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Design of residential ventilation systems using performance-based evaluation of Indoor Air Quality: application to a Danish study case

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Abstract

A Demand-controlled ventilation (DCV) has been recognized as a promising solution for decreasing energy consumption while ensuring good Indoor Air Quality (IAQ) in buildings. However, its application in the residential sector has increased first recently. Implementation of DCV systems brings the problem related to assessing their performance, not only in the view of energy savings but also in the ability to ensure IAQ. The objectives of this paper were to introduce a multicriteria performance-based approach for the evaluation of residential ventilation systems with CONTAM airflows simulations; illustrate its applicability to three DCV strategies in the context of renovated apartment buildings in Denmark and challenge the minimal background airflow requirements anchored in the Danish building code.

Our performance-based approach allows assessing ventilation performance regarding IAQ (CO_2, humidity, $PM_{2.5}$, and formaldehyde-based indicators), energy consumption, and ventilation heat loss.

Our results show that DCV strategies can improve IAQ while decreasing airflows. For example, application of DCV reduced the cumulative indicator of occupant exposure to formaldehyde, I_{HCHO} by 6 to 28 %, compared to the constant-airflow system. For humidity controlled mechanical exhaust ventilation, the heat loss can be reduced up 51%.

Introduction

The current pandemic has been highlighting the crucial role of ventilation. At the same time, ventilation impacts building energy consumption through ventilation heat loss and the electricity consumption of fan(s) and other components. Smart ventilation, especially demand-controlled ventilation (DCV) with variable airflows strategies, has been recognized as a promising solution for decreasing energy consumption while ensuring good Indoor Air Quality (IAQ) (Durier, Carrié, and Sherman 2018; G. Guyot, Sherman, and Walker 2018). In a Danish context, a study by Nielsen and Drivholm (2010) showed that 37% reduction of time at low airflow rates can lead to theoretical 35 % fan energy saving thanks to DCV based on CO_2 and humidity at the air handling unit level, without compromising the indoor air quality (IAQ). Designing such smart ventilation strategies requires an optimisation task calling for a dynamic simulation to achieve the best IAQ with minimum energy demand, i.e. ventilate more where and when the needs are high and ventilate less where and when the needs are low.

Even though the smart ventilation seems to represent obvious future solution, currently, there are still challenges to overcome. The two most important are:

1. Building regulations do not always allow decreasing airflows below certain minimum thresholds, for example a minimum background ventilation rate 0.3 $l/s.m^{-2}$ in the Danish building code (Zukowska et al. 2020);
2. The requirements are prescriptive, based on constant airflows or constant air change rates, while for strategies with varying airflows a performance-based approach expressing the consequence of the control strategy expressed as suitable IAQ indicators is needed to exploite their potential.

Some countries worldwide have introduced such performance-based approaches. Their limitation is that the used IAQ indicators are considering only CO_2 and humidity (G. Guyot, Walker, and Sherman 2018; G. Guyot et al. 2019). In this context, we defined the three main objectives of this paper:

- To demonstrate the potential of smart ventilation strategies for improving IAQ and energy savings;
- To introduce a performance-based approach using CONTAM airflow simulation to calculate a set of relevant IAQ and energy performance indicators and to illustrate their applicability in a case study, a typical Danish apartment building after renovation.
- To demonstrate how minimum airflow requirements can be challenged by applying a simulation with reduced minimum airflows.

Methods

Building renovation project usually represents a good opportunity to install or change the ventilation system to avoid building damages, save energy, and improve the provided IAQ. With a performance-based method, it is possible to compare the performances regarding provided

IAQ, ventilation heat loss and energy consumption of several ventilation strategies.

We decided to investigate five residential ventilation strategies:

1. mechanical exhaust-only ventilation with constant air volume (**MEV-cav**)
2. mechanical exhaust-only ventilation and humidity control **(MEV-rh)**
3. mechanical balanced ventilation with heat recovery and constant air volume (**MVHR-cav**)
4. mechanical balanced ventilation with heat recovery and humidity control at the apartment level (**MVHR-rh**)
5. mechanical balanced ventilation with heat recovery and CO_2 & humidity control at the room level (**MVHR-rb**).

These strategies will allow for a performance comparison between currently prevailing residential ventilation with constant airflows (reference) and smarter ventilation strategies with variables airflows.

Our performance-based approach allows to quantify the theoretical advantages and disadvantages for the compared ventilation strategies: provided IAQ (based on the calculation of CO_2, humidity, $PM_{2.5}$ and formaldehyde-based indicators), energy consumption of ventilation system, ventilation heat loss. We used CONTAM multi-zone building simulation to calculate selected performance indicators. Simulations considered scenarios for inputs data, including pollutants emission rates ($PM_{2.5}$ from cooking and formaldehyde from building) and occupant's emissions (CO_2 and water vapour).

We decided to demonstrate the potential of such a performance-based approach in a case study. We evaluated suitable airflows for the five mentioned ventilation strategies in two steps. The first step consisted of a performance evaluation of the strategies with the standards required airflows as a reference case (Danish Building Code (0.30 l/(s m^2) heated floor area). Then a second step included simulations with reduced minimum airflows for MEV-rh, MVHR-rh, MVHR-rb strategies in the range of [0; 0.3] l/(s m^2). We used the corresponding systems with constant airflows a reference system; i.e. MEV-cav was the reference for MEV-rh and MVHR-cav was the reference for MVHR-rh and MVHR-rb.

Performance indicators

We evaluated the IAQ performance of the tested ventilation strategies using the previously developed method (Poirier, Guyot, Woloszyn, et al. 2021), which proposes a set of five IAQ performance indicators based on four relevant parameters and corresponding acceptable threshold (AT), with *d* the total duration of the period simulated:

- **I_{CO2}:** Maximum cumulative CO_2 exposure exceeding the reference value ofover 1000 ppm in bedrooms ; AT = 1000.*d* (ppm.h)
- **I_{HCHO}:** Maximum occupant formaldehyde cumulative exposure ; AT = 9.*d* (µg.m^{-3}.h)
- **$I_{PM2.5}$:** Maximum occupant $PM_{2.5}$ cumulative exposure ; AT = 10.*d* (µg.m^{-3}.h)
- **I_{RH30_70}:** Maximum percentage of time spent by the occupants with RH outside a range: [30%–70%] (health risk); AT= 14.4%
- **I_{RH70}:** Maximum percentage of time with RH higher than a threshold of 70%) in all rooms (condensation risk); AT = 18% in bathroom, 10.8% in kitchen, 1.8% in other rooms

To complement the five indicators, we proposed two additional short term exposure indicators for $PM_{2.5}$ and formaldehyde:

- **$I_{PM2.5\_short}$:** the maximum occupant exposure on 24 hour average period according to (Cony Renaud Salis et al. 2017; HCSP 2013); AT = 25 µg.m^{-3}

- **$I_{HCHO\ short}$** : the maximum occupant exposure on one hour average period according to (Cony Renaud Salis et al. 2017; HCSP 2019; WHO 2010); AT = 100 µg.m-3

As the second step focused on reducing the minimum airflow, we proposed in equation (1) to complement those IAQ indicators with an energy indicator for ventilation systems based on the ventilation heat loss (Abadie et al. 2017):

$$Q_{load} = C_{p_m}.q_m.(1-\varepsilon_{heat_{ex}}).(T_{in}-T_{ex}) \quad (1)$$

With q_m the total exhaust mass airflows in *[kg.s^{-1}]*, *Cpm* the thermal mass capacity of air (we used 1 $kJ.kg^{-1}.°C^{-1}$), $\varepsilon_{heat_{ex}}$ the heat exchanger efficiency (we used 0 for MEV and 0.8 for MVHR as a conservative value), T_{in} the zone temperature where the air is extracted, and T_{ex} the external temperature *[°C]*. We assumed balanced airflows across the heat recovery. The capacity reduction due to frost formation was not considered.

Consequently, we performed the calculation of the fan power consumption according to ASHRAE Standard 90.1 (ANSI/ASHRAE/IES s. d.) :

$$P_{fan}(t) = P_{fan} . P_{nom} \quad (2)$$

$$P_{nom} = Qmax .SFP \quad (3)$$

$$P_{fan} = 0.0013 + 0.1470 . PLR_{fan} + 0.9506 . PLR_{fan}^2 - 0.0998. PLR_{fan}^3 \quad (4)$$

$$PLR_{fan} = Q(t) / Qmax, \quad (5)$$

With P_{nom} the nominal power of the fan, Qmax the maximal design aiflow, SFP the specific fan power (supposed equal to 0.935) and Q(t) the current total exhaust (or supply) airflow.

We assumed that the MEV systems used one fan while the MVHR systems used two equal fans for exhaust and supply.

Table 1: Occupancy schedules and pollutants emissions scenarios by room

Room	Occupant 1	Occupant 2	Occupant3	Bio-effluent	Moisture	HCHO	$PM_{2.5}$
Bedroom	21h00-6h20	21h00-6h20	21h00-6h20	By occupants in rooms based on occupancy schedules CO_2 awake / asleep: 18 / 15 L.h^{-1} H_2O awake / asleep: 55 / 40 g.h^{-1}		In each room 12µg.h^{-1}.m^2 (m^2 floor area)	
Bathroom	6h20-7h00	7h00-7h40	20h20-21h00				
Kitchen	7h00-7h20 12h00-12h40 19h00-20h10	6h20-6h40 12h00-12h40 19h00-20h10	6h20-6h40 12h00-12h40 19h00-20h10		Breakfast / lunch / dinner: 1512 / 2268 / 2844 g.h^{-1} During 15 / 30 / 40 minutes		Cooking event: 1.91 mg.min^{-1} During 28 minutes
Livingroom	7h20-8h30 12h40-14h00 20h10-21h00	6h40-7h00 7h40-8h30 12h40-14h00 20h10-21h00	6h40-8h30 12h40-14h00 20h10-20h20				

The MVHR-rb system represented so-called room-based ventilation (Smith and Kolarik 2019). In this system a main air handling unit delivered the airflow into a manifold equipped with three axial fans with continuous control of rotation speed. These fans provided airflow to particular rooms (a living room and bedrooms) based on the demand measured by IAQ sensors. We determinned the power of the fans as:

$$P_{sfan}(t) = (Q(t) / Q_{nom})^3 .P_{nom} \quad (6)$$

With Q_{nom} = 120 m^3.h^{-1} and P_{nom} = 18 W.

Finaly the proposed total energy consumption indicator $\mathbf{I_{EC}}$ [Wh] for ventilation system (equation 7) was an aggregation over the entire simulation period of the instant heat loss from exhausted airflows and the instant fan power.

$$\boldsymbol{I_{EC}} = \sum_{t=0}^{d} (Q_{load}(t) + P_{fan}(t)).\,\mathrm{dt} \quad (7)$$

To present and compare the performance of the strategies in a radar graph, we normalized each IAQ indicator using its AT (Table 3).

Input scenarios

We used detailed inputs scenarios for pollutant emissions and occupancy schedules, by Poirier, Guyot, Woloszyn, et al. (2021). These scenarios propose occupancy time spent in rooms for exposure calculation associated with bio-effluent emissions (CO_2 and moisture) from the occupants. Based on the occupancy time, we built daily schedules of rooms occupancy adapted for the three occupants (Table 1).

Moisture emission rates with the associated duration represented showering, cooking, and laundry. Then, we applied three scenarios a low, medium, and high level of emissions for the two remaining pollutants. We specified formaldehyde emission per m² of floor area as constant. We used data from in situ campaign, including ten recent French low-energy houses (Gaëlle Guyot et al. 2017; Poirier, Guyot, and Woloszyn 2020). Indeed there is a lack of exploitable data on variable formaldehyde emission rates from materials and furniture (Poirier, Guyot, Geoffroy, et al. 2021). For $PM_{2.5}$, we considered cooking activities producing most of the emissions. We used three scenarios corresponding to types of cooking ranging from the least emissive, such as boiled meals, to highly emissive dishes, such as grilled beef. We assumed a constant outdoor concentration of CO2 at 400 ppm; 2.6 µg.m^{-3} for formaldehyde based on average concentration in European cities (Bruinen de Bruin et al. 2008) and 10.6 µg.m^{-3} yearly average concentration for $PM_{2.5}$ in Copenhagen between 2015 and 2020 calculated from weather data measurement (« Annual AQ statistics » s. d.).

Study case presentation

The study case building for this application is a renovated apartment in a Danish building located in Copenhagen (Figure 1). The buildings of such type are very common in large Danish cities. They belong to a building type 1 (year of construction 1850-1890) according to Danish building typology (Danish Buidling Practice s. d.). According to Odgaard (Odgaard 2019), 25% of apartments in Danish residential building stock are situated in buildings constructed between 1850 and 1930. We investigated an apartment situated on the first floor. It had a ceiling height 2.6 m and heated floor area of 60.95 m2. It had two bedrooms, a living room and separate kitchen. We assumed three occupants, based on the configuration of the dwelling with two persons in the "parent bedroom" (bedroom 1) and one in the second bedroom (bedroom 2).

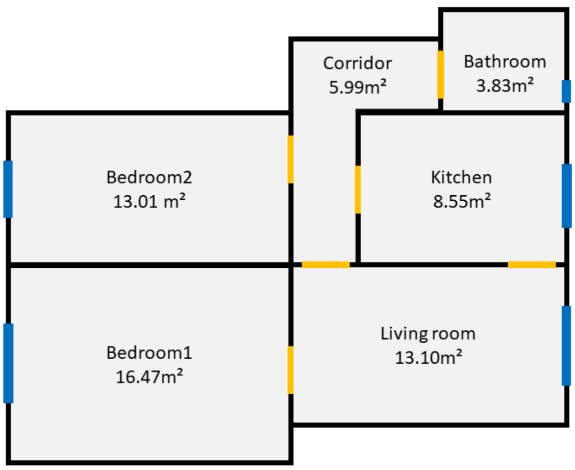

Figure 1 : Plan of the Danish study case apartment

Multi-zone model description

The proposed simulation work is based only on airflows simulation with CONTAM multi-zone model which is scientifically validated (Dols and Polidoro 2015; Walton and Emmerich 1994). In this model the airflows between the zones are determined by pressure difference calculation. The CONTAM model has been chosen in order to take into account detailed air leakage distributions, several pollutant simulation (CO_2, water vapour/moisture, $PM_{2.5}$, HCHO in the method, but other can be added) and the possibility of modelling very different ventilation strategies. We used the modelling results such as pollutant concentration levels in zones or occupant exposure to calculate the IAQ performance indicators. One limit of CONTAM is the absence of a thermal model, this means the temperature inside the zone is considered constant. However, in this performance approach for ventilation performance assessment, the simulation period is only during the heating period from October 15, 00:00 a.m to April 14, 12:00 p.m (Poirier, Guyot, Woloszyn, et al. 2021). The assumption of constant temperature in zones corresponds to a case where the heating demand is Ideally covered by the heating system.

We modelled the airflows between zones with a leak having an equivalent leakage area (ELA) at 4 Pa of 0.01 m².(Filis, Kolarik, and Smith 2021). We considered infiltration to be pressure driven and described in CONTAM by a power-law model (Dols and Polidoro 2015)

$$Q = C.(\Delta P)^n \quad (8)$$

With C the flow coefficient and n the characteristic exponent of the flow between 0.5 and 1 with here equal to 0.6 as the usual indicate flow exponent for typical infiltration (Dols and Polidoro 2015). We have determined the C = 0.012 $m^3.s^{-1}.Pa^n$ based on estimated airtightness of the building envelope of 2 L/s.m^2 (heated floor area) at 50 Pa distributed uniformly on the external surfaces (Smith and Kolarik 2019). We haven't applied any filtration coefficient to the air inlets in this study.

Ventilation strategies description

Mechanical ventilation systems used in the present paper represent a variability of solutions available on European market. Their use in practice is often determined by design traditions in particular countries, for example humidity-based exhaust only variable ventilation is widely used in France, while CO_2 based ventilation is used in Belgium. We selected ventilation systems and strategies based on available technical documentation and/or previous research projects (Poirier, Guyot, and Woloszyn 2020; Smith and Kolarik 2019):

Mechanical exhaust-only ventilation with constant air volume (MEV-cav): a mechanical ventilation system composed of air exhaust in the bathroom and kitchen with a one-hour boost during cooking events in the kitchen. This system does not directly conform with current Danish building regulations but can be eventually applied in project where installation of balanced ventilation with heat recovery is not possible due to lack of space or rentability issues.

Balanced mechanical ventilation with heat recovery with constant air volume (MVHR-cav): a system with the air exhaust in the kitchen and bathroom and air supply in bedrooms and living room. We assumed 60% of the total exhaust airflow through the kitchen (with additional 1-hour boosts during cooking events) and the remaining 40% of the exhaust airflow through the bathroom. Supply airflows were distributed proportionally to the floor area in the bedrooms and the living room.

Mechanical humidity-controlled exhaust-only ventilation (MEV-rh): a demand-controlled system with relative humidity (RH) as a controlled variable. The system adjusts the airflows according to the RH measurement, through the extensions and retractions of a hygroscopic fabric modifying the cross-section of inlets and outlets (Jardinier et al. 2018). We considered the air inlet in the bedrooms providing airflow rates between 4 $m^3.h^{-1}$ and 31 $m^3.h^{-1}$ (reference pressure of 10 Pa). The kitchen exhaust provided minimum airflow for RH < 23% and maximum airflow (55 m^3/h) for RH > 55%, with a one-hour boost of 135 m^3/h during cooking event. The bathroom exhaust provided minimum airflow for RH < 45% and maximum airflow (45 m^3/h) for RH > 85% (Aldes 2018).

Balanced, humidity controlled mechanical ventilation with heat recovery (MVHR-rh): a ventilation system with RH sensor integrated in the exhaust duct of the air handling unit. The system represents a commercially available system frequently installed in renovated apartments. The control is based on a combination of 24-hour running mean RH and the immediate rate of RH change (Nilan, s. d.). According to the control logic, the system works with three levels of airflow/ fan rotation speed (low, nominal, and high) see Figure 2. In the modelling we assumed that the high airflow is triggered for one hour during cooking event as same as the ventilation boost in the other studied systems.

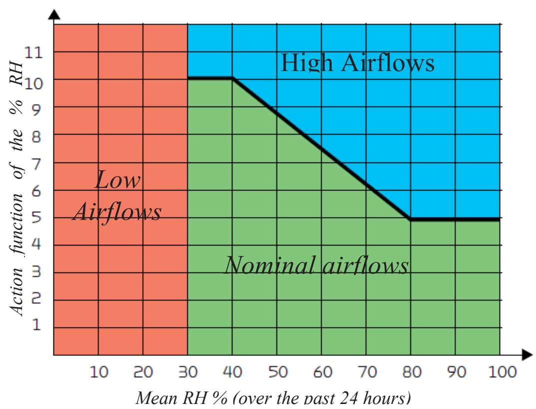

Figure 2 : MVHR-rh ventilation airflows modes diagram function of RH% levels (modified from (Nilan, s. d.))

Table 2: Reference exhaust airflows for simulated systems

	MEV/MVHR-cav		MEV-rh			MVHR-rh			MVHR-rb	
Airflows [m3/h]	*Nominal*	*Max Qboost*	*Lower limit*	*Upper limit*	*Max Qboost*	*Lower limit*	*Nominal*	*Upper limit*	*Lower limit*	*Upper limit*
Kitchen	39.5	108	49.4	55.0	108	39.5	73.7	108	39.5	108
Bathroom	26.3	26.3	16.5	45.0	45	26.3	49.20	72	26.3	72
Total	65.8	134.3	65.8	100.0	153	65.8	122.9	180	65.8	180
Total [l/s.m²]	0.3	0.61	0.3	0.46	0.69	0.3	0.56	0.82	0.3	0.82

Balanced mechanical ventilation with heat recovery with room-based control (MVHR-rb): an innovative ventilation system with ability for a separate control of airflow into each room. The room demand is specified by the IAQ sensor placed in the room. The modelled system considered measurements of RH and CO_2. A controller determined the airflow needs based on C_{co2} for bedrooms and the living room. For kitchen, the airflow was determined using C_{co2} and RH. The following setpoints were used:

- for lower limit $C_{co2} < 800$ ppm (RH < 57% at 21°C) the airflow demand was low
- for upper limit $C_{co2} > 900$ ppm (RH > 77% at 21°C) the airflow demand was high,
- the demand was proportional between lower and upper limit

When the humidity ratio between outdoor is $0.003 kg_{H2O}/kg_{Air}$ higher than the indoor level, the demand stays low, to avoid additional moisture load from the outdoor air. (Smith and Kolarik 2019). As same as the other systems we assume a one-hour boost during cooking events in the kitchen

Results and discussion

To present and analyse the performances of the reference phase and optimisation phase we will focus only on the results of medium scenario for pollutants emissions rates.

Reference phase

The Figure 3 presents the IAQ indicators determined for the studied ventilation systems. Firstly, the MVHR provide better IAQ when considering the CO_2 and HCHO. At the same time, none of the studied systems achieved good IAQ with respect to the exposure to $PM_{2.5}$. Regarding the In_{RH70} indicator (exposure to the relative humidity over 70%), all studied systems yielded acceptable performance. The systems with variable airflows strategies outperformed the ones with the constant volume. On the opposite, no systems succeeded to keep acceptable humidity levels in the range [30%-70%], with however an advantage for the MEV (I_{rh30_70} in range [1.29;1.36]) on the MVHR (I_{rh30_70} in range [1.87;2.19]).

The absence of heat recovery in MEV systems led, as expected, to significantly higher (2 to 4.6 times) energy consumption in comparison to the MVHR systems. The reference ventilation systems with constant airflows had lower energy consumption efficient than systems with variable MEV-cav used 8.5% less compared to MEV-rh. MVHR-cav used up to 51% less than MVHR-rh. The reason for this is the possibility to increase the airflow over the level of constant airflows strategies when needed. But in return for higher energy consumption, system with variable airflows is improved IAQ regarding CO2, RH >70% and HCHO.

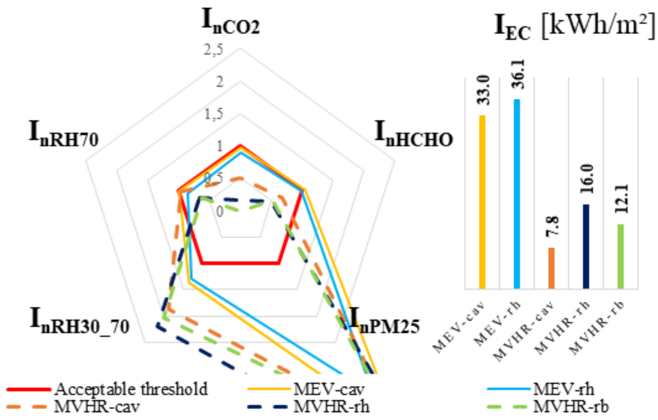

Figure 3: Performance results for the reference phase

Finally, the MEV-rh had a small advantage over the MEV-cav for all the IAQ indicators (from 6 to 16% low) but redeemed by higher energy consumption. The MVHR-rh and MVHR-rb provided a clear IAQ benefit. The MVHR-rb had even no risk regarding exposure to CO_2. But the energy consumption is also lower with these variable strategies compared to the MEV-cav.

Reduced minimum airflows application

The Figure 4 visualizes the relation between IAQ indicators and energy performance for investigated ventilation strategies. To complete the IAQ indicator results we also show the minimum airflows in relation to the total energy consumption. This is to highlight the relation between minimal control airflow and energy consumption.

As a general results, none of the tested ventilation strategies provided acceptable IAQ with respect to all indicators used. Especially for the $PM_{2.5}$ indicator, the results regarding short-term$PM_{2.5}$ are exceeded the acceptable threshold (1.69 up to 4.18), this was even more pronounced for long term exposure (3.43 up to 5.05). On the contrary the short-term indicator was close to 0 for formaldehyde. This means that the formaldehyde source used in the study was not posing any short-term exposure risk.

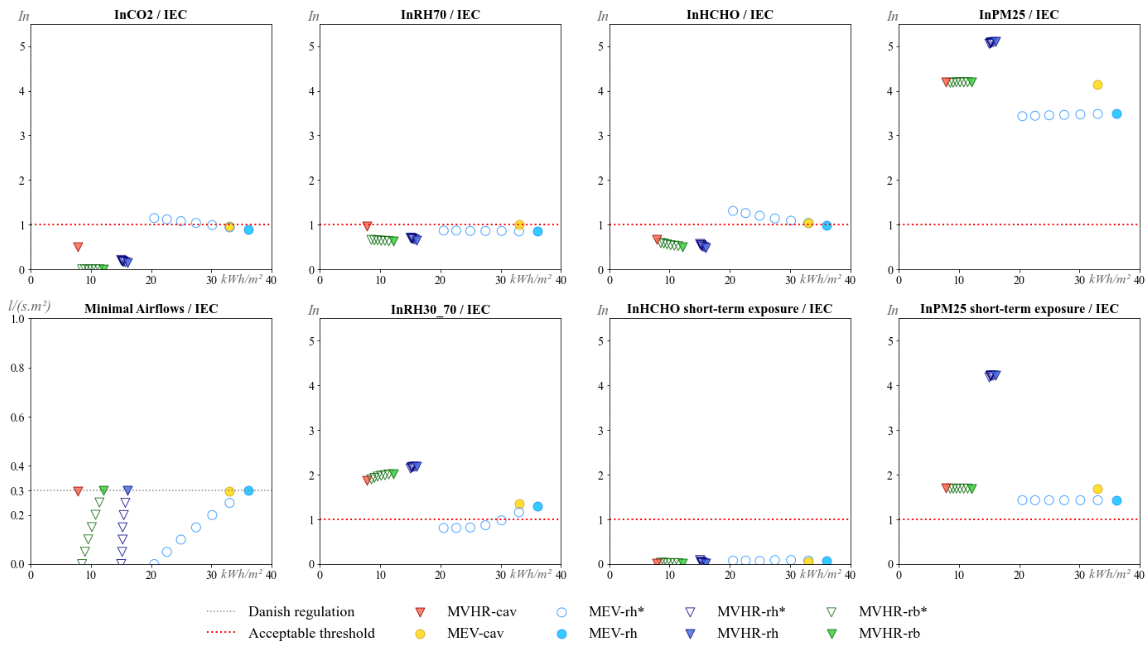

*Figure 4: Performance results of the optimisation phase by indicator; *results with min exhaust airflows from 0 to 0.3 l/s.m^{-2}*

As result for the next analysis in this paper we propose to focus mainly on the I_{CO2}; I_{RH70}; I_{RH30_70}; I_{HCHO} which are more related to energy consumption than I_{PM25}, I_{PM25_short}, I_{HCHO_short}.

Regarding CO_2 exposure risk, majority of the systems provided the acceptable level. The MVHR-rb, showed the best performance with I_{CO2} = 0 for all the tested minimal airflows, indeed this system was the only one with a control strategy based on CO_2 and moreover the control set point was 900 ppm that is lower than the acceptable threshold of I_{CO2} (1000 ppm). For the two constant volume ventilation systems and the MEV-rh, lower minimal airflows could increase the CO_2 exposure and in some configurations lead to exposure over the acceptable threshold. This could play a role in the optimisation focused on trade-off between energy saving and increasing CO_2 level.

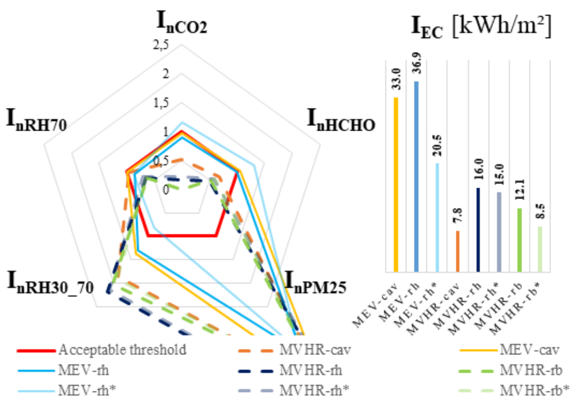

*Figure 5: Performance comparison between 0.3 l/s.m^{-2} reference exhaust airflows and 0 l/s.m^{-2} as lower airflows**

Almost the same conclusion can be done with the high humidity risk indicator I_{RH70}, all the systems provide acceptable performance. Concerning the performances for humidity levels between 30-70%, MVHR systems were exceeding the AT (between 1.9 and 2.19). Only the MEV-rh succeed to reach acceptable level on I_{RH30_70} even with lower energy consumption thanks to the reduction of the minimal airflows.

Finaly the Figure 5, highlight that variable ventilation strategies with a minimal exhaust airflows equal to 0 l/s.m^{-2} can succefully provide IAQ performance equivalent to that obtained with 0.3 l/s.m^{-2} but with lower energy consumption

General discussion

In addition to assessing the IAQ and energy performance of the ventilation strategies tested, these results raised some points that could be discussed.

In this configuration, the results of the I_{RH30_70} exceeding the acceptable thresholds, while the performance of the I_{RH70} was achieved by all systems, showed dry air issue in the apartment. In general, with MVHR systems RH is low in modern houses, the heat recovery dries the outdoor air, especially at low outdoor temperatures and there is not enough humidity production to increase the RH. One solution could be heat recovery that recovers also moisture such as rotating heat exchanges which help to elevated the minimum relative humidity in rooms (Smith and Svendsen 2016).

Regarding energy use, the lower minimal airflows improved the energy consumption of the MVHR-rb and which is now comparable to that of the MVHR-cav.

*Table 3: Normalised indicators performance results ; **Total minimum exhaust airflows l/s.m^{-2}*

	InCO2	**InHCHO**	**InPM25**	**InHCHOs**	**InPM25s**	**InRH30_70**	**InRH70**	**IEC** [kWh]	**Airflow****
MEV-cav	0.97	1.05	4.14	0.06	1.69	1.36	1	2012	0.3
MEV_rh	0.89	0.99	3.49	0.08	1.43	1.29	0.85	2199	0.3
MEV_rh*	1.15	1.31	3.43	0.08	1.43	0.81	0.87	1251	0
MVHR-cav	0,51	0.68	4.19	0.02	1.7	1.87	0.97	478	0.3
MVHR-rh	0.16	0.49	5.1	0.02	4.22	2.19	0.66	976	0.3
MVHR-rh*	0.21	0.57	5.05	0.09	4.18	2.14	0.71	917	0
MVHR-rb	0	0.51	4.2	0.02	1.69	2.03	0.63	740	0.3
MVHR-rb*	0	0.59	4.18	0.03	1.69	1.9	0.66	521	0

In addition to this comparable energy consumption, the MVHR-rb provides better IAQ performance on CO_2, HCHO and high humidity risk than the reference MVHR-cav. Lower airflows also present a significant benefit for MEV-rh with up to 51% energy saving compared to the MEV-cav, but this saving need to be balanced with a small degradation of the IAQ.

We also paid attention to the results obtained with the I_{PM25}, which are well above the acceptable threshold, and which seem to be independent of ventilation strategies. This questions the emission scenarios used, but even with a low $PM_{2.5}$ emission scenario, the exposure reached over the AT as also pointed out in the description of the proposed performance approach (Poirier, Guyot, Woloszyn, et al. 2021). The hight PM_{25} levels could also be explained by the apartment configuration due to the closed kitchen as it is a small volume so the concentration will increase, may be in future experiment a comparison with open kitchen can confirm this assumption.

Moreover, we simulated the exhaust airflow boost provided by the cooking hood, but the placement of the hood was not defined, thus the $PM_{2.5}$ entered the whole zone, which would not be the case in reality. A more precise modelling for the cooking hood weld be needed to obtain more realistic $PM_{2.5}$ values on a zone level.

Conclusion

The results demonstrate the potential of smart ventilation strategies for improving IAQ, while maintaining, in case of MVHR-rb, or even improving energy performance in case of MEV-rh.

With variable airflow strategies of the smart ventilation systems (MEV-rh, MVHR-rh and MVHR-rb) it is possible and relevant to use lower exhaust airflows than the 0.3 l/s.m^{-2} required. Indeed, the provided IAQ with lower airflows down to 0 l/s.m^{-2} were comparable to the reference cases (MEV-cav and MVHR-cav) and even better depending of the strategy used.

Finally, the performance-based approach brings the possibility to directly evaluate consequences of reducing/variating airflows. On an example of the Danish case, we demonstrate that decreasing the ventilation rate does not necessarily mean compromising the IAQ. Thus, the code requirements asking for fixed minimum ventilation rates seems to be unnecessary when smart ventilation strategies are applied.

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