International Journal of Ventilation

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tjov20

Assessing the “sufficient ventilation” requirement for Austrian buildings: development of a Monte Carlo based spreadsheet calculation to estimate airing intervals and mould risk in window ventilated buildings

Gabriel Rojas, Andreas Greml, Rainer Pfluger & Peter Tappler

To cite this article: Gabriel Rojas, Andreas Greml, Rainer Pfluger & Peter Tappler (2023): Assessing the “sufficient ventilation” requirement for Austrian buildings: development of a Monte Carlo based spreadsheet calculation to estimate airing intervals and mould risk in window ventilated buildings, International Journal of Ventilation, DOI: 10.1080/14733315.2023.2198788

To link to this article: https://doi.org/10.1080/14733315.2023.2198788

Published online: 18 Apr 2023.

INTERNATIONAL JOURNAL OF VENTILATION
https://doi.org/10.1080/14733315.2023.2198788

Assessing the "sufficient ventilation" requirement for Austrian buildings: development of a Monte Carlo based spreadsheet calculation to estimate airing intervals and mould risk in window ventilated buildings

Gabriel Rojas[a], Andreas Greml[b], Rainer Pfluger[a] and Peter Tappler[c]

[a]University of Innsbruck, Innsbruck, Austria; [b]Verein komfortlüftung.at, Kufstein, Austria; [c]IBO Innenraumanalytik OG, Vienna, Austria

ABSTRACT

In Austria the lack of guidelines or standards has caused many discussions and disputes on the question if "sufficient ventilation" can be ensured with window airing only, in particular in newly constructed, airtight residential buildings. This work presents the development of a calculation method aiming to provide a simple-to-use tool to estimate the risk of mould growth and the window airing interval required to ensure good indoor air quality assuming a range of different boundary conditions and occupant behaviours. The method implements a Monte Carlo approach calculating 1000 single zone mass balances for carbon dioxide (on a room level) and water vapor (on a housing level). Air infiltration through the building envelope is accounted using the so-called LBL-model. The time interval between window airing required to comply with CO_2 limit value is estimated by calculating the time evolution of the CO_2 concentration for 1000 different parameter combinations. The mould risk is estimated by a 1000-fold calculation of the daily averaged indoor air humidity and the resulting water activity on critical wall surfaces. The results are displayed as probability distributions providing information on the risk that the queried situation can or cannot ensure "sufficient ventilation". Exemplary calculations for bedrooms of new multifamily buildings estimate that intervals between window airing events (to keep time-averaged CO_2-concentration below 1000 ppm), will vary between 23 and 190 minutes (representing the 5th and the 95th percentile). This is clearly below an acceptable intervention interval for bedrooms. For living rooms, the assessment shows a strong sensitivity on the "accessible" air volume. The humidity assessment for this type of housing suggests that mould growth could occur in about 17% of the cases even though air exchange corresponding to two airing events per day were assumed. An additional outdoor air exchange of up to 40 m^3/h would be required to reduce the mould risk fraction to <1%, suggesting the need for mechanical ventilation concepts in residential housing to enable healthy indoor environment independently of occupant behaviour.

ARTICLE HISTORY
Received 6 March 2023
Accepted 11 March 2023

KEYWORDS
Ventilation requirement; mould risk; indoor air quality assessment; Monte Carlo simulation; window airing

CONTACT Gabriel Rojas gabriel.rojas@uibk.ac.at Unit for Energy Efficient Buildings and Digital Science Center, University of Innsbruck, Technikerstraße 13, Innsbruck, Austria.

1. Introduction

Increasing energy efficiency and building airtightness requirements have led to an ongoing debate about suitable measures to ensure proper indoor air quality and humidity levels in residential buildings. In Austria "sufficient ventilation" is required by building regulations (OIB, 2019), without further specifying how this should be accomplished or to what extent active intervention by building occupants, for example, by window airing, is reasonable to assume. The lack of guidelines or standards has caused many discussions and disputes on the question if "sufficient ventilation" can be ensured with window airing only, in particular in newly constructed residential buildings. This work presents the development of a calculation method commissioned by the Austrian ministry of climate action, environment, energy, mobility, innovation and technology. It estimates the risk of mould growth and the time intervals between window airing events required to maintain carbon dioxide (CO_2) concentration below the Austrian guideline limit value (Tappler et al., 2017). This calculation method has been implemented in MS Excel and is freely available for download (BMK, 2021) with the aim of providing an objective decision basis for stakeholders. Further details are documented in the project report (Greml et al., 2021), the following two chapters are a translated summary thereof.

2. Method

As required by the contracting authority the calculation method should be easy to implement. It should not require a special software, for example, building performance simulation tool, and its application should allow for different levels of user knowledge and engagement. That means that it should not be necessary to enter all calculation parameters as this could overwhelm the user. However, the use of many static default parameters could create a substantial bias in the calculation results. Therefore, the authors opted for a Monte Carlo (MC) based approach where the results of one query are based on 1000 calculations with varying input parameters (except for those parameters fixed by the user). The extend of variation of the parameters not specified by the users are defined in probability density functions (PDFs). In that way, the result is not a single value but a value range providing also information about the uncertainty. The calculations use a single zone mass balance model for estimating CO_2 and water vapour concentration (H_2O) in the zone's air volume.

2.1. Single zone mass balance

For this calculation the air density can be considered constant in good approximation. Therefore, a mass balance or volume balance model can be used interchangeably. In the mass balance models CO_2 serves as an indicator for the indoor air quality and H_2O as a relevant quantity for the evaluation of the mould risk. It is assumed that the respective component (CO_2 or H_2O) can be introduced either from the outside via natural infiltration, window ventilation or via a source located in the room or building. The removal is represented in the model via exfiltration or window ventilation. Water vapour buffering in walls and interiors is not considered. Since H_2O mass balance is calculated for daily averages this simplification is considered reasonable. It is assumed that the component under consideration (CO_2 or H2O) is ideally mixed in the zone being evaluated (Barp et al., 2009; Schnieders, 2003). For the CO_2 assessment a certain room of the building is evaluated. The H_2O assessment is applied to the entire dwelling zone. Since mould risk is only considered an issue in residential settings, the H_2O assessment is only applied to residential buildings, while CO_2 assessment can also be performed for schools and office buildings.

2.2. Estimation of intervals between window airing

CO_2 concentration is often used as an indicator of indoor air quality. It is important to note that in general it should only be considered an indicator for occupancy related ventilation demand

(Persily, 1997, 2015). Nevertheless, previous studies suggest that for typical Austrian residential dwellings, fresh air supply needed to maintain decent CO_2 concentration is greater than air supply needed to control other pollutants like VOC's from building materials (Rojas et al., 2015; Tappler et al., 2014). CO_2 is inert and sorption effects can be neglected in indoor environments. Therefore, the difference in mass balance between inflow and outflow can be represented as an increase or decrease in concentration, resulting in the following differential equation:

$$\dot{V}_{in}c_a + \dot{V}_{CO2} - \dot{V}_{out}c_{out} = \frac{dc}{dt} \quad (1)$$

Here, $\dot{V}_{in}$ and $\dot{V}_{out}$ are the incoming and outgoing air flow rates, respectively, due to in-/exfiltration (or window ventilation). Neglecting density differences, these can be equated and $\dot{V}_{in} = \dot{V}_{out} = AER * V$ is obtained. Where AER is the air exchange rate in (1/h) and V is the room volume in (m^3). $\dot{V}_{CO2}$ is the emission rate of CO_2 by occupants in (m^3/h), c_a, c_{out} and c are the respective CO_2 concentrations in volume fractions (–). In the model, CO_2 is assumed to be emitted only by people present in the room through respiration. The emission rate depends on the activity level and the age of the persons. The outdoor air concentration c_a is assumed to be 450 ppm. The above differential equation can be easily solved to determine the concentration profile as a function of time t as follows:

$$c(t) = (c_0 - c_\infty)e^{-AER\cdot t} + c_\infty \quad (2)$$

Here, c_0 is the initial concentration and c_∞ is the steady-state equilibrium concentration, which can be determined as follows:

$$c_\infty = c_a + \frac{\dot{V}_{CO2}}{AER \cdot V} \quad (3)$$

As stated above, the question of whether the "sufficient ventilation" requirement can be fulfilled via in-/exfiltration and window airing is answered by assessing if the time intervals between window airing events needed to stay below a CO_2 limit value c_{LV} is reasonable. In this case AER is solely determined by natural in-/exfiltration. Starting from an initial concentration c_0, the time period until the limit value c_{LV} is reached can be determined as follows:

$$t_{LV} = \frac{ln\frac{c_0 - c_\infty}{c_{LV} - c_\infty}}{AER} \quad (4)$$

In general, it cannot be assumed that a window airing event (after the limit value has been reached) will bring indoor air concentration to ambient air level. Therefore, the initial concentration c_0 has to be determined by estimating the concentration after a typical window airing event. If the air exchange rate during the window airing event AER_{WA} and the duration of the ventilation process t_{WA} are given, c_0 can be determined as follows:

$$c_0 = (c_{LV} - c_{\infty WA})e^{-AER_{WA}\cdot t_{WA}} + c_{\infty WA} \quad (5)$$

The stationary concentration for the window airing event $c_{\infty WA}$ can be calculated in analogy to Equation (3). Note that this concentration will typically not be reached during t_{WA} by far.

$$c_{\infty WA} = c_a + \frac{\dot{V}_{CO2}}{AER_{WA} \cdot V} \quad (6)$$

In the Austrian IAQ guideline different air quality classes are defined (Tappler et al., 2017). For the context of this work, Class 2 ($\leq$ 1000 ppm) or Class 3 ($\leq$ 1400 ppm), depending on the room type, are relevant. However, the guideline does not specify limit values for instantaneous CO_2 values, but for the arithmetic mean of the CO_2 concentration over a defined assessment period t_{AP}. Therefore, Equation (4) must be adjusted accordingly to give the time until the limit value as defined in the Austrian guideline $\overline{c}_{\overline{LV}}$, is reached. The concentration mean $\overline{c}(t)$ can be written as a function of time as:

$$\bar{c}(t) = \frac{1}{t}\int_0^t c(t)dt = \frac{c_{\bar{0}} - c_\infty}{AER \cdot t}\left(1 - e^{-AER \cdot t}\right) + c_\infty \tag{7}$$

Equation (7) can no longer be solved for t analytically. Therefore, a numerical approach is implemented. Equation (7) is solved for 192 timesteps, from 0 to $2t_{AP}$. The time $t_{\overline{LV}}$ when the limit value is reached or exceeded, is determined when $\bar{c}(t) \geq \bar{c}_{\overline{LV}}$. To obtain the initial value $c_{\bar{0}}$ an iterative calculation must be applied. To reduce computational demand, an approximative calculation for $c_{\bar{0}}$ was developed, showing reasonable accuracy and little influence on the final results (Greml et al., 2021).

Additionally, the window airing interval required when assuming ideal airing events $t_{\overline{LV},\ id}$ is also calculated for informational purpose. This corresponds to the assumption that initial concentration after airing is equal to ambient concentration, i.e. $c_0 = \ c_a$.

2.3. Estimation of mould risk

In order to assess the mould risk, the indoor air humidity must be determined. In contrast to CO_2, it depends not only on internal sources and outdoor air exchange. It is also significantly influenced by the buffer effect of building materials, furnishings and objects of daily use. Therefore, a time-dependent calculation on a room level was not considered sensible. Instead, the humidity mass balance is calculated over an entire dwelling as daily average. The mould risk calculation was only implemented for residential housing. The vapor density ρ_a of the ambient air at indoor temperature T_i (K) is calculated for a given ambient air temperature T_a (K) and ambient air humidity φ_a (–) as follows. Herein, the saturation vapor pressure E is calculated according to Magnus' formula, for example (WMO, 2018):

$$\rho_{a(Ti)} = \frac{\varphi_a \cdot E(T_a)}{461.5 \cdot T_i} \tag{8}$$

Assuming that humidity is distributed evenly throughout the home and that temperature differences between rooms might exist, for example, cooler bedroom, the vapour density in the coolest room with temperature $T_{i,\min}$ (K) can be calculated as follows.

$$\rho_{i(Ti,\min)} = \left(\frac{\dot{m}_{H2O}}{\dot{V}} + \rho_{a(Ti)}\right) \cdot \frac{T_i}{T_{i,\min}} \tag{9}$$

Here, $\dot{m}_{H2O}$ is the humidity source strength and $\dot{V}$ is the average outdoor air flow rate for the entire home (referenced to the spatially averaged indoor temperature T_i). Note that the vapor density, which has the unit mass per unit volume, for example (kg/m^3), is converted via a linear approach (ideal gas law) to the reference temperature $T_{i,\min}$. On the basis of this vapor density, the so-called water activity a_w of the mould-critical wall surfaces can be calculated as follows.

$$a_w = \frac{\rho_{i(Ti,\min)} \cdot 461.5 \cdot T_{i,\min}}{E(T_{si})} \tag{10}$$

It corresponds to the relative humidity of the bulk (room) air as it takes the temperature of the wall surface T_{si}. The risk of mould growth is high at a_w values >0.8, provided this condition is present over a certain period of time (few days) (see, e.g., ÖNORM B 8110-2,2 2003; Sedlbauer, 2001; UBA, 2016). This calculation method assumes substantial risk of mould growth if the calculated daily average is >0.8. For Austrian climates the mould-critical wall surfaces are the ones with the lowest temperature, that is, at thermal bridge locations. The interior surface temperature T_{si} of a thermal bridge, can be estimated using the so-called f_{RSI} factor. It is a dimensionless quantity for assessing thermal bridges, see for example, DIN 4108-2.

$$T_{si} = f_{Rsi} \cdot \left(T_{i,\min} - \widehat{T_a}\right) + \widehat{T_a} \tag{11}$$

Depending on the building age and thermal standard, assumptions can be made for f_{RSI}, for example, old building: 0.5, new construction: 0.7, passive house: 0.9. Since the temporal variation of the ambient air temperature T_a is strongly damped on the inner surface (due to the heat capacity of the wall structure), the 24 h moving average of the ambient temperature $\widehat{T_a}$ is used in Equation (11). This has shown to be a good assumption for typical massive construction in previous studies (Rojas et al., 2015).

2.4. Estimation of natural in-/exfiltration

Both, the estimation of the time interval between airing and the estimation of the mould risk, require input regarding the air exchange rate due to in- and exfiltration. It depends on the airtightness of the building and is driven by wind and temperature differences between inside and outside (chimney effect), resulting in a high temporal variability. Various approaches to determine natural in-/exfiltration are known from the literature, they can be roughly divided into the following categories (see, for example, Liddament, 1996):

- Category 1: "Rules of thumb"/empirical factors, for example, DIN 1946-6
- Category 2: Simplified theoretical models, for example, LBL model (Sherman, 1980)
- Category 3: Detailed physical multi-zone model/simulation, for example, CONTAM (NIST n.d.)

The contracted assignment for this work precluded the use of simulation software with a detailed physical model according to category 3. The input effort would be too extensive and the use would ultimately be reserved for experts only. Thus, a choice had to be made between the first two categories. While the first category has the advantage of simplicity, it has the disadvantage that it cannot directly consider influences of weather, i.e. the temporal variability of natural in-/exfiltration which is critical when evaluating indoor air quality. Therefore, a well-known and well documented model from category 2, the Lawrence Berkeley Laboratory (LBL) model (Sherman, 1980) was chosen. Numerous studies have validated this model or used it for their investigations (e.g., Berge, 2011; Binamu & Lindberg, 2002; Hayati et al., 2014). In the LBL model, the in/exfiltrated air flow rate is calculated as follows:

$$\dot{V}_{inf} = A_0 \sqrt{f_s^2 \cdot \Delta T + f_w^2 \cdot v^2} \tag{12}$$

Herein, A_0 is the effective leakage area, a measure of the air leakage of the building envelope. It can be derived from a building air tightness measurement, i.e. from the n_{50} value. The temperature difference ΔT between indoor and outdoor air and the meteorological wind speed v are weighted (non-linearly) by a stack effect factor f_s and a wind factor f_w, respectively. Further details on the LBL model and its parameters can be found in general summary literature (e.g., Liddament, 1996) or in the original literature (Sherman, 1980).

2.5. Monte Carlo approach

The calculations described above require a number of input parameters with respect to building type, geometry, tightness, terrain, etc. and information about the building occupants and the resulting source strengths (of CO_2 and H_2O). Furthermore, the highly variable ambient conditions (temperature, humidity and wind strength) enter into the calculations. The question arises how to deal with the uncertainty or variability of these input parameters. Most input parameters can be assigned a value range rather than a single value. In a deterministic calculation approach, one would have to select a single representative value for each input parameter. The big disadvantage of this is, that the information about the variance of the input parameters and their influence on the variance of the result is lost. Especially for the evaluation of indoor air quality and mould risk, this loss of information is problematic, because issues might occur for non-representative conditions. The methodology should therefore be able to identify and quantify not only the "worst case" but also the "intermediate" and "best case" conditions and their probability of occurrence. For this purpose, all input parameters must be varied within their value range. This quickly leads to an unmanageable number of combinations. The so-called Monte-Carlo (MC) approach offers a remedy (see, e.g., Rubinstein & Kroese, 2017). Instead of computing the entire parameter space (every possible combination), this approach computes only a random sample from the entire pool of value combinations. In the method presented here, 1000 parameter combinations are computed for each query. The value of each parameter is randomly chosen according to a stored probability distribution function (PDF). In total 170 PDFs are defined, see Table 1. Beta-distributions are used to generate the PDFs as their shape can be defined with two shape parameters, resulting a useful choice to model random variables with finite limits. Most of them were defined based on “estimated guesses” by the authors, some of them based on literature values. It is the goal to continually update the PDFs as soon as the necessary empirical data is available. Nevertheless, for any given parameter, users can alter the stored PDFs as needed or specify a single value depending on the uncertainty of the query. Figure 1 shows three examples of the stored PDFs based beta distributions with different shapes.

Table 1. Summary of all relevant input parameters and the corresponding number of defined probability density functions (PDFs) and what the selection of the PDF depends on {in curly brackets}.

Building and room parameters	No. PDFs {dependency}	Parameters for mould risk assessment	No. PDFs {dependency}
Location	–	Thermal bridges (f_{RSI})	5 {bld. standard}
Building type	–	Total humidity load (l/d)	–
n_{50}-value (1/h)	5 {bld. standard}	Emi. rate occupancy (g/(h m^2))	1 {hum. load}
Room type	–	Emi. rate occupancy (g/(h per))	1 {hum. load}
Room area (m^2)	9 {room type}	Emi. rate absence (g/(h m^2))	1 {hum. load}
Room height (m)	9 {room type}	Dwelling area (m^2)	4 {bld. type}
Window area (m^2)	9 {room type}	No. of person	4 {bld. type}
Window airing AER (1/h)	2 {bld. type}	Window airing AER (1/h)	2 {bld. type}
Window airing dura. (min)	2 {bld. type}	Window airing dura. (min)	2 {bld. type}
Window class (EN12207)	5 {bld. standard}	Temperature avg. (°C)	5 {bld. standard}
Terrain class (wind)	15 {location}	Temperature min. (°C)	5 {bld. standard}
Shielding class (wind)	15 {location}	Temperature abs. (°C)	5 {bld. standard}
Occupancy parameters	**No. PDFs {dependency}**	**“Hidden” parameters (not shown in entry mask)**	**No. PDFs {dependency}**
No. adults	9 {room type}	Factor n_{50} bld. vs. n_{50} room	1 {–}
Activity adults (met)	9 {room type}	Factor leakage distribution	2 {}
No. children	9 {room type}	Building height (m)	6 {bld. type}
Activity children (met)	9 {room type}	Rel. stack eff. height (–)	6 {bld. type}
Avg. age children (a)	9 {room type}	Rel. wind press. height (–)	6 {bld. type}

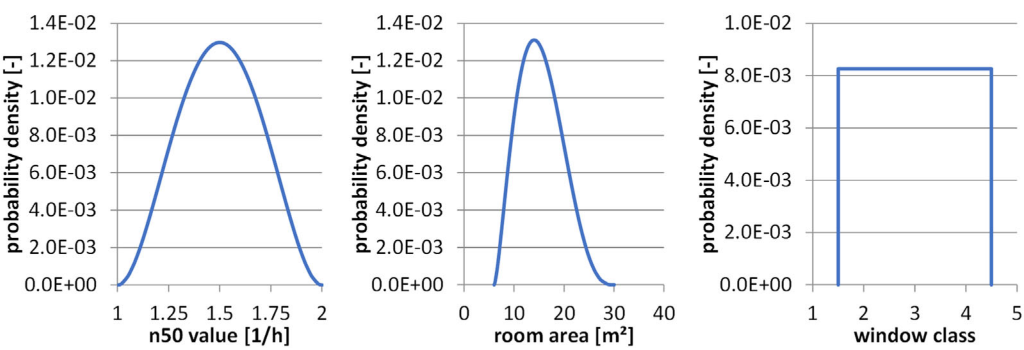

Figure 1. Examples of probability density functions based on beta distributions used to define variability of input parameters. Left: airtightness value for standard new constructions [1/h], Center: room area for bedrooms [m^2], Right: window tightness class for old buildings (is consequently rounded to integer value).

As can be seen in Table 1 one or more PDFs have been defined depending on the parameter, for example, the PDF of the room area should depend on the selected room type (bedroom, living room, etc.). For many parameters, the PDF must be selected depending on the building type (single-family house, multi-family house, office building, etc.) or building standard (old building, standard new construction, low-energy construction, etc.). Further details about all the assumed PDFs can be found in (Greml et al., 2021).

It should be noted that this approach requires statistical independence of the different parameters, for example, the number of children in the classroom, should not depend on the parameter "room size". In reality, there may be dependencies between some of the parameters. However, this was considered when defining the PDFs and their value range. For example, in reality, in rare cases, class occupancy with only 5 or 40 students will occur, but it can be assumed that a correspondingly smaller or larger classroom will be selected. Thus, the range of values for the number of students was restricted to 15 to 25 students. Altogether, the authors assume that the effect of these dependencies on the final results are small. Nevertheless, this should be investigated further. An obvious exception regarding statistical independence are the parameters describing the weather conditions, i.e. temperature, humidity and wind speed. Therefore, those value ranges are not defined via PDFs, but with metrological data sets. These contain hourly values for representative years for the stored locations (15 Austrian cities). The weather data sets were generated using Meteonorm software (Meteotest n.d.). A random number is used to select any hour between January 1 and February 28. Only core winter months were chosen to focus on critical periods within which insufficient window ventilation by occupants may occur.

2.6. Assessment metric

The results of the presented calculation method are used to assess the "sufficient ventilation" requirement in terms of CO_2 concentration and mould risk in the following manner.

CO_2 concentration: The median of the 1000 calculated time intervals between window airing events, required to comply with the Austrian IAQ guideline, is compared with a time interval defined as reasonable for occupant intervention depending on the room type. This definition is summarised in Table 2. If the calculated time interval is smaller than the reasonable intervention time, than ventilation solely via manual window airing (and in-/exfiltration) is not considered acceptable. Note that the median is used for comparison, i.e. 50% of the calculated cases are expected to require shorter window airing intervals.

Mould risk: The calculation tool estimates the mould risk for two separate scenarios. One considers regular occupancy. Here, the corresponding humidity sources (persons, cooking, showering, plants, aquarium, …) and a reasonable minimal occupant intervention (window airing twice a day) are accounted for. The other scenario considers absence, for example, during a winter vacation. Here, reduced humidity sources (plants, aquarium, …), no window airing and reduced indoor temperatures are assumed. The mould risk is reported as fraction of cases (of the 1000 calculations) where the calculated water activity a_w is >0.8. Based on the authors judgement, a mould risk fraction $<1\%$ is considered uncritical, fractions $>5\%$ are highlighted as critical.

Table 2. Assumptions of reasonable time interval between occupant intervention.

Room type	Time interval
Bedroom	480 min
Living room, office	120 min
Meeting room	60 min
Classrooms	45 min

3. Exemplary results

This section presents selected calculation examples to show the applicability of the calculation tool and the plausibility of the results. The only three obligatory inputs are the location, the type of building and the building standard. The following exemplary queries show the results for a standard newly constructed multifamily building in Vienna. Unless otherwise noted all the other parameters were not further specified. Their values were chosen based on the stored probability density functions generating random variations for the 1000 Monte-Carlo calculations.

3.1. Window airing requirement based on CO_2 concentration

In an exemplary query the window airing requirement for the bedroom was assessed. Note that for each query the results vary slightly. Figure 2 shows the results of the timely evolution of the CO_2 concentration and the histogram of the required window airing interval. The query results estimate that for 50% of the cases (median) the limit value of the Austrian guideline (average concentration in assessment period of 8 hours <1000 ppm) would be exceeded every 68 minutes or sooner. In 5% (95%) of the cases the window airing interval would need to be 23 (190) minutes or shorter. This result shows that for newly constructed multi-family buildings a ventilation strategy based on manual window airing is unacceptable for the bedroom if one wants to comply with the guideline and assumes that airing within an 8 h rest period is unacceptable.

In another exemplary query the window airing requirement for the living room was assessed. For living rooms, the Austrian guideline suggests that the average CO_2 concentration should not exceed 1400 ppm. This work assumes that a time interval between manual interventions by the occupants of greater two hours is acceptable for the living room. Therefore, the results for the living room are not as clear as for the bedroom. When the variable input parameters are based on the defined PDFs, the 5th percentile, the median and the 95th percentile of the airing interval are 24, 64 and 146 minutes, respectively. So only in a few cases (5-10%) the airing interval would be greater two hours. However, when the floor area of the living room is specified to be 50 m^2 instead of being variable between 16 and 46 m^2 (P5 and P95), the median airing interval is 130 minutes and therefore assessed as acceptable (see Figure 3). This sensitivity to air volume underlines the importance of using dynamic models when assessing bio-effluents.

3.2. Mould risk based on daily averaged indoor air humidity

In an exemplary assessment of the mould risk around 17% of the cases show a risk of mould growth (water activity $a_w > 0.8$) during occupancy if the variable input parameters are based on

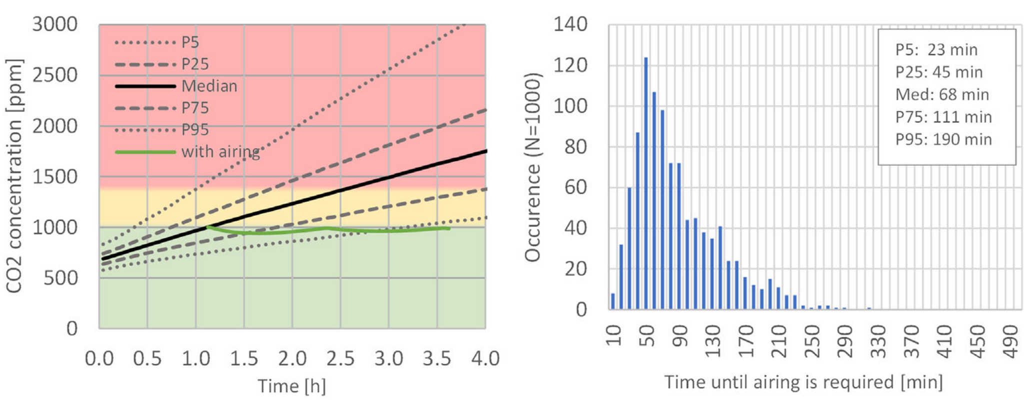

Figure 2. Window airing requirement for the bedroom of a new multifamily building (see text). Left: Evolution of time average of CO_2 concentration without and with airing for the median case, and for selected percentiles without airing. Right: Histogram of window airing interval if Austrian limit value is not to be exceeded.

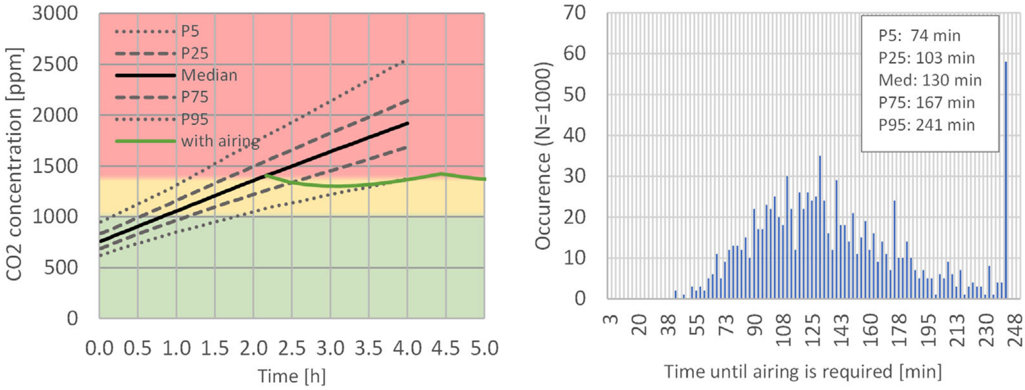

Figure 3. Window airing requirement for a 50 m^2 living room of a new multifamily building (see text). Left: Evolution of time average of CO_2 concentration without and with airing for the median case, and for selected percentiles without airing. Right: Histogram of window airing interval if Austrian limit value is not to be exceeded.

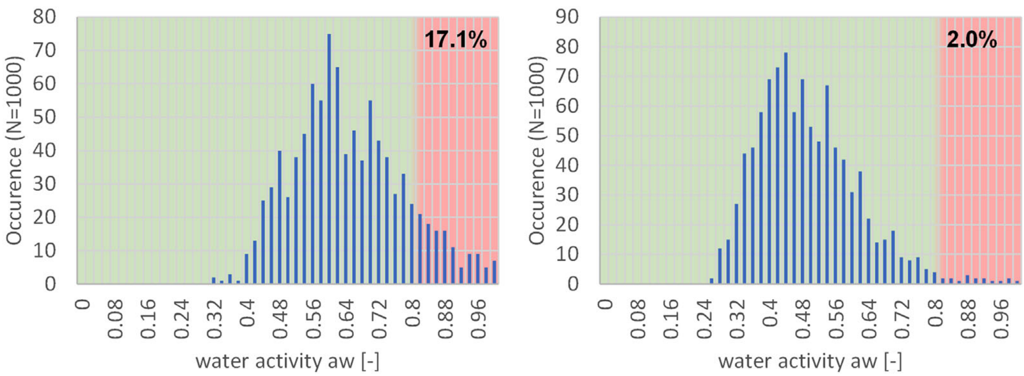

Figure 4. Histogram for number of cases with different water activity results. Values >0.8 correspond to cases with substantial mould risk. Left: Result for standard newly constructed multifamily building in Vienna. The remaining parameters are defined by the stored PDFs. Right: Results for newly constructed multifamily building in Vienna with minimal thermal bridges (Passive House standard) and low humidity load assumption.

the defined PDFs (Figure 4a). The tool also calculates the additional air exchange required to reduce the mould risk fraction to 1%. For this example, up to around 40 m^3/h would be needed. If a construction with minimal thermal bridges (f_{RSI} = 0.9 +/- 0.03 corresponding to Passive House quality instead of 0.7 +/- 0.06 corresponding standard new construction) is assumed, the fraction exhibiting mould risk is reduced to about 4.5%. In this case an additional air flow rate of up to ~10 m^3/h would be needed to reduce the fraction to 1%. If the humidity source strength is assumed to be “low” (resulting in a P5-P95 range of 2.0 – 6.7 L/day, instead of 2.3 – 8.4 L/day) the mould risk fraction is at around 9%. Only the combination of both assumptions (minimal thermal bridges and low humidity source strength) would reduce the fraction with mould risk to about 2% (Figure 4b). Note that, although not shown here, results indicate that for certain cases (e.g., high airtightness values) the absence scenario will be more critical in terms of mould risk.

4. Conclusions

The presented calculation method, and its implementation in a spreadsheet software, can be used to asses if natural in-/exfiltration and window airing can provide sufficient ventilation to comply with given CO_2 concentration limits and ensure low mould risk. The novelty is the “simple-to-use” stochastic approach based on simplified physical models. It accounts for uncertainty and variability of the input parameters providing uncertainty information in the outputs. The current implementation is geared towards Austrian buildings and circumstances, reflected in the stored PDFs defining the variance of input parameters and in the applied assessment metrics. An adaption or amendment for other countries or regions is easily possible. Exemplary results indicate that for current Austrian construction practices, it is not reasonable to rely solely on window airing by the occupants to provide sufficient ventilation in multifamily housing in terms of CO_2 concentration and mould risk. Current limitations are the lack of empirical data to justify stored PDFs and to validate the outputs. Future work should address these limitations.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

Funding

This work was financed by the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK).

References

Barp, S., Fraefel, R., & Huber, H. (2009). Luftbewegungen in Frei Durchströmten Wohnräumen.

Berge, A. (2011). *Analysis of methods to calculate air infiltration for use in energy calculations*. Chalmers University of Technology.

Binamu, A., & Lindberg, R. (2002). Estimation of air infiltration of buildings based on the degree of air tightness and climatic data. In *Indoor Air 2002* (pp. 382–387).

BMK. (2021). Lüftungskonzept Österreich. https://nachhaltigwirtschaften.at/de/sdz/publikationen/schriftenreihe-2021-33-lueftungskonzept-oesterreich.php.

Greml, A., Rojas, G., Pfluger, R., & Tappler, P. (2021). Lüftungskonzept Österreich.

Hayati, A., Mattsson, M., & Sandberg, M. (2014). Evaluation of the LBL and AIM-2 air infiltration models on large single zones: Three historical churches. *Building and Environment*, *81*, 365–379. https://doi.org/10.1016/j.buildenv.2014.07.013

Liddament, M. (1996). AIVC Guide to Energy Efficienct Ventilation, 274

Meteotest. (n.d). Meteonorm Software. http://meteonorm.com.

NIST. (n.d). CONTAM - NIST Multizone Modeling. https://www.nist.gov/el/energy-and-environment-division-73200/nist-multizone-modeling.

OIB. (2019). OIB - Richtlinie 3: Hygiene, Gesundheit Und Umweltschutz.

ÖNORM B 8110-2. (2003). ÖNORM B 8110-2 Beiblatt 4:2003 Thermal Insulation in Building Construction – Part 2: Water Vapour Diffusion and Condensation Protection – Instructions to Avoid Moisture Damages Due to Indoor Environment Influences (pp. 1–9).

Persily, A. (2015). Indoor carbon dioxide concentrations in ventilation and indoor air quality standards. In *Proceedings of 36th AVIC, Conference on effective ventilation in high preformance buildings* (pp. 1–12).

Persily, A. K. (1997). *Evaluating building IAQ and ventilation with indoor carbon dioxide* [Paper presentation]. In ASHRAE Transactions.

Rojas, G., Pfluger, R., & Feist, W. (2015). Recommendable supply air rates for residential housing – A simulation study considering CO_2 concentration, relative humidity, TVOC emissions and mould risk. In 36th AIVC Conference: Effective *ventilation in high performance buildings* (vol. 6038, pp. 937–948).

Rubinstein, R., & Kroese, D. (2017). *Simulation and the Monte Carlo Method* (3rd ed). Wiley.

Schnieders, J. (2003). Wirkung von Position Und Art Der Lüftungsöffnungen Auf Den Schadstoffabtransport. In W. Feist (Ed.), *AKKP 23: Einfluss der Lüftungsstrategie auf die Schadstoffkonzentration und -ausbreitung im Raum* (pp. 85–123). Passivhaus Institut.

Sedlbauer, K. (2001). *Vorhersage von Schimmelpilzbildung Auf Und in Bauteilen*. TU Muenchen.

Sherman, M. H. (1980). *Air infiltration in buildings*. University of California.

Tappler, P., Damberger, B., Greml, A., Hutter, H.-P., Kundi, M., Moshammer, H., Twrdik, F., & Wallner, P. (2017). Richtlinie Zur Bewertung Der Innenraumluft - Kohlenstoffdioxid Als Lüftungsparameter.

Tappler, P., Hutter, H.-P., Hengsberger, H., Ringer, W., & Energien, N. (2014). Lüftung 3.0 - Bewohnergesundheit Und Raumluftqualität in Neu Errichteten Energieeffizienten Wohnhäuser.

UBA. (2016). Leitfaden Zur Vorbeugung, Erfassung Und Sanierung von Schimmelbefall in Gebäuden - 'Schimmelleitfaden.

WMO. (2018). Guide to instruments and methods of observation. Vol. I.