOE) and one passive overflow element is installed in each room. It will move air from the connecting room, e.g. corridor orliving room, into the room in question and back out. In its minimal form, such AOE consists of a sound protected passage, a silent fan, and a control mechanism that ensures the fan is only running when the door of that room is closed. The AOE is often integrated in the door itself, which can simplify the refurbishment process (Sibille and Pfluger 2015). The connecting room, i.e. the corridor or living room, has to be well ventilated by the MVHR system. Extract air rooms should be connected to the MVHR via conventional ducting, which is usually not a problem (e.g. within a suspended ceiling). Figure 3 shows the implementation of this concept in the floor plan of the herein investigated dwelling. Note that the total supply air for the entire dwelling is 120 m³/h compared to 90 m³/h for the conventional MVHR concept.

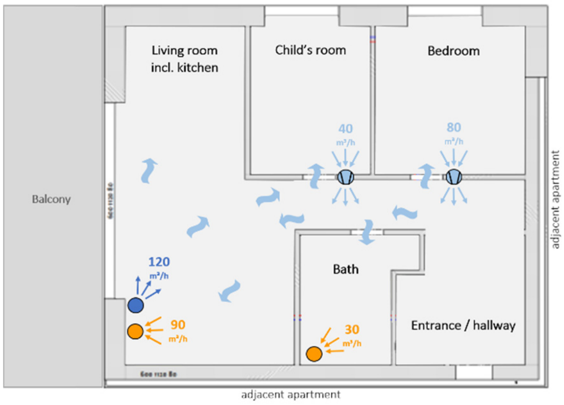

Figure 3: Floor plan of the simulated dwelling with an active overflow ventilation concept: no supply air ducting is needed as the bedroom and the child's room are ventilated with active overflow elements.

SIMULATION METHOD

In a simple co-simulation approach, applying the building energy simulation (BES) software DynBil (PHI n.d.) and the multi-zonal air flow simulation software CONTAM (Dols and Polidoro 2015), the room concentration of CO_2, formaldehyde and particulate matter as well as air humidity is calculated for a representative Austrian dwelling. Besides sources and sinks for CO_2, humidity and particulate matter (PM), the temperature and humidity dependence of the emission rate of formaldehyde from building materials is modelled.

Based on a residential low-energy building project in Austria (Ploss and Hatt 2016), a two-bedroom apartment was modelled in DynBil and in CONTAM. The floor plan is shown in Figure 1-3. It has a floor area of 76 m² and represents a typical Austrian apartment. The occupancy and window use is based on a literature review undertaken for previous simulation studies, e.g. (Rojas, Pfluger, and Feist 2016) with three occupancy schedules representing a full-time employed person, a person staying at home and a school child.

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Airflow model

All airflow relevant aspects, such as air terminals, overflow openings, in-/exfiltration cracks, etc. are modelled within CONTAM. Envelope leakages are modelled with two “cracks” in each exterior wall at two different heights (1 m and 2.2 m representing regular windows and 0 m and 2.2 m representing tall windows) to allow for stack-effect driven infiltration. The cracks are evenly distributed and dimensioned to result in an air exchange of 0.6 h^{-1} at 50 Pa, the threshold for Passive House certification. The wind pressure is calculated using a wind speed modifier, representing a height of 10 m in suburban terrain and wind pressure profile representing a low-rise building (ASHRAE 2005). Wind speed, ambient temperature, solar radiation, etc. are defined by a standardised weather file for the city of Vienna generated with the software Meteonorm.

The reference model has a balanced mechanical ventilation with heat recovery (MVHR), with filtered ambient air being supplied into bedrooms and living room and “used” air being extracted from kitchen area and bathroom. The supply and extract airflows are shown in Figure 1. The investigated extended cascade ventilation concept has same amount of air coming from the MVHR system (filtered) being supplied into bedroom and child’s room. However, no air from the MVHR is directly supplied into the living room, see Figure 2. The active overflow concept model has 120 m^3/h of air from the MVHR system (filtered) being supplied into the living room. Bedroom and child’s room are supplied only indirectly via active overflow elements. For comparison, an extract air system was also simulated. The extract air flows from kitchen area and bath were 60 m^3/h and 30 m^3/h. The make-up air enters via dedicated openings in living room, child’s room and bedroom. Those openings were modelled with a nominal pressure drop of 10 Pa at 30 m^3/h, 20 m^3/h and 40 m^3/h, respectively. For all cases the bedroom and child’s room door, modelled as two-way airflow paths, are closed during the night and open during the day. The bathroom door opens five times for 10 minutes each over the course of the day. The opening between hallway and living room is also modelled as a permanently open two-way airflow path, with 2.5 m height and 1.2 m width.

Thermal model

In the BES-software (DynBil), all airflows are aggregated to two values per interzonal exchange (including exchange with ambient and MVHR system). The unknown values (e.g. in-/exfiltration flows) are estimated for the first simulation run. The thermal model reflects a brick construction in Passive House standard. The external walls are composed of an outer plaster layer, 30 cm EPS insulation, 12 cm of brick and an inner plaster layer resulting in an U-value of 0.11 W/(m^2K). The living room has a glazing area of 6.3 m^2 (south-facing), the child’s room and the bedroom have a glazing area of 2.0 m^2 each (west-facing). The triple pane glazing was modelled with an U-value of 0.72 W/(m^2K) and a g-value of 0.53. An ideal heating with a set-point temperature of 22°C for living room, child’s room and bedroom and a set-point temperature of 23°C was implemented in the reference model. Further details of the BES model are documented in (Rojas et al. 2015).

Pollutant sources and sinks

CO_2 emission from the occupants and humidity sources (occupants, cooking, showering, etc.) are based on weekly schedules representing the three-person household. Details are documented in (Rojas et al. 2016).

The exposure to particulate matter (PM) was simulated for particle diameters ranging from 1 nm to 10 µm with 21 bins evenly distributed on a log scale. Ambient air concentration, filtration efficiency, particle penetration through the bulding envelope, particle deposition and particle sources were considered as size dependent functions.

<u>Particulate matter</u>

The outdoor PM distribution was modelled based on values for archetypical urban air as reported in (Ruprecht 1993).

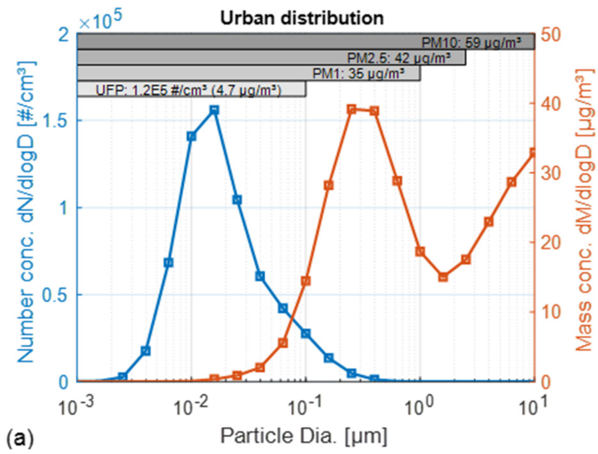

Figure 4: Characteristic ambient particle distributions for urban areas taken from (Ruprecht 1993). *The plots show the log-normalized distributions for particle number and mass concentration assuming a particle density of 1 g/cm³. From: (Rojas 2019)*

Due to lack of time-resolved data, ambient air concentration was modelled constant. Note that the concentration levels for the reference case, i.e. a $PM_{2.5}$ of 42 µg/m^3, will not necessarily represent a typical long-term average of a European city. E.g. the yearly $PM_{2.5}$ average in Austrian cities has been declining and was roughly around 15 µg/m^3 in 2017.

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However, the used distribution may very well present a short-term average in an urban area in Europe or e.g. a long-term average in a moderately polluted Asian city.

For the simulation case with MVHR, the ambient air filter quality reflect a F7 standard according to EN 779:2012, with fractional efficiency curves taken from (Shi 2012). The simulated extract air system assumed no filtration for the make-up air (unfiltered trickle-vent openings). Particle penetration through the envelope was modelled based on measurements results for an aluminium crack with a width of 0.25 mm and a flow length of 9.4 cm (Liu and Nazaroff 2003). Deposition is also an important particle loss mechanism which strongly depends on particle size. Deposition rates in residential settings has been investigated numerously. For this study, the deposition loss coefficient function as specified in (Riley et al. 2002) was used for the reference model. It is based on experimental data for particle diameters >0.06 µm and on the smooth indoor surface particle deposition theory of (Lai and Nazaroff 2000) for diameters below that value.

Cooking is considered one of the major indoor PM source and numerous studies have investigated the resulting PM concentrations and/or characterised emission rates from various cooking activities, e.g. (Abdullahi, Delgado-Saborit, and Harrison 2013; Wallace, Emmerich, and Howard-Reed 2004). Therefore, this study only implemented indoor PM sources representing cooking activities, i.e. toasting, frying burger and heating oil. These three source events, modelled as a burst source (instantons release during one simulation time step of 5 min), were scheduled in the morning (7:30), at noon (12:00) and in the evening (18:30), respectively. The source strength was determined from experimental data gathered during laboratory measurements. Preliminary results were reported in (Rojas, Delp, and Singer 2018).

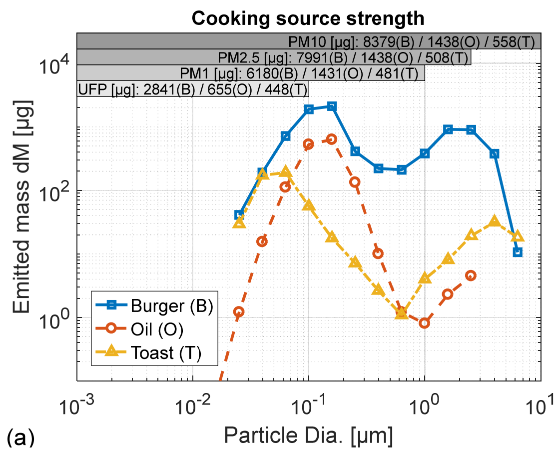

Figure 5: Cooking source strength extracted from experimental data from measurements in a test chamber. From: (Rojas 2019)

Further details on the PM modelling are documented in (Rojas 2019).

Formaldehyde

The formaldehyde emissions from the floor material within each zone were modelled based on the approach developed in (De Jonge 2018). Therein, the emission rate $E(t)$ is modelled as a function of time t, material thickness δ (emitting floor layer in our case), diffusion coefficient D_m and initially emitable concentration C_0 as proposed in (Xiong et al. 2013).

$$E(t) = 2.1\,\frac{D_m C_0}{\delta}\,e^{\left(-2.36\,\frac{D_m t}{\delta^2}\right)} \qquad (12)$$

D_m and C_0 are expressed as functions of temperature T and absolute humidity x as derived empirically in (Deng, Yang, and Zhang 2009; Liang, Lv, and Yang 2016). See Equation 2 and 3:

$$D_m(T) = d_1\,T^{1.25} e^{\left(-\frac{d_2}{T}\right)} \qquad (2)$$

$$C_0(T,x) = (1 + C_1 x)\,C_2\,T^{-0.5} e^{\left(-\frac{C_3}{T}\right)} \qquad (3)$$

The temperature evolution of the upper floor layer calculated in the previous BES-run (see Co-simulation below) and the calculated zone humidity were used as input for this formaldehyde source model. The chosen parameters $d_1=7.14\ 10^{-17}$, $d_2=284$, $C_1=0.19$, $C_2=1\ 10^{17}$, $C_3=6640$ result in emissions representing a 12 mm thick medium density fiber (MDF) board. The initial emission rate (at 20°C and 6 g/kg absolute humidity) of this source model was calibrated to 12 µg/(m$^2_{FA}$h), the median floor area specific formaldehyde emission rate obtained in a monitoring study in 10 almost new low-energy houses in France (Guyot et al. 2015).

Co-simulation

The co-simulation was organized very simplistically in a so-called "ping-pong" method, i.e. the two tools calculated alternatingly the full simulation period. A Matlab script was developed to automize and monitor the simulation and convergence progress. The simulation and assessment period was limited to a winter period of two months (January and February) to speed up computation. This period can be considered the most critical time in terms of IAQ, which is the main focus of this simulation study. Each BES simulation run included a one month long pre-calculation period to ensure that initial conditions have no impact on the assessment period. The alternating simulation cycle was started with a CONTAM simulation. Its post-processed results for interzonal airflows were provided in form of an input file for the subsequent DynBil simulations. The results of this

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BES simulation, were post-processed to provide an input file for next CONTAM simulation. Specifically, for each zone, the air node temperature and the temperature of the top layer of the discretized floor construction was provided as input for the entire simulation period. After a minimum fo five cycles the root-mean-square of the residuals of zone temperatures and interzonal flows results were below 0.01 K and 7% of the flow value which was considered sufficiently accurate. At that point the concetration results from CONTAM were used to evaluate IAQ.

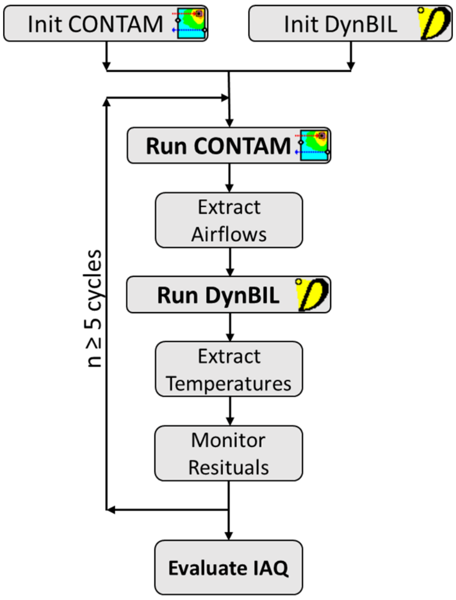

Figure 6: Simulation scheme for the presented "ping-pong" co-simulation

Indoor Air Quality (IAQ) Assessment

The resulting IAQ was assessed according to the methodology developed within Subtask 1 of IEA project EBC Annex 68 (Abadie and Wargocki 2017). This assesment method is implemented in a spreadsheet based calculation tool (with VBA macros) which will be freely available under https://www.iea-ebc-annex68.org/.

Therein, three IAQ indices are proposed. The IAQ-STEL (short-term expousre limit) index evaluates the risk associated with short-term exposure. It quantifies the frequency of exceedance of the exposure limit value (ELV) for short term exposure of the respective pollutant. The other two indices evaluate the risk associated with long-term exposure. The IAQ-LTEL (long-term exposure limit) index is calculated as the ratio of the average pollutant exposure over the ELV for long-term exposure. The IAQ-DALY index evaluates the long term expose using disability adjusted life years (DALYs) (Logue et al. 2012).

Within this paper, the long-term exposure to formaldehyde and $PM_{2.5}$ is evaluated using the IAQ-LTEL and IAQ-DALY index. Furthermore it compares the ventilation concepts by quantifying the IAQ-STEL index for CO_2. Note, that CO_2 concentrations around the ELV is solely used as a proxy for IAQ.

Table 1:
Long-term and short-term exposure limit values (ELV) for selected pollutants from IEA EBC Annex 68 (Abadie and Wargocki 2017)

POLLUTANT	LONG-TERM ELV	SHORT-TERM ELV
Formaldehyde	9 µg/m³	123 µg/m³
PM2.5	10 µg/m³	25 µg/m³
CO_2	-	1000/1250 ppm

SIMULATION RESULTS

Figure 7 quantifies the formaldehyde exposure applying the IAQ-LTEL and the IAQ-DALY index. The first compares the simulated average formaldhyde exposure to the recommended long-term exposure limit value (ELV) while the latter quanitifies the disability-adjusted life years. Note that guideline values for formaldehyde differ substantially throughout the world and that only a few countries define a long-term exposure guideline or exposure limit value (Abadie and Wargocki 2017). Short-time guideline values range from e.g. 100 µg/m³ (30 minutes average; Austria) to 9 µg/m³ (8 hour average; California). The herein used long-term ELV is based on the strictest available value applicable in California.

One can see that in the bedroom all four ventilation concepts can keep the average concentrations during occupancy (night-time) around or below the ELV of 9 µg/m³ with the active overflow concept having the highest value. In contrast, it has the lowest LTEL index in the living room. Here, the extended cascade ventilation concept shows the highst exposure value. This is due to the fact that the living room is ventilated via overflowing air from the bedrooms only, resulting in the lowest total air exchange rate of all four concepts for this ventilation concept. A very similar ranking between the different ventilation concpets can also be observed when looking at the DALY index (Fig. 7 b).

Figure 8 applies IAQ-LTEL and IAQ-DALY index to assess $PM_{2.5}$ exposure. It shows the benefit of ventilation conepts with ambient air filtration. As the extract air system draws unfiltered air through the openings ("trickle-vents"), the exposure to $PM_{2.5}$ from outdoor sources is notably higher, in this simulation case. Note that ambient particulate matter concentration was modelled constant with a $PM_{2.5}$ concentration of around 40 µg/m³, representing a medium polluted city on an international scale and not

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necessarily the air pollution in Vienna. The measured yearly avarage in Austrian cities has been slowly declining from 15-20 $\mu g/m^3$ to 10-15 $\mu g/m^3$ over the last decade (Buxbaum and Nagl 2018).

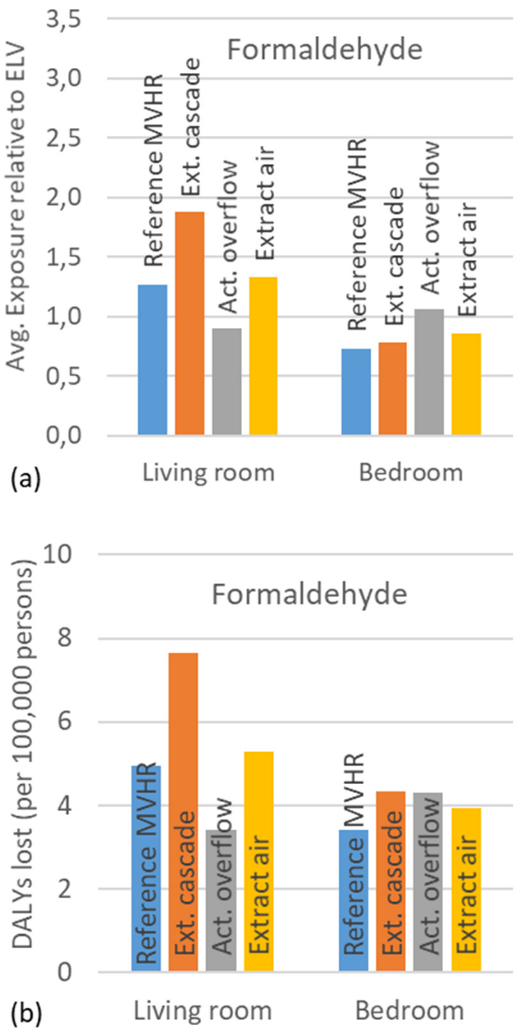

Figure 7: Simulated formaldehyde exposure in living room and bedroom evaluated with (a) the long-term exposure limit index (IAQ-LTEL) and (b) the DALY index (IAQ-DALY). See text for details.

Again, the ranking between the ventilation concepts is independent of the applied assessment index. When comparing the health impact of formadehyde and $PM_{2.5}$ one can see that, for the simulated conditions, the exposure to $PM_{2.5}$ should be considered more relevant, in particular when looking at the values of the DALY index (see Fig. 7b and 8b).

The assessment in terms of short term exposure, i.e. counting the exceedance of the short-term exposure limit value by applying the IAQ-STEL method, shows that all four ventilation concepts perform well. No exceedance is recorded for any of the investigated pollutants (formaldehyde, $PM_{2.5}$, PM_{10} and CO_2). When applying a stricter ELV value for CO_2 as proposed in (Cony Renaud Salis et al. 2017), i.e. 1000 ppm vs 1250 ppm, the extract air concept results in an exceedance in 33% of the occupancy hours in the bedroom vs. 0% for the other three ventilation concepts. The simulation shows no exceedance in the living room. This merely reflects the fact that the extract air ventilation concept is somewhat less effective in supplying the air into the bedroom, as a substantial portion of the overall air supply happens through (uncontrolled) envelope leakages. As a consequence, simulated bedroom CO_2 concentrations regularly peak around 1100 ppm in the bedroom. This only slightly higher than for the other concepts.

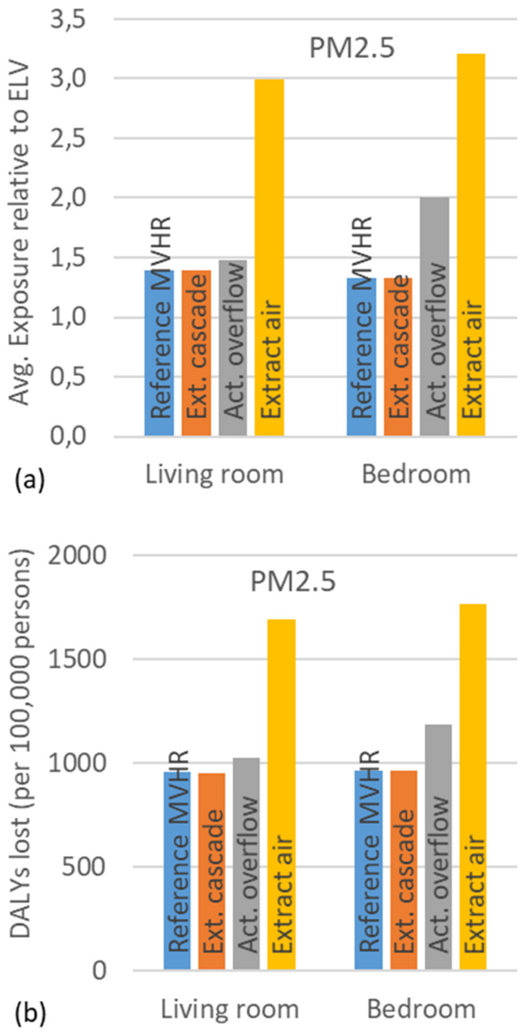

Figure 8: Simulated particulate matter ($PM_{2.5}$) exposure in living room and bedroom evaluated with (a) the long-term exposure limit index (IAQ-LTEL) and (b) the DALY index (IAQ-DALY). See text for details.

CONCLUSION

The results show that the investigated ventilation concepts perform well compared to the reference MVHR or an extract air ventilation (EAV) system.

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They outperform the extract air system for $PM_{2.5}$ exposure due to the use of ambient air filters (Figure 8). An exception is the formaldehyde exposure in the living room. Here, slightly higher formaldehyde concentration can be expected with the extended cascade principle, due to the reduced total air exchange rate. However, the exposure to bioeffluents does not notably increase for this "supply air effective" ventilation concept as the short-term exposure evaluation of the CO_2 concentration remains at 0% compared to 33% for the extract air ventilation (when applying the stricter 1000 ppm threshold). The active overflow concept is less effective in terms of ventilation efficiency compared to a cascading ventilation, as it mixes the air between all rooms (except extract air rooms). The total air exchange has to be set higher than for the other systems, potentially leading to a lower indoor air humidity in winter.

The presented work made use of a simple co-simulation method to study the performance of different ventilation concepts, including two innovative concepts aiming at reducing ductwork. The focus of this paper was the assessment of IAQ, particulary for formaldehyde, particulate matter and CO_2. The indoor sources were modelled in detail, including temperature- and humidity-dependent formaldehyde sources and size-dependent particle sources and sinks. The results confirm previous studies identifing these ventilation concepts as promising solutions for cost and space effective implementation of MVHR systems. The applied methodology was developed to a great extend within the IEA EBC Annex 68.

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