Recommendable supply air rates for residential housing – A simulation study considering CO_2 concentration, relative humidity, TVOC emissions and mould risk

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ABSTRACT

In an extensive simulation study using a multi-zone airflow and contaminant transport calculation software (CONTAM) recommendations for the supply air rates for residential housing were derived as input for the revision of the Austrian standard ÖNORM H 6038 (2014). The floor plan, the occupancy and the contaminant and humidity sources are modelled to represent a typical Austrian housing situation. A humidity buffering model is also implemented. Based on common thresholds for CO_2, relative humidity (r.h.) and TVOC the so-called relative threshold deviation is determined. It is used as a combined parameter to evaluate indoor air quality in terms bio-effluents, air humidity and pollutants arising from building and interior products. Additionally the potential mould risk due to high air humidity and low surface temperatures is calculated using the isopleth model.

The results suggest a supply air flow into the bedroom of 20 m³/h per person for the chosen reference climate. It represents the best compromise between exceeding the target value of CO_2 and avoiding overly dry periods during winter. If low emitting building products are used, TVOC concentrations seem not to play an important role for the definition of the supply air rates. If the floor plan permits, the implementation of the so-called extended cascade ventilation principle is recommendable. It allows a reduction of the relative threshold deviation with an air exchange rate as low as 0.3 h^{-1}. Prerequisite for the implementation of such low air exchange rates is a high thermal quality of the building envelope. It ensures surface temperatures that exclude potential spore germination. The same applies for the use of ventilation systems with humidity recovery. For typical recovery rates of 60%, an air exchange rate as high as 1.0 h^{-1} might be required for the same reference apartment to avoid mould problems, in case the building envelope has a temperature coefficient (f_{Rsi} value) of 0.5 as frequently observed in existing buildings (thermal bridge). For residential housing, humidity recovery should therefore be limited to locations with very cold and dry winters as observed in mountain regions.

KEYWORDS

Mechanical ventilation, ventilation rates, supply air, CONTAM, simulation

1 INTRODUCTION

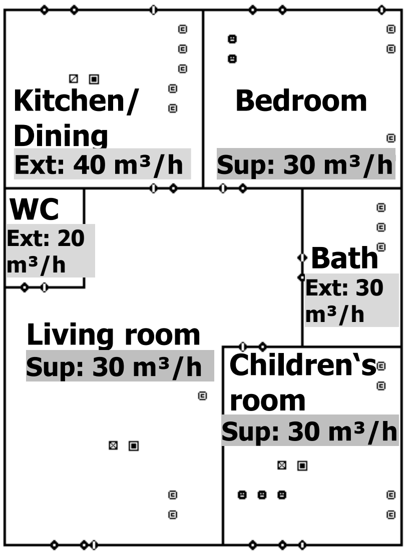
There are several aspects to consider when defining the supply air flow in residential housing. Especially in regions with cold and dry periods contradictory requirements can arise. On one hand bio-effluents from human activities as well as pollutants emitted from building products etc. have to be diluted. On the other hand excessive air exchange rates can decrease the air humidity below recommended limits. This work presents the methodology used for deriving recommendable supply air rates as used as an input for the revision of the Austrian standard for residential ventilation ÖNORM H 6038 (2014).

2 METHOD

This simulation study was performed with the multi-zone airflow and contaminant transport simulation software "CONTAM" (Walton and Dols 2010). MATLAB scripts were used for automated parameter variations (e.g. the volume flow) and for the evaluation of the simulation results.

2.1 Simulation model

A typical Austrian residential living situation was defined based on statistical data (Janik and Vollmann 2001). The floor plan has a living area of 76 m^2 and is shown in Figure 1 (left). The occupation was modelled with three persons (two adults, one of them working, and one child), the occupation hours and some of the chosen user behaviour are summarized in Figure 1 (right). The indoor air temperatures affect the air exchange between rooms (with open doors). They were modelled constant and they represent the average measured indoor temperature of various Passive House measurement projects. A reference climate dataset for Vienna was used.



	Occupation Schedule[a] [h]			Settings	
	Adult 1 WD/WE	Adult 2 WD/WE	Child WD/WE	Doors	Temp. [°C]
Kitchen	1.75/2	3/3	1.25/1.75	Always open	22[b]
Bed-room	8/9	10/10	--	Day: open Night: closd	21.4[b]
Living room	2.25/6	5/5	3/6.25	n.a.	22[b]
Child. room	--		9.5/10	Day: open Night: closd	21.4[b]
Bath-room	1/1	1/1	0.75/0.75	10 min per use	23
Total	13/18	19/19	14.5/18.75	--	--

Figure 1: CONTAM sketch of the floor plan (Ext=Extract Air, Sup=Supply Air), Occupation schedule and user behaviour in terms of temperature and door position (WD=weekday, WE=weekend).
[a] **based on stat. Data** (Ghassemi-Bönisch and Kronsteiner-Mann 2011), [b] **based on various PH measurement studies** (Rojas, Wagner, et al. 2015; Schnieders and Hermelink 2006)

The human carbon dioxide (CO_2) emission rates were taken from the IEA ECBCS Annex 27 Report (Månsson (Ed.) 2002), being 18 l/h per adult and 12 l/h per child when awake and 2/3 of that when sleeping. The humidity production rate is also literature based (Hartmann et al. 2001; Månsson (Ed.) 2002) and is summarized in Table 1. To depict the humidity buffer potential of the walls a “two layer buffer model” was developed and implemented in CONTAM. The required parameters were calibrated with the results of dynamical hygro-thermal simulations using “Delphin” (Grunewald 2015) of a 20 cm thick concrete wall.

An additional contaminant source was added in living room, bedroom, children’s room and kitchen. They represent the emissions that are independent of the occupant-presence, i.e. from building products, furniture, etc. and will be referred as TVOC source. For the reference model, the floor area (FA) specific average source strength was roughly estimated to be 500 µg/m^{2}h. The sources were modelled as constant sources representing long-term emissions. This value was based on older field studies (Mølhave, Sparks, and Wolkoff 1996; Norbäck et al. 1995; Schulz et al. 2010) with limited information regarding the boundary conditions (air exchange rates and floor area per occupant were assumed).
Note that in light of more recent measurement projects (Rojas, Wagner, et al. 2015; Tappler et al. 2014) this value seems rather high. These studies indicate that low emitting building products (as required by the Construction Products Regulation EU 305/2011) are being used

for the construction of energy efficient housing in Austria. According to the author of the mentioned study (Tappler et al. 2014), where the VOC concentrations were measured roughly after one year of occupation, a long term emission rate of 115 µg/m^2_{FA}h would be a better representative value for occupied new homes. Simulations were also performed using this source strength.

Table 1: Humidity sources

Sources	Magnitude [g/d]	Type	Model parameters
Occupants	1900 [a]	Const.	Adult/Child wake(sleep): 55/45 (30/15) g/h
Cooking	800 [a]	Const.	Morning/Noon/Evening: 110/320/320 g/h [b]
Pers. hygiene	800 [a]	G_0*exp(-kt)	G_0=325 g/h; k=0.12h^{-1}; 2x /(day pers.)
Plants, etc	670 [a]	Const.	0.365 g/(h m^2_{FA})
Laundry	1150 [a]	G_0*exp(-kt)	G_0=68 g/h; k=0.5h^{-1}; 1x/(week pers)

[a] based on (Hartmann et al. 2001), [b] daily distribution according to (Månsson (Editor), 2002).

In- and exfiltration through the building envelope was modelled in all rooms with external walls (living room, bedroom, children's room and kitchen) with two "leakage-openings" per room (stack effect) resulting in an exfiltration of 0,6 h^{-1} at 50 Pa over-pressure (n_{50}-value).

2.2 Evaluation method

The simulation results for the various evaluation parameters (CO_2, r.h., TVOC) are plotted room by room for the evaluation period (1. Dec – 1. Mar) and only for hours with occupancy. The resulting area ("C" in Figure 2) between threshold and cumulative distribution function is a measure for the duration and magnitude of the respective threshold deviation. It is equivalent to an area resulting from an (hypothetical) constant value "A" above the threshold (e.g. 162 ppm in Figure 2). For the parameter CO_2 it means, that having a concentration of 700 ppm during the entire evaluation period would be rated equally to having a concentration of 1600 ppm during 10% of the evaluation period. Note that the use of the area as an evaluation measure implies a linear weighting of duration and magnitude of a threshold exceedance. Ideally, a physiological derived weighting (not yet established) should be used.

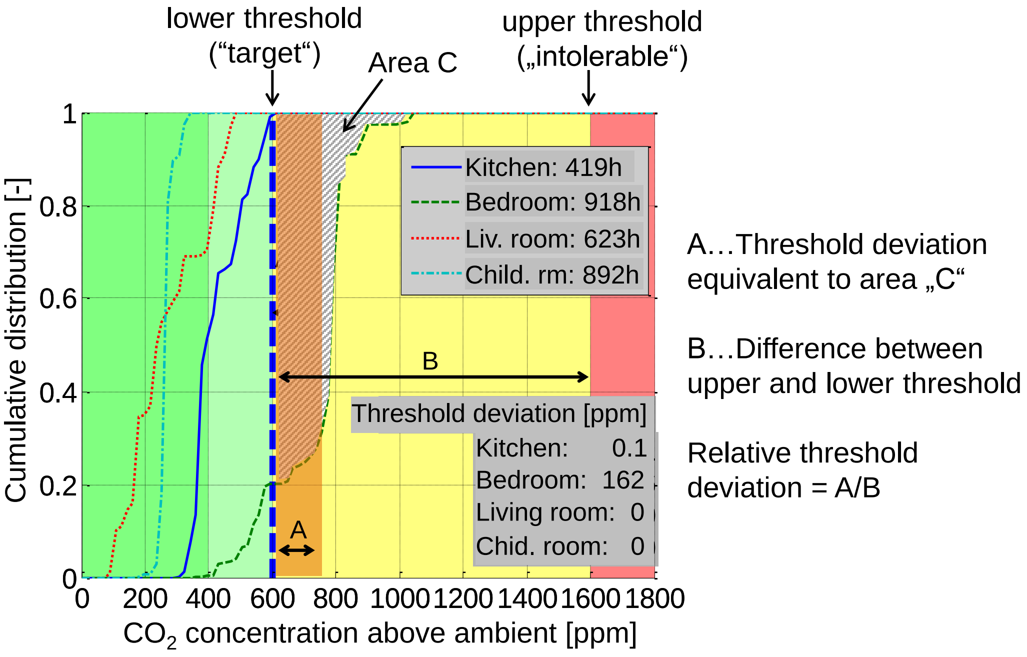


Figure 2: Cumulative distribution of CO_2 concentration of kitchen (blue), bedroom (green), living room (red) and children's room (cyan). Additionally the principle for determination of the threshold deviation is illustrated.

The ratio of this value "A" and the "bandwidth" or the "tolerance" of the threshold of the respective evaluation parameter ("B" in Figure 2) gives the relative threshold deviation. It can be calculated for each evaluation parameter and allows a direct comparison or even summation. For this, different aspects like comfort or physiological impairment (health related aspects) must not be mixed. The herein chosen threshold values (target, intolerable) aim to evaluate possible physiological impairments resulting from a given ventilation situation. They were derived from existing literature and standards and are listed in Table 2.

Table 2

Evaluation criteria[1]	CO_2^{abs} [ppm]	r.h. [%]	TVOC [mg/m³]
Target value	<1000	>30	<0.3
Temporarily tolerable	1000-2000	20-30	0.3-3
Intolerable	>2000	<20	>3

[1] Threshold values for CO_2 and TVOC based on (Heinzow and Sagunski 2007; Lahrz, Bischof, and Sagunski 2008). Target value for r.h. according to EN 13779:2004 and ÖNORM B 8110-2 Bbl 4. Note: The lower r.h. threshold is frequently disputed, but growing evidence of long term effects are being reported, e.g. (Hahn 2007; Pfluger et al. 2013; Wolkoff and Kjærgaard 2007).

To evaluate the mould growth potential, the risk of spore germination is determined as a function of the temperature, r.h. and the exposure time by the isopleth model (Sedlbauer 2001). The isopleth-number is calculated for various ventilation rates and different "qualities" of the building envelope (thermal bridges). The thermal quality of the construction is quantified for this purpose with the temperature coefficient (f_{Rsi}). According to the German standard DIN 4108-2 it is defined as

$$f_{Rsi} = \frac{T_{si} - T_{amb}}{T_i - T_{amb}} \qquad (1)$$

with $T_{si,}$ T_i and T_{amb} being the internal surface temperature, the internal room temperature and the ambient temperature. Given T_i and T_{amb}, the internal surface temperature can simply be calculated. To account for damping due to the thermal mass the 24h moving average of the ambient temperature is used for the calculation of T_{si}. The appropriateness of using a 24h moving average was tested by comparing the results of this quasi-stationary approach and a full dynamical hygrothermal simulation (using "Delphin") for two exemplary cases (concrete wall with 3 cm and 20 cm EPS-insulation).

3 RESULTS

Figure 3 shows the relative threshold deviation for CO_2, r.h. and TVOC as a function of the supply air volume flow into the bedrooms (parents and children's room). For the given reference case the target values cannot be met for all evaluation criteria concurrently. The sum exhibits a minimum at around 30-40m³/h for the bedroom (Figure 3, left). It represents the best "compromise" between high CO_2-concentrations (at low supply air rates) and periods with overly dry air (at high supply air rates).

Looking at the living room the minimum is at even lower volume flow rates, indicating that it is being over-ventilated compared to the bedrooms. This is due to the fact that the living room is being indirectly supplied with supply air from both bedrooms via the overflowing air. This floor plan, like most modern floor plans, allows the application of the so-called extended cascade ventilation principle (Rojas, Pfluger, and Feist 2015; Sibille and Pfluger 2013; Sibille et al. 2013).

Figure 4 shows that the sum of the relative threshold deviation is reduced in all rooms when the extended cascade ventilation is applied, i.e. no supply air outlet is provided in the living room. Note that the TVOC target value (<0.3 mg/m³) is not always fulfilled. With the assumed emission sources, the TVOC concentration needs to be considered when defining the supply air rate (see also living and children's room in Figure 3). But in light of recent results of an IAQ measurement study involving newly built energy efficient homes after one year of occupation (Tappler et al. 2014), the modelled emission rate of 500 µg/m²$_{FA}$h seems to be too high to represent a typical Austrian residential housing situation.

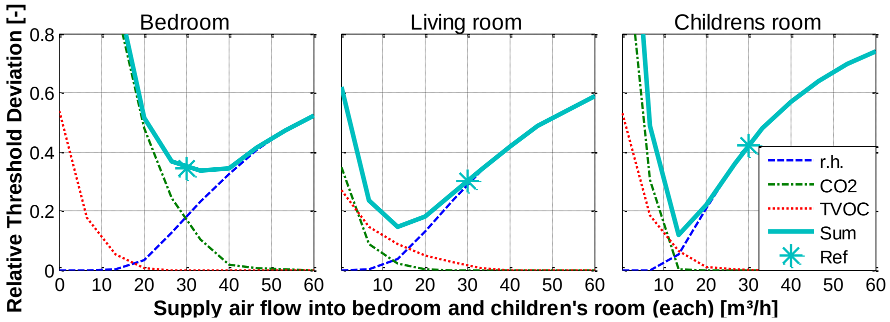


Figure 3: Relative threshold deviation as a function of the supply air flow into the bed and children's room. The supply air flow into the living room was kept constant at 30 m³/h.

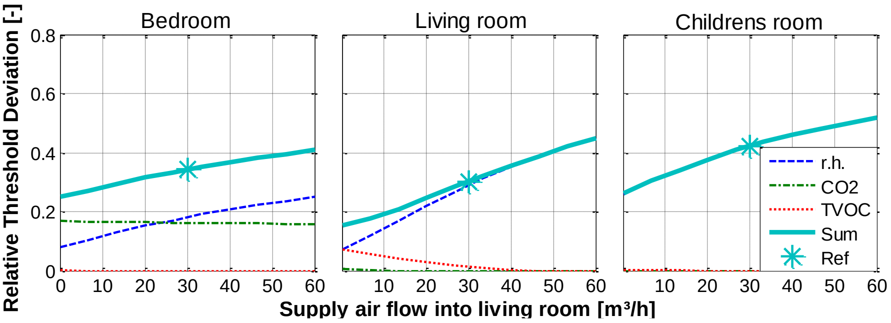


Figure 4: Relative threshold deviation as a function of the supply air flow into the living room. The supply air flow into the bed and children's room was kept constant at 30 m³/h.

Therefore additional simulations were performed with an emission rate of 115 µg/m²$_{FA}$h. As one can see in Figure 5 the target value for the TVOC concentrations are fulfilled even for quite low supply air rates. This means that under these conditions, the supply air rates should be defined considering the necessary dilution of bio-effluents (CO_2 concentration) while maintaining a proper humidity level. The dilution of contaminants from building products does not seem to be the "driving" criteria for the definition of ventilation rates when low emitting building products are used.

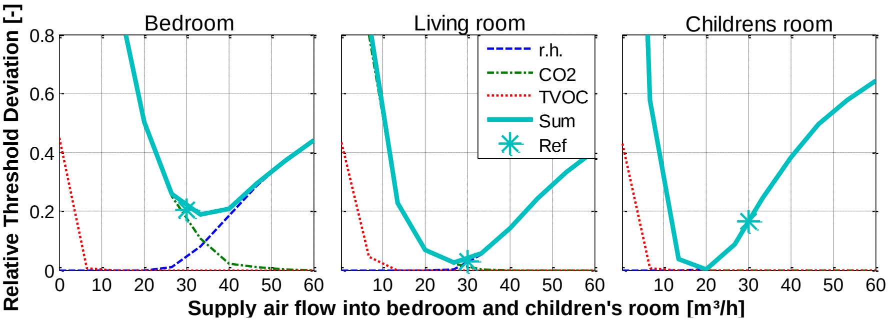


Figure 5: Relative threshold deviation as a function of the supply air flow into the bed and children's room for TVOC emissions rate of 115 µg/m²$_{FA}$h. The extended cascade ventilation principle is applied, i.e. there was no additional supply air flow into the living room.

A floor plan where the extended cascade ventilation principle cannot be applied, was also investigated by separating the living room from the hallway in the reference model. Here, the sum of the relative threshold deviation has its minimum somewhere between 5 and 30 m³/h depending on the assumed door usage (between living room and hallway). Therefore a supply air flow into the living room of 30 m³/h is recommended for the assumed occupation.

3.1 Variations in climate and occupancy

In a previous study using the same methodology and reference model (Rojas, Sibille, and Pfluger 2012), the sensitivity of the result on various model parameters (user behaviour and climate) was investigated. The climate or more precise the content of water vapour in ambient air influences the resulting threshold deviation strongly (see Figure 6). Note that the results are shown for the supply air rates as defined for the reference model (total 90 m³/h). They might not necessarily represent the setting with the minimal possible relative threshold deviation. Especially for locations with higher vapour content (mild winters) a higher air exchange rate would further reduce the threshold deviation.

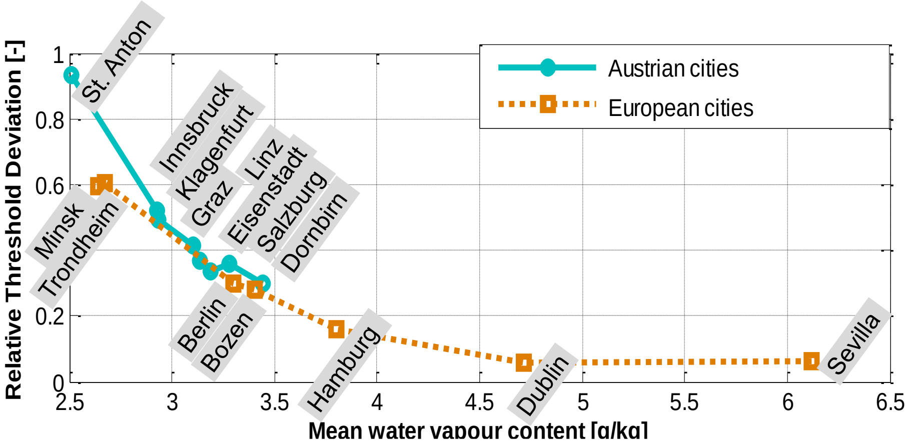


Figure 6: Relative threshold deviation as a function of the mean water vapour content in the ambient during the evaluated winter period. The occupancy-weighted average of kitchen, living-, bed- and children's room is shown. The respective city of the used climate data set is also noted in the graph.

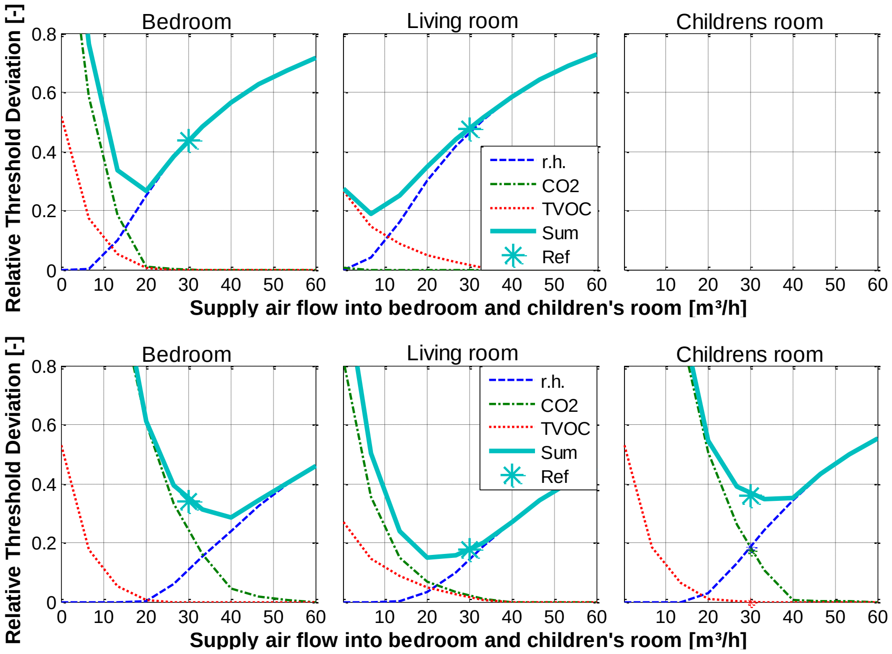


Figure 7: Relative threshold deviation as a function of the supply air flow into the bed and children's room for a one-person household (top) and a five-person household (two adults and three children). The supply air flow into the living room was kept constant at 30 m³/h.

Various simulations with different occupancy profiles were performed. Figure 7 shows the two “extreme” cases with a one and five person occupancy profile. It confirms that a person-specific supply air rate of 20 m³/h reduces the relative threshold deviation in the bedroom. For the children’s room a supply air rate of 15 m³/h per child results in the lowest relative threshold deviation (also considering Figure 3). Note that the modelled CO_2 emission represents a 10 year old child.

3.2 Ventilation system with humidity recovery

As seen from the simulation results without humidity recovery it is practically not possible to continuously meet the recommended target values for CO_2 concentration and r.h. especially in climates with cold and dry winters. In principle this contradiction can be relieved by some sort of humidification measures. In the following, the effect of installing a ventilation system with humidity recovery (the most energy efficient form of humidification) was investigated. A typical humidity recovery rate of 60% defined as

$$\eta_x = \frac{x_{\text{sup}} - x_{amb}}{x_{ext} - x_{amb}} \qquad (2)$$

with x_{sup}, x_{ext} and x_{amb} being the vapour content of the supply air, extract air and ambient air respectively, was integrated in the CONTAM model. A humidity dependent control of the ventilation rate was not implemented. The energetic impact of using a ventilation system with humidity recovery is thoroughly evaluated in (Schnieders 2008).

As seen in Figure 8 the relative threshold deviation can be reduced to zero with a supply air flow of 40-50 m³/h for bedroom and children’s room (each). From the point of view of meeting the target values for CO_2, TVOC and r.h. a further increase would not be required. It would only increase the ventilation losses and the electric power consumption of the ventilation unit. Nevertheless, depending on the humidity recovery rate and the quality of the thermal envelope a higher ventilation rate might still be needed to avoid the risk of mould growth.

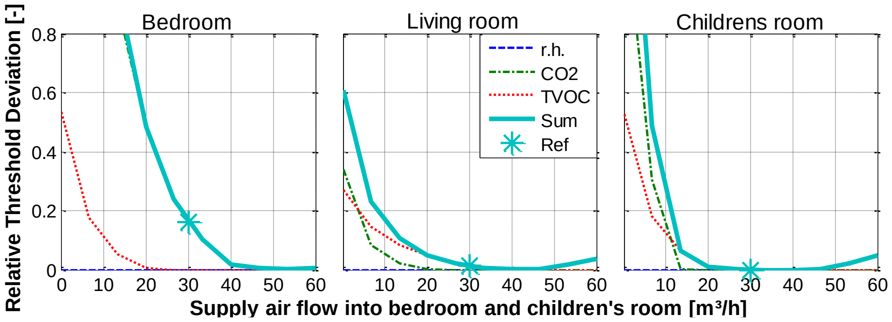


Figure 8: Relative threshold deviation as a function of the supply air flow into the bed and children’s room for a ventilation system with a humidity recovery rate of 60%. The supply air flow into the living room was kept constant at 30 m³/h.

3.3 Considering mould risk

Therefore the risk of spore germination was determined as a function of the ventilation rate and the quality of the building envelope (thermal bridges) quantified by the temperature coefficient (f_{Rsi} value). Figure 9 shows the isopleth-number as a function of the total supply air flow assuming a ventilation system with a humidity recovery rate of 60%. The distribution of the supply air into the three supply air rooms was set according to the results shown in Figure 8, i.e. 45.4% into bedroom and 27.3% each into children’s room and living room. A minimal supply air flow of 90 m³/h is required to avoid mould growth (in the kitchen) for a f_{Rsi} value of 0.9. This f_{Rsi} value represents an envelope of high thermal quality, i.e. high insulation and only minor thermal bridges as required for the Passive House standard. (An exception is the edge bond of the windows, where f_{Rsi} values around 0.7 are possible even for Passive House certified windows. Here a spore germination is less likely and not critical as it would be easy to clean.) Therefore a ventilation rate of 110 m³/h as derived by the CO_2 and r.h. criteria (see above), would also fulfill the “no-mould” criteria for a humidity recovery rate of 60%. If the envelope (thermal bridge) has a f_{Rsi} value of 0.7 (as required within DIN 4108-2 for new buildings in Germany) the volume flow has to be increased to >130 m³/h to avoid mould growth. For f_{Rsi} value of 0.5 (as often encountered in older buildings) the ventilation rate should be at least 180-200 m³/h to obtain an isopleth-number <1. As a consequence, the use of humidity recovery systems should be limited to buildings with a high thermal quality, i.e. low energy or passive houses.

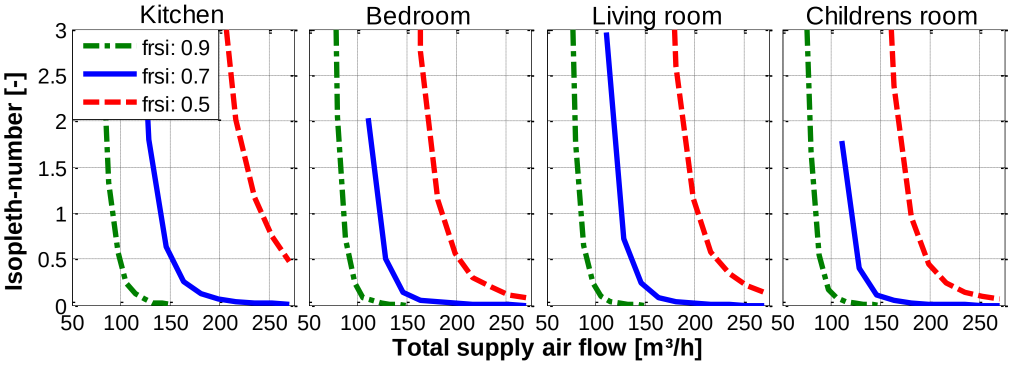


Figure 9: Isopleth-number as a function of the total supply air flow for a ventilation system with a humidity recovery rate of 60% for three different quality levels of the building envelope. A value <1 indicates that the biohygrothermal conditions for spore germination are fulfilled and mould growth is possible.

The mould risk evaluation for the extended cascade ventilation without humidity recovery is shown in Figure 10. According to the relative threshold deviation a total supply air flow of 60 m³/h (40 m³/h into the bedroom and 20 m³/h into the children’s room) would be “optimal” (see Figure 5). The results clearly indicate potential mould growth in kitchen and living room for a f_{Rsi} value of 0.5 (e.g. existing building). For buildings with a f_{Rsi} value of >0.7 (which is generally met in new buildings in Austria and Germany) this simulation results show no risk of spore germination at an volume flow of 60 m³/h. Therefore, the cascade ventilation principle is only recommendable for new buildings or existing buildings which have been appropriately refurbished.

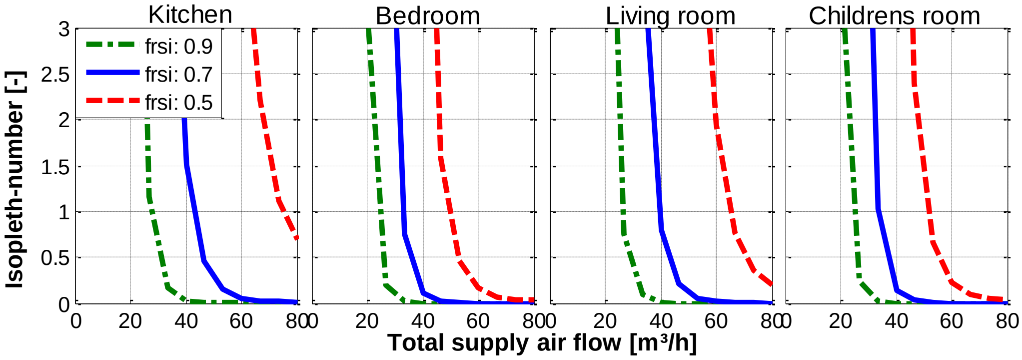


Figure 10: Isopleth-number as a function of the total supply air flow for the extended cascade ventilation principle and no humidity recovery. A value <1 indicates that the biohygrothermal conditions for spore germination are fulfilled and mould growth is possible.

4 CONCLUSIONS

This work derives recommendations for supply air rates in residential housing based on simulations using a multi criteria evaluation method considering bio effluents, emissions from building products and relative humidity. Additionally the mould growth potential is assessed using the isopleth model. The results were incorporated in the revision of the Austrian standard for residential ventilation ÖNORM H 6038 (2014).

Based on this study a supply air flow into the bedroom of 20 m³/h per person is recommended for the chosen reference climate (Vienna). It represents the best compromise between exceeding the target value of CO_2 and avoiding overly dry periods during winter. Pollutants arising from building products and furniture (herein modelled as "TVOC source") seem not to play an important role for the definition of the supply air rates, if low emitting building products are used. For floor plans where the living room is supplied via overflowing air from the bedrooms (more than one bedroom required), no additional supply air into the living room is required. This results in a low air exchange rate for the dwelling. The extended cascade ventilation principle is not recommended for buildings with low internal surface temperatures (thermal bridges) due to mould risk. In this case or simply if the floor plan does not allow the implementation of the extended cascade principle, a supply air rate of 30 m³/h is recommended for the living room (for the investigated 3 person household).

Depending on the water vapour content of the ambient air, these values might need to be adapted. Especially for regions with very cold and dry winters (e.g. mountain regions), ventilation systems with humidity recovery are advisable. Prerequisite is a good thermal building envelope with no heavy thermal bridges ($f_{Rsi} > 0.7$). Otherwise, a potential risk of mould growth exists or a very high (and energy inefficient) increase in air exchange rate is needed.

5 ACKNOWLEDGEMENTS

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