Indoor Carbon Dioxide Metric Analysis Tool

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SUMMARY
Indoor carbon dioxide has been used for decades to evaluate indoor air quality (IAQ) and ventilation. However, many applications of CO_2 as an indicator or metric of IAQ or ventilation reflect a lack of understanding of the relationship between indoor CO_2, ventilation rates and IAQ. Often a single CO_2 concentration is used as a metric for all spaces, ignoring important differences between spaces, including their occupancy and ventilation requirements. Use of CO_2 as an IAQ metric also ignores important indoor air contaminants that are unrelated to occupancy. An approach has been developed to derive CO_2 levels that can serve as indicators of outdoor ventilation by estimating the expected concentration based on the intended ventilation rate, the number of occupants and the rate at which they generate CO_2. This paper describes an online tool QICO2 that has been developed to perform these calculations.

KEYWORDS: *CO_2 concentrations, IAQ metric, online calculator, ventilation*

1 INTRODUCTION

Indoor CO_2 concentrations have been prominent in discussions of ventilation and IAQ since the 18th century, when Lavoisier thought that CO_2 build-up rather than oxygen depletion was responsible for "bad air" indoors (Klauss et al, 1970). About one hundred years later, von Pettenkofer suggested that biological contaminants from humans were causing indoor air problems, not CO_2. Discussions of the relationships between CO_2, IAQ and ventilation have continued to evolve, focusing on the impacts of CO_2 on building occupants, how CO_2 concentrations relate to occupant perception of bioeffluents, and the use of indoor CO_2 to estimate and control outdoor air ventilation rates (Persily, 1997; ASHRAE, 2022).

Indoor CO_2 concentrations are relevant to the outdoor air ventilation rates per person specified in standards, guidelines and building regulations (e.g., ASHRAE, 2019a and 2019b; CEN 2019). These ventilation requirements reflect almost 100 years of research, which initially focused on the amount of ventilation needed to control the perception of odors from human bioeffluents (Persily, 2015). These studies showed that about 7.5 L/s to 9 L/s per person of ventilation air diluted body odor to levels judged to be acceptable by about 80 % of individuals entering the room from relatively clean air, i.e., unadapted visitors. Some of these experiments also included measurements of CO_2 concentrations, allowing examination of the relationship between CO_2 concentrations and body odor acceptability. These studies showed that the ventilation rates needed to control human body odor to levels that were acceptable to unadapted visitors were associated with CO_2 concentrations about 700 ppm_v above outdoors. For a 300 ppm_v outdoor concentration, this corresponds to an indoor concentration of 1000 ppm_v. (Note that outdoor CO_2 levels have since increased to over 400 ppm_v.) These findings lead to 1000 ppm_v of CO_2 as a reflection of the acceptability of body odor as perceived by unadapted visitors to a space. Of course, there are many other important indoor air contaminants that are not associated with the number of occupants, and CO_2 is not a good indicator of them.

ASHRAE Standard 62-1981 contained an indoor CO_2 limit of 2500 ppm_v for use when applying the performance approach in the standard, i.e., the Indoor Air Quality Procedure. That limit was changed to 1000 ppm_v in the 1989 version of the standard, and that value was viewed by many as a de facto IAQ standard without an understanding of its basis as an indicator of body odor acceptability (Persily, 1997 and 2015). Several studies have shown associations of elevated CO_2 levels with sick building syndrome symptoms and other effects (Apte et al., 2000; Shendell et al. 2004; Gaihre et al., 2014), but those associations are likely due to lower ventilation rates elevating the concentrations of other more important indoor contaminants (Lowther et al. 2021; Wargocki, 2021). Indoor CO_2 concentrations are typically well below values of interest based on health concerns, though recent research has shown evidence of impacts on human performance. However, the studies to date have yielded inconsistent results and further research is needed (Lowther et al. 2021; Du at al., 2020; ASHRAE 2022).

While indoor CO_2 is not a meaningful indicator of overall IAQ, this paper proposes using CO_2 as an indicator or metric of outdoor air ventilation rates. Indoor CO_2 concentrations depend on the rate at which occupants generate CO_2, the outdoor air ventilation rate, the time since occupancy began, and the outdoor CO_2 concentration. If these factors are properly accounted for then indoor CO_2 concentrations can serve as meaningful indicators of ventilation. This paper describes how to use CO_2 concentrations as ventilation rate metrics, specifically describing an online tool QICO2 (Quick Indoor CO_2) to support these calculations. Note that while indoor CO_2 concentrations have been discussed as an indicator of the risk of airborne infectious disease transmission (Peng and Jimenez, 2021), this discussion and the tool do not consider infection risk directly. However, if one has identified a ventilation rate to manage infection risk, this metric concept and the online tool can be used to assess whether a space is being ventilated at that risk-based ventilation rate. More detailed explanations of the metric approach and the tool can be found in Persily (2022) and Persily and Polidoro (2022), respectively.

2 THEORY AND BACKGROUND

The underlying model on which the metric concept and tool is based is a single-zone mass balance of a ventilated space. This section describes that model, the approach used to estimate CO_2 generation rates from building occupants, and the metric concept itself.

Single-Zone Mass Balance

The approach described in this paper employs a single-zone mass balance of CO_2 in the space of interest, which can be expressed as follows:

$$V\frac{dC}{dt} = Q(C_{out} - C) + G, \tag{1}$$

where V is the space volume in liters, C is the CO_2 concentration in the space in ppm_v, C_{out} is the outdoor CO_2 concentration, t is time in hours, Q is the volumetric flow of air into the space from outdoors in L/s, and G is the CO_2 generation rate in the space in L/s. Q, C_{out} and G are generally functions of time, but they are assumed to be constant. This single zone mass balance ignores air density differences between indoors and out as well as concentration differences between the space and other building zones. This assumption needs to be acknowledged by users of this analysis approach as well as the QICO2 tool, as a single-zone mass balance does not apply in all buildings and spaces. The solution to Eq. 1 can be expressed as follows:

$$C(t) = C(0)e^{-\frac{Q}{V}t} + C_{SS}\left(1 - e^{-\frac{Q}{V}t}\right), \tag{2}$$

where $C(0)$ is the indoor concentration at $t = 0$ and C_{ss} is the steady-state indoor concentration. Note that the indoor concentration will only reach steady-state if Q and G are constant for a sufficient length of time. A constant value of G requires that the occupancy and intensity of occupant activities remain constant, but in many spaces. occupancy will be too short and too variable for steady-state to be achieved. A convenient means of assessing whether steady-state is likely to be achieved is by considering the time constant of the system, which is equal to the inverse of the air change rate Q/V. One can consider that the system is essentially at steady-state after three time constants, at which time the concentration (relative to outdoors) will have reached 95 % of its steady-state value. For a space with an air change rate of 1 h^{-1}, that will take about 3 hours, and it will take 6 hours for an air change rate of 0.5 h^{-1}.

The steady-state concentration C_{ss} can be expressed as follows:

$$C_{SS} = {}^{G}/_{Q}, \quad (3)$$

If G and Q are in units of L/s, the right side of Eq. (3) is multiplied by 10^6 to yield C_{ss} in ppm_v.

CO_2 Generation from Building Occupants

This analysis estimates CO_2 generation rates from building occupants using the basal metabolic rate *BMR*, which is the energy required to sustain the basic functions of human life and depends on sex, age and body mass (Persily and DeJonge, 2017). The *BMR* is multiplied by an individual's level of physical activity M in met (nondimensional) to yield their rate of energy expenditure, which is converted to a CO_2 generation rate V_{CO2} and can be estimated as follows:

$$V_{CO2} = BMR\ M\ \left({}^{T}/_{P}\right)\ 0.000179, \quad (4)$$

where T is the air temperature in K and P is the pressure in kPa.

Indoor CO_2 Metric

While CO_2 concentrations would be an attractive IAQ metric, indoor CO_2 concentrations only relate to contaminant sources that are associated with the number of occupants in a space. There are many other indoor air contaminants that do not correlate with occupancy, such as chemical emissions from building materials and contaminants that enter from outdoors. Instead of a general metric of IAQ, a CO_2 metric can be used to evaluate outdoor air ventilation rates relative to design values or requirements from a standard, but the metric value must be based on the space and its occupancy. The required space information includes the target outdoor air ventilation rate, the space volume, the number of occupants, and the sex, age, body mass and met level of the occupants. This information can then be used to calculate the expected CO_2 concentration at a point in time, which can serve as a ventilation metric for the space.

To make these calculations more accessible, an online tool QICO2 was developed. Persily and Polidoro (2022) contains example calculations of CO_2 ventilation metrics for several commercial/institutional and residential spaces, which are available in the QICO2 tool. Table 1 shows calculations selected from those cases. Note that the ventilation rates for the commercial cases are based on ASHRAE Standard 62.1. For each space type listed, the table includes the outdoor air ventilation rate per person, the average CO_2 generation rate per person, the time for the CO_2 concentration to achieve steady-state, and the steady-state CO_2 concentration. Note that the time to reach steady-state varies over an order of magnitude for the commercial spaces, and the steady-state concentrations range from about 1000 ppm_v to 2000 ppm_v above the outdoor concentration. The steady-state concentrations are below for 500 ppm_v for the residential cases.

Table 1. Example CO_2 concentration calculations

Space Type	Outdoor air ventilation (L/s per person)	Average CO_2 generation rate per person (L/s)	Time to steady-state (h)	CO_2 concentration at steady-state above outdoors (ppm_v)
Office space	8.5	0.0051	5.9	999
Lecture hall	4.3	0.0049	0.7	1626
Conference room	3.1	0.0051	1.6	2042
House, Standard 62.2	9.8	0.0046	9.8	468
House, 0.5 h^{-1}	15.9	0.0046	6.0	288

Note: House volume = 685 m^3, with an assumed family of 6.

3 QICO2 ON-LINE METRICS TOOL

This section provides an overview of the online tool QICO2 for implementing the CO_2 metric approach just described. This online tool is available at https://pages.nist.gov/CONTAM-apps/webapps/CO2Tool/#/, with a more detailed description and Users Guide in Persily and Polidoro (2022). To summarize, the user can select from a number of predefined spaces with defined occupants and design ventilation rates, or they can create their own case. The QICO2 tool estimates the indoor CO_2 concentrations in the space at steady-state, 1 h after occupancy and at a value of t_{metric}. The time t_{metric} is a length of time over which the particular space may be expected to be fully occupied, which in many cases is less than the amount of time required for the CO_2 concentration to achieve steady-state. The calculated concentrations can be compared with measured CO_2 concentrations with a measured CO_2 concentration that is above the metric value at a given time indicating that the ventilation rate is below the intended value.

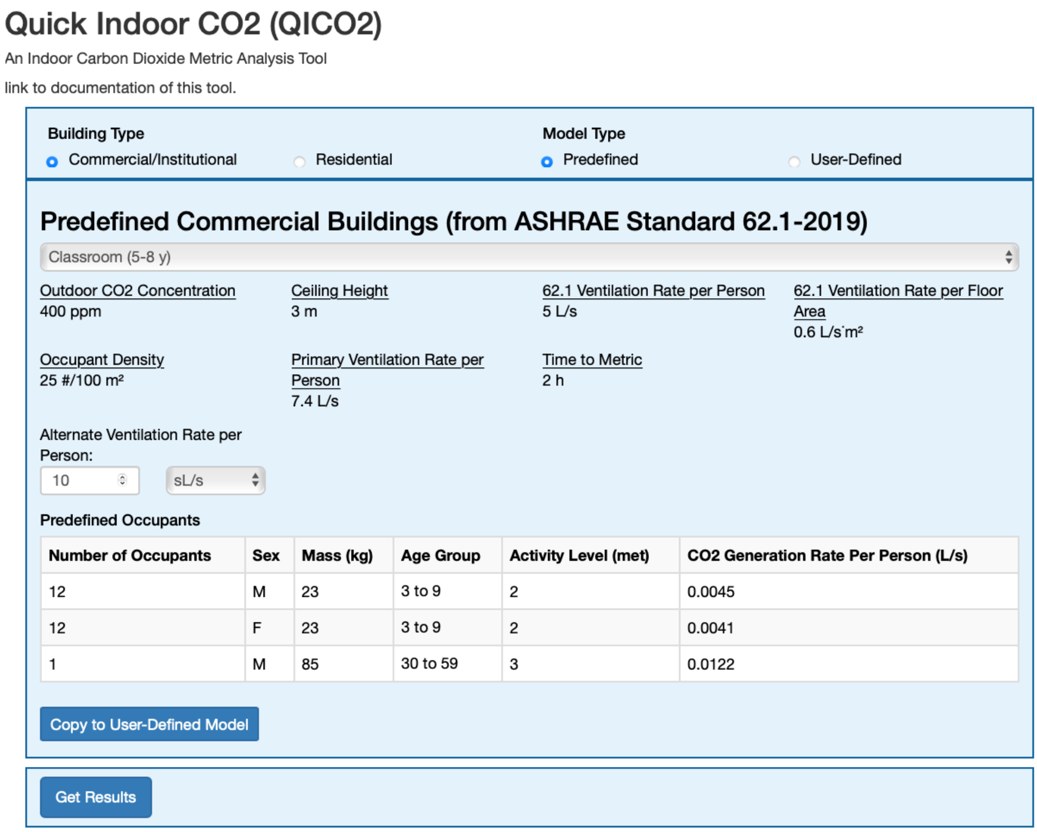

Figure 1. QICO2 Metric Tool Interface (Inputs for Commercial Buildings)

The first step in using the tool is to select whether to analyze a commercial/institutional or residential building. Figure 1 shows the screen when selecting commercial/institutional, in which case the user can select from a predefined case or define their own. The predefined cases include space types listed in ASHRAE Standard 62.1-2019 and use the default values in the standard for outdoor ventilation requirements and occupant density, i.e., number of occupants per 100 m^2 of floor area. The tool also makes assumptions about the occupants in each space, i.e., sex, body mass, age and activity level, needed to calculate their CO_2 generation rates. Other required inputs include the outdoor CO_2 concentration, the floor area and celling height of the space, and the value of t_{metric}. All inputs are defined in the predefined cases but can be modified by selecting User-Defined. If desired, an Alternate Ventilation Rate per Person can be input to allow comparison of the results to those obtained with the Primary ventilation rate.

If the user selects residential building, the screen shown in Figure 2 appears. Again they can select from a number of predefined cases or define their own. The user also needs to select whether they are performing a whole building or bedroom analysis. If whole building, the ventilation requirement can be based on ASHRAE Standard 62.2-2019 or a whole building air change rate in h^{-1}. If performing a bedroom analysis, they need to select the whole building ventilation requirement from Standard 62.2 or enter a L/s per person ventilation rate. If they use Standard 62.2, they also need to define the air distribution as Perfect or Uniform. Under Perfect Distribution, the whole house rate is divided by the number of occupants in the house. That normalized value is then multipled by the number of occupants in each bedroom to determine the ventilation to each bedroom. Under Uniform Distribution, the whole house rate is divided by the floor area of the house. That normalized value is multipled by the floor area of each bedroom to determine the outdoor air ventilation to each bedroom.

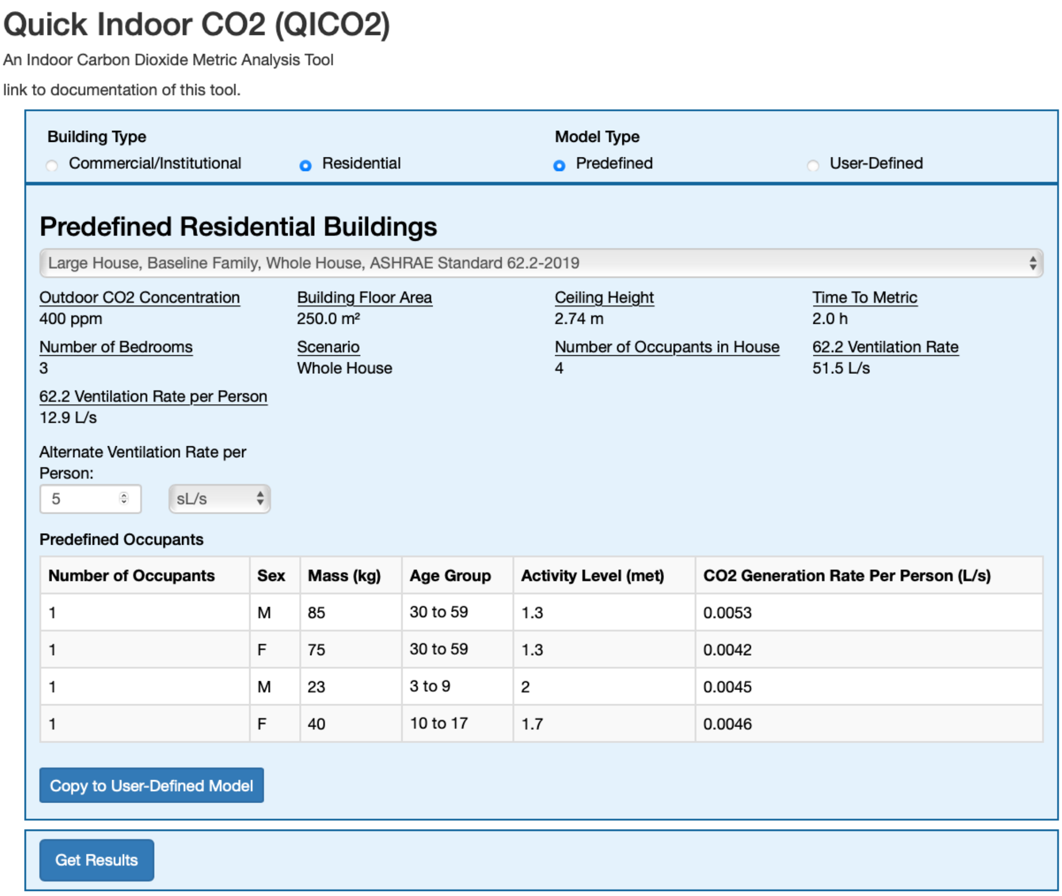

Figure 2. QICO2 Metric Tool Interface (Inputs for Residential Buildings)

Once the user has completed the inputs, clicking on at the bottom of the Inputs page brings up the Results screen shown in Figure 3. This screen summarizes the inputs and displays a plot of the indoor CO_2 concentration versus time and a table of the concentrations at steady-state, t_{metric} and 1 h after occupancy for the Primary and Alternate ventilation rates.

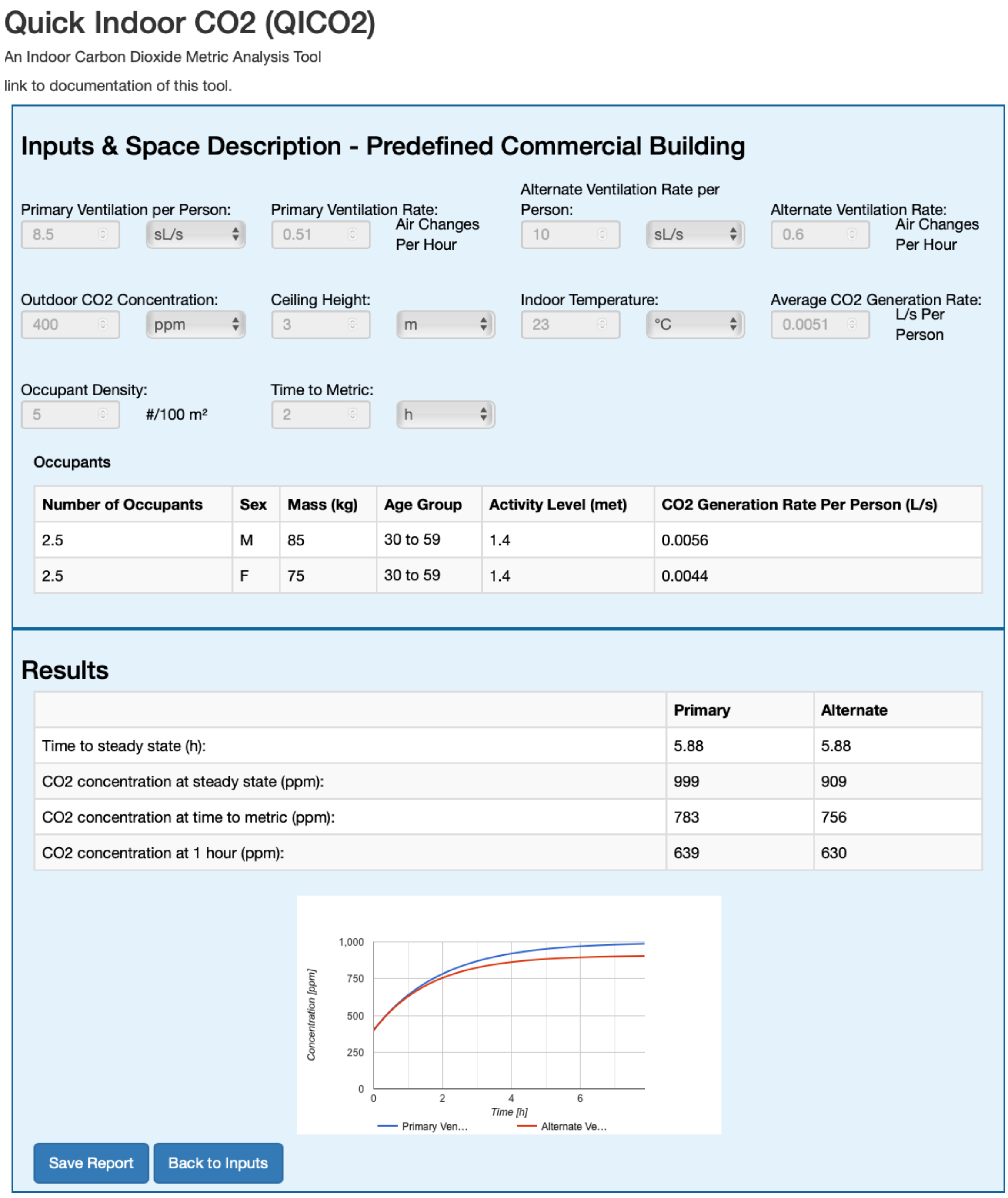

Figure 3. QICO2 Metric Tool Interface (Results)

The tool is applied by comparing measured CO_2 concentrations at a specific time to the calculated values, with a measured value that is higher serving as an indication that the actual ventilation rate is below the assumed or desired ventilation rate. The relative values of the measured and calculated CO_2 concentrations do not indicate the degree of underventilation, but by entering an Alternative Ventilation rate the user can explore the impacts of different ventilation rates. Since the calculations assume constant occupancy, the measurement needs to occur while occupancy is constant, which can be limited in duration. Ideally, a constant occupancy period that lasts for t_{metric} occurs for the building or space being considered, and the calculated value at that time can then provide a more reliable comparison. If constant occupancy does not last that long, the t_{metric} value in the tool can be modified.

For comparisons with a whole house CO_2 metric, the measured concentration should be a volume-weighted, whole house average based on the concentration measured in each room. For bedrooms, with more stable bedroom occupancy during sleeping, the CO_2 metric should be applied several hours after the bedroom is occupied. Note that the initial concentration in the bedroom may be higher than outdoors due to previous activities in the house, in which case the calculated concentration will be lower than if the actual initial concentration were considered. This situation would result in the calculated metric value being conservative, meaning it would lead to a conclusion that the ventilation rate is lower than it may actually be.

4 DISCUSSION

This paper describes the use of indoor CO_2 concentrations as a metric of outdoor air ventilation rates that considers the unique features of the space of interest, i.e., geometry, ventilation requirements and occupant characteristics. This paper also describes how to exercise this metric in practice using an online tool QICO2. More detailed explanations of the metric approach and the tool can be found in Persily (2022) and Persily and Polidoro (2022) respectively.

As with all simplified analyses, there are limitations that need to be understood by users of the metric concept and the QICO2 tool. For example, while a measured CO_2 concentration that is higher that the predicted value serves as an indication that the actual ventilation rate is below the assumed or desired ventilation rate, this analysis neglects interzone transport of CO_2 from other spaces, which is particularly important when considering bedrooms. Also, if the CO_2 generation rate of early occupants of a space are different from those at full occupancy, it will complicate application of this approach. This approach can also be particularly challenging to apply in spaces with transient occupants, such as retail spaces and lobbies, which may not be at constant occupancy long enough to provide a reasonable period for analysis. Also, in spaces with long time constants, i.e., low air change rates, the CO_2 concentration will not necessarily increase significantly relative to the concentration measurement uncertainty during constant occupancy. In some cases, the analyst may need to perform a more detailed transient analysis using other tools, such as the CONTAM airflow and IAQ model (Dols and Polidoro 2020).

While this paper and the referenced publications (Persily 2022; Persily and Polidoro 2022) contain example calculations for several example spaces, the analysis of more space types and a wider range of input values would be useful to the future development of this concept, as would its application by practitioners. These efforts would help to gauge its practicality and identify issues regarding its use as a ventilation metric. Field studies in which calculated metric values are studied in conjunction with measured outdoor air intake rates would also be helpful. Also, additional analyses would allow the estimation of the uncertainty associated with the variation in the input parameters.

4 CONCLUSIONS

While indoor CO_2 is not a good metric of overall IAQ, it can be used as a ventilation metric if one considers the specific space in question and its occupants. Applying a single CO_2 concentration to all spaces ignores these important variations. The ventilation metric discussed here and implemented in the QICO2 tool allows practitioners to use indoor CO_2 concentrations to evaluate ventilation rates in a more rigorous manner. It is hoped that use of this concept and tool will lead to improved practice and better building ventilation and IAQ.

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