A method for determining the time-dependent indoor CO_2 concentration to evaluate air hygiene

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ABSTRACT

This paper deals with new ways to describe and assess indoor air CO_2-levels to provide a sufficient clarity. Besides common illustrations of measured or calculated CO_2 concentrations over a certain period of time different computed indicating values like CO_2 hours over a specific threshold exist. However, most of these diagrams need interpretation by experts and a sum of CO_2 hours over a specific threshold does not provide information on extreme values in difficult phases. Thus, a new kind of categorization and additional indicating value was developed. By generating ppm-hours as an integration of the $C0_2$ curve e.g. over 1000 ppm with the correlative time duration an advanced characteristic parameter can be proposed. Own calculations with dynamic thermal building tools (IDA-ICE) and measurements were applied to set-up use cases and validation. Further improvements could lead to a standard procedure in terms of the assessment of indoor air CO_2-levels.

INTRODUCTION

Max von Pettenkofer, one of the first hygiene engineers, evaluated the indoor air quality by means of the carbon dioxide content. He also recommended a corresponding threshold of 1000 ppm (initially published as 0.1 Vol.-%) already in 1858 as a value that should not be exceeded "Pettenkofer (1858)". As long as humans are the main source of air pollution through their continuous release of metabolic products such as CO_2, carbon dioxide can still be used as a good indicator for evaluating the indoor air quality. However, rooms with a high rate of occupancy, such as classrooms or lecture halls, often do not have sufficient indoor air quality and therefore an increased demand for fresh air is necessary. Different standards like "ASTM D6245:2018", the German workplace guidelines "ASR 3.6:2012" and others deal with ventilation requirements by defining indoor limit values for the overall CO_2 concentrations.

The CO_2 concentration in a room usually depends on the air volume, the occupancy rate and the activity rate of the users together with the air change rate and the outside CO_2 content. With a rising outside CO_2 content, today ca. at 410 ppm in rural areas and ca. 260 ppm during 1858 "CO2levels.org (2021)", the interesting part of the CO_2 content caused by human metabolism indoors is the difference between any measured content between inside and outside ΔCO_2. Hereby, even Pettenkofer published different outside contents in rural areas, cities and central parts of bigger cities varying from ca. 300 ppm up to 800 ppm, the latter mainly caused by burning wood, coal or even turf. Today's outside CO_2 content rose due to the global use of fossil fuels and in the cities traffic and heating systems are the main reason for even higher levels in the outside air. Yet, most requirements deal with the overall CO_2 content as threshold values. Besides 1000 ppm numerous other thresholds are available for different purposes like 1200 ppm, 1400 ppm or 2000 ppm which is used as a limit value for urgent action towards better ventilation and 5000 ppm as a threshold of unhealthy conditions like in "ANSI/ASHRAE 62.1". Unfortunately, related measurements or pre-calculations with dynamic simulation tools and virtual persons inside of rooms as a source of CO_2 are often only carried out randomly or not at all.

STATE OF THE ART

There are various ways to evaluate indoor air quality. For example, Fanger developed the units olf and decipol to assess the perceived indoor air quality. An olf is defined as the rate of emissions of air pollutants caused by a standard person. One olf under a ventilation of 10 l/s of unpolluted air, is defined as decipol. As a function of the perceived air pollution in decipol, the percentage of dissatisfied with the indoor environment can be determined. Fanger emphasized that the decipol value expresses the air quality perceived by humans, but does not indicate whether the pollution has health effects. "Fanger (1988)"

Often, prevailing CO_2 concentrations are considered to indicate health effects of air quality. Research has shown that increased CO_2 levels, often found indoors, are associated with perceptions of poor air quality, increased prevalence of acute health symptoms (e.g., headaches, mucous membrane irritation), slowed work performance, and increased absenteeism "Myhrvold (1996), Seppänen (1999), Apte (2000), Erdmann (2004), Zhang (2016)". Depending on CO_2 levels, users experience different symptomatology. For this reason, there are different limits and categories for CO_2 concentrations. There are various ways of displaying measured or calculated CO_2 concentrations to evaluate indoor air quality. Conventional methods often evaluate the percentage of the time the air can be assigned to which quality category or calculate average values with indication of extreme values. The results are usually given in hours above a certain threshold value like 1000 ppm or as hours of CO_2 concentrations in certain categories like 400 ppm to 1000 ppm, 1000 ppm to 1400 ppm and above 1400 ppm. For example, results are often shown as in Table 1 providing a quick overview.

Table 1. CO_2-hours above 1000 ppm and in different categories depicting the same data set of a lecture hall, see use cases.

	CO_2-hours above 1000 ppm		
test room	874 h		
	CO_2-hours in categories		
	400 – 1000 ppm	1000 – 1400 ppm	> 1400 ppm
test room	294 h	96 h	778 h

This representation does not implement a fine resolution of the results and continuous curves of the CO_2 content over time with changes per day sometimes may produce difficulties in the interpretation. Therefore, more sophisticated diagrams were used to depict CO_2 content. For example, box plots were applied accordingly (Figure 1).

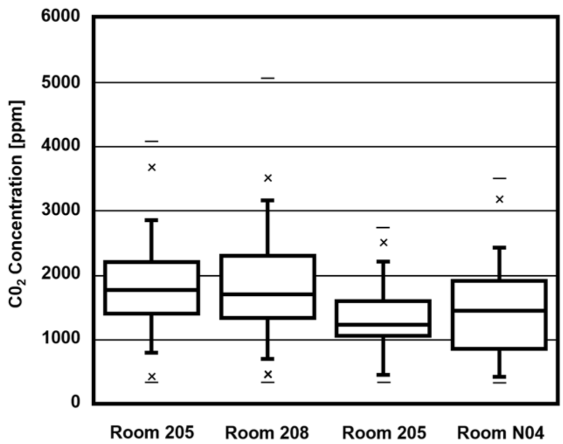

Figure 1. Utilizing box plots to depict indoor CO_2 contents during the winter months "Hellwig (2009)".

Yet, a statement about the temporal distribution of the CO_2 concentrations is here only possible in a limited way. The sum of hours above a certain threshold or the percentage distribution of time over the different categories of CO_2 concentrations (e.g. 20% of the time between 1000 to 1400 ppm) is more common, mainly because a statement is made about the distribution of concentrations over time. This provides information on how long which air quality prevails. But it is not clear whether the concentrations are constantly close to the upper or lower limit to the next category.

Some dynamic software programs like IDA ICE also calculate CO_2 concentrations dependent on the air change rate and the number of occupants. Here, the annual mean value of the CO_2 concentration is multiplied by the number of simulated hours. This mean value provides a first rough classification of the air quality. However, further information on the distribution of periods when higher and lower CO_2 levels are present would be necessary to evaluate indoor air more accurately.

Moreover, the occupancy ratio should be considered, or given as an additional information otherwise it is difficult to quantify indoor air quality. In general, many evaluation methods do not take occupancy ratio into account. Yet, all CO_2 contents over a simulation period can be plotted using sophisticated software tools like IDA ICE and corresponding diagrams show a general overview. Graphical analyses are possible as well showing CO_2 concentrations as color values for instance in a so-called carpet plot, see Figure 2.

However, there is no single indicating value available for a quick but accurate representation of high CO_2 levels over a certain period of time. A more detailed consideration would provide additional information: The integration of the CO_2 curve over time takes into account the prevailing concentrations with associated occurrence durations. Thus it can be seen whether the prevailing concentrations tend to be distributed around the upper or lower limit of the category. The description of this calculation method is explained below.

DESCRIPTION OF THE DEVELOPED METHOD

For a better representation of the overall impact of high CO_2 contents, a concept can be adapted that is widely used to describe thermal comfort indoors over a certain period of time by utilizing degree-hours.

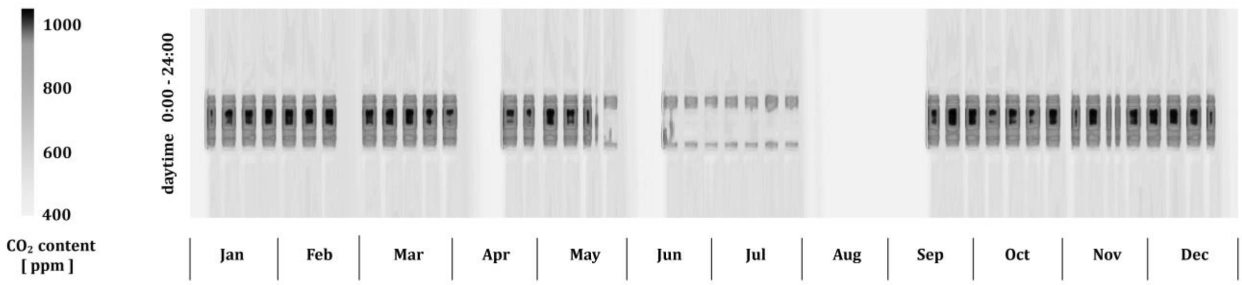

Figure 2. Distribution of CO_2 concentrations over one year within a classroom. Carpet plot from a building simulation software.

Hereby, a threshold value like 26 °C is used as well as the exceedance in operative temperature given as the difference between the existing indoor operative temperature and the threshold operative temperature, see Equation 1 and Figure 3.

$$dh_{26} = \sum_{i}^{|hours\ \theta_o > \theta_{o,26}|} (\theta_{o,i} - \theta_{o,26})t \qquad (1)$$

where:
dh_{26} is degree-hours above 26°C [K·h], θ_o is operative temperature [°C], t is 1 [h], indices: *26* is threshold value, *i* is indoors.

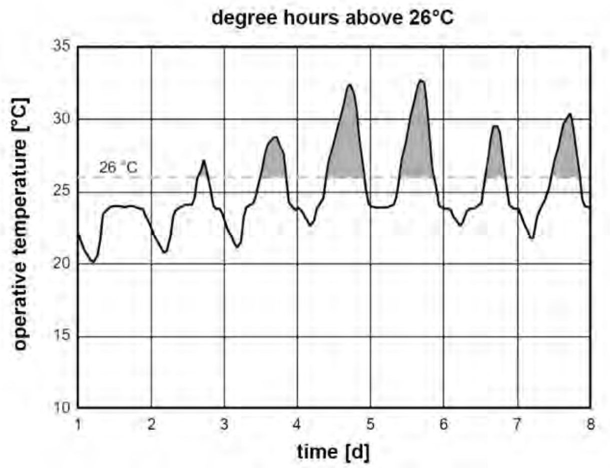

Figure 3. Example of degree-hours above 26 °C during one week, the grey area represents the integral value.

The adaptation of this principle for CO_2 concentrations leads to ppm-hours. The ppm-hours can be determined by means of integration of a temporal concentration curve over e.g. 1000 ppm, or a different threshold value or within a previously determined category.

To facilitate integration, CO_2 concentrations can also be classified in 100 ppm steps, as shown in Figures 4 and 5. The classification specifies how many hours of occupancy are in which class (e.g., 1150 h between 1100 and 1200 ppm). The sum of hours within a category or above a threshold results in CO_2 hours. The calculation of CO_2 hours for each category is shown in Equation 2 and is a summation of those hours when a concentration emerges in a specific range.

$$hCO_{2,cat} = \sum_{i}^{|hours\ c_{Co2,l1} \leq c_{Co2} < c_{CO2,l2}|} t \qquad (2)$$

where:
hCO_{2,c_cat} is CO_2 hours in a specific category [h], *t* is the time during occupancy [h], c_{CO2} is mean CO_2 concentration during 1 h of occupancy [ppm], indices: *l1* is lower limit value, *l2* is upper limit value.

These hours can be multiplied by the mean value of the associated CO_2 class to ppm-hours and then summed up. Equation 3 shows the calculation.

$$hCO_{2,c\_th} = \sum_{i}^{|hours\ c_{CO2} > c_{CO2,th}|} (c_{CO2,i} - c_{CO2,th})t \qquad (3)$$

where:
hCO_{2,c_th} is CO_2 concentration hours above a specific threshold [ppm·h], *t* is the time during occupancy [h], c_{CO2} is CO_2 concentration [ppm], indices: *th* is threshold value, *i* is indoors.

Hence, ppm-hours help to approximate the area under the CO_2 distribution curve within the given boundaries using the Riemann summation. An exact integration of the CO_2 distribution provides accurate values but is also more time-consuming. The principle of Riemann summation is implemented in a tool by means of programming in MATLAB. Exemplary results and diagrams are shown at the use cases.

Calculating the ppm hours within a category (e.g., 1000 - 1400 ppm) results in a value which, in addition to the existing CO_2 concentrations, also takes into account the occurring duration. If, for example, the mentioned category (1000 ppm – 1400 ppm) is considered acceptable and above 1400 ppm is considered insufficient, because above this value headaches, concentration difficulties or similar may occur "Pulimeno (2020)", the CO_2 curve within the category is of high relevance. If the values are close to 1000 ppm, an acceptable air quality can be assumed. If the values are mainly around the upper limit of 1400 ppm, it must be questioned whether headaches or similar symptoms do not already occur here. In the new method, by integrating the CO_2 trend over time as accurately as possible, the trend within the category is considered. This allows a more differentiated picture of the air quality in the room. In order to classify this value, the maximum and minimum possible values are given. This allows to classify whether the determined value tends more towards the worst-case scenario or towards the best possible value.

However, some German municipals took quite rough categories of 1000 ppm to 1400 ppm in classrooms being still acceptable according to the definition in the Standard "DIN EN 13779". In such a case the categories in the MATLAB tool can be adjusted to

- 400 ppm – 1000 ppm (good air quality),
- 1000 ppm – 1400 ppm (sufficient air quality),
- > 1400 ppm (not sufficient air quality).

Especially when really high CO_2 levels occur these categories do not represent the problem. Therefore, depending on individual necessities, the limits of the categories can be freely selected in the tool and we recommend one category every 100 ppm. If only CO_2-hours in broad categories are available as mentioned above, for instance from any kind of documentation, a best, medium and worst case scenario can be utilized to produce ppm-hours as well. Hence, the lower, medium or upper limit value (actual ppm minus ppm threshold of 1000 ppm) will be multiplied with the overall hours of that category. This allows for estimations of existing data to classify them according to the proposed method.

So far, higher CO_2 concentrations contribute linearly to the ppm-hours. But these higher CO_2 concentrations are connected to increasing health issues. Here, it might be helpful to define factors or exponential functions to not only multiply with the ppm-difference. Defining a function which represents the higher risks needs more research, since the correlation between CO_2 content, the exposition period and the strength of negative health effects is largely unknown. Yet, it is possible to implement that in our software tool too. As a first approximation, a simple solution was considered, by utilizing the sum of squared differences between a certain threshold value and a current concentration. Hereby, higher values contribute considerably more to the final result.

In addition, in the new method a reasonable observation period can be defined, omitting holidays and times without occupancy in daily schedules in the following calculations. Commonly CO_2 concentrations increase during occupancy, but often remain at a critical level even though the users have left the room. These times should not be considered, as they are irrelevant. Since data from simulations as well as measurements can be analyzed, it is not possible to derive the usage time from the input data, thus the usage times must be entered manually.
Measurements have shown that CO_2 concentrations show seasonal differences, with a peak during winter when windows are often closed. It is reasonable to split an evaluation period into multiple equally sized parts, like seasons or months, and investigate the differences between them. In this case, it is important to consider holidays, office hours, lecture hours, and so on, otherwise unrealistic results may occur.

It would be also possible to set the value to the surrounding environmental CO_2 concentration. In this case it would be possible to evaluate to which extend the values indoors diverge from the background concentration (ΔCO_2).

USE CASES

The described method is demonstrated by dynamic computer simulations of two use cases. A class room and a medium-sized lecture hall were chosen because of the known indoor air problems which typically occur here. The simulation models are based on real examples of lecture halls and classrooms as well as data from the literature "Lederer (2011), Macquarie University". All simulations were executed using IDA-ICE version 4.8. The outdoor CO_2 concentration was set to 410 ppm and the pressure coefficients were adapted for an exposed building site. The validation of the simulation results was completed using corresponding typical values from field measurements.

School Building

The school building model has a classroom located in Würzburg, Germany with the dimensions of 10 m × 7.5 m × 3 m (225 m^3) resulting in 75 m^2 floor area with a total capacity of 30 pupils and one teacher. The weekday occupancy lasts from 8 am to 1 pm as it is typical in many German schools. Direct ventilation is executed twice during that period, at 9:30-9:50 am and 11:20-11:30 am between April and September, and at 9:30-9:35 am and 11:20-11:25 am during the rest of the year. The summer ventilation time corresponds with the break, meaning that all occupants leave the room. At the beginning and at the end of the breaks the doors (1.25m × 2.25m) are opened for 5 minutes, resulting in additional ventilation. Also, a central air-handling unit is installed supplying the classroom constantly with 2 l per (sec·m^2) of fresh air. The buildings airtightness results in an infiltration air change rate of 0.1 h^{-1}, meaning that 10% of the air volume is exchanged within an hour due to leakage around windows and other openings, even though when windows are closed.

Since the mayor interest lies on the period of time when the classroom is in use, only these time-slots were observed.

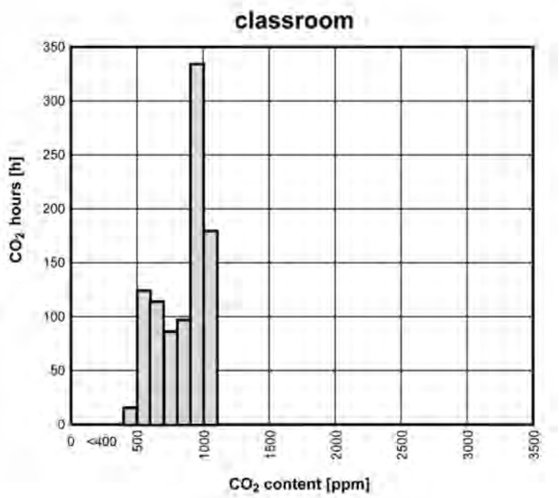

Figure 4. Distribution of CO_2 [ppm] between 8 am and 1 pm accumulated over one year in classroom with 30 pupils and 1 teacher.

The simulation shows that in the described classroom not always high air quality below 1000 ppm is achievable with the given boundary conditions. But with a maximum of not exceeding 1100 ppm the overall performance in terms of air quality definitely is sufficient. Figure 4 illustrates that most of the time CO_2 levels are below the 1000 ppm limit. Approximately, within 180 hours the CO_2 concentrations are above 1000 ppm, which correlates to almost one quarter of the total usage time. The maximum CO_2 concentration reached 1013 ppm. Thus, accurate integration of the CO_2 concentration hours with a threshold of 1000 ppm results in ~2447 ppm hours. This value can now be compared to other classrooms. By determining the maximum, mean and minimum possible ppm hours in the corresponding category, the value can also be categorized without references for comparison. The minimum value in the 1000 to 1100 ppm category is 0 ppm above the 1000 ppm threshold, the mean value is 50 ppm and the highest is 100 ppm. By multiplication with 180 hours this results in 0 ppm·h, 9000 ppm·h or 18 000 ppm·h. This example shows that the accurately calculated 2447 ppm hours are much closer to the lower value of the category. Thus, it can be deduced that exact integration is necessary especially if threshold values are exceeded hardly during the observation period.

If the indoor air quality were assessed exclusively by using CO_2-hours above 1000 ppm a typical evaluation would result in relative disadvantageous indoor air comfort. Due to the fact that during one quarter of the occupancy hours the indoor air quality exceeds the limit value of 1000 ppm. Applying the integration and using ppm hours for evaluation, it becomes clear that the indoor air comfort is rather good.

After recognizing, that being below a targeted limit of 1000 ppm, often can not be fulfilled constantly, the accumulation times of relatively high CO_2 concentrations are of special interest. By analyzing the carpet plot (Figure 2) it becomes clear that almost no problems occur during summer, whereas CO_2 contents above 1000 ppm are more common during winter. Thus, the ventilation habits during winter should be adapted, just by opening the windows more often or using mechanical ventilation systems correspondingly.

Lecture Hall

The lecture hall, used as a second example, has quite different periods of occupancy compared to the classroom. Furthermore, the lectures take place at various times during one day and then the occupancy density is generally higher and often less than 1 m² per person. Here a room was modelled, providing no option for direct ventilation, a lecture hall in a historic building in a city with windows nearby a very loud street and no sufficient air conditioning system. Such a room exists at our University building with a size of 11 m × 16 m × 4 m (704 m³). CO_2 concentrations up to 3100 ppm have been measured in the field. Similar concentrations were reproduced in the corresponding simulation with only 2 l per (sec·m²) of airflow generated by a central air-handling unit. Due to the usage of an insufficient air conditioning system, the general distribution of CO_2 contents and its values show only marginal seasonal differences, but instead, large daily variations. During the lecture period (07.01-12.02, 12.04-16.07, 18.10-23.12), the room is occupied by 200 students from 8 am to 12 am and from 2 pm to 6 pm. In this model, the infiltration rate is set to 0.5 h^{-1} due to windows that were made in the 1950ies. Two doors (each 2 m × 2 m) are opened half an hour before and after a lecture, providing additional ventilation towards a connected hallway. The results of the distribution of CO_2 hours in categories of 100 ppm width give a quite different impression compared to the classroom with much more usage hours at higher CO_2 levels (Figure 5).

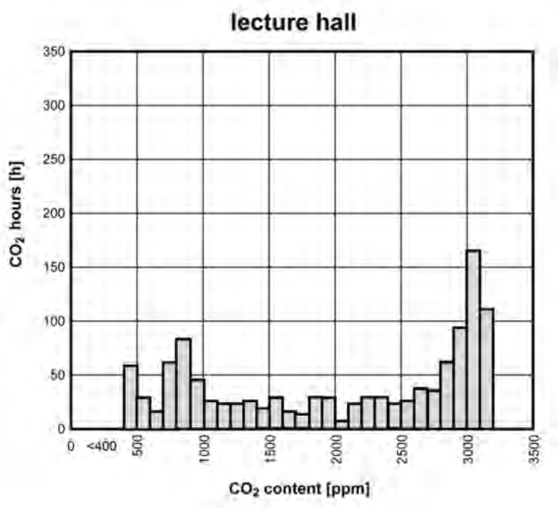

Figure 5. Distribution of CO_2 hours in categories [ppm] during lectures (8 am – 12 am and 2 pm - 6 pm) of a lecture hall with 200 occupied seats accumulated over one year.

When typical frequency distributions are utilized to depict the results over a whole year, again these figures may lead to misinterpretation. Because during a whole year a lot of hours exist with very low CO_2 contents, it seems that no severe problems occur during most of the time. The sum of all hours with values above 1000 ppm does not exceed ca. 20% (Figure 6).

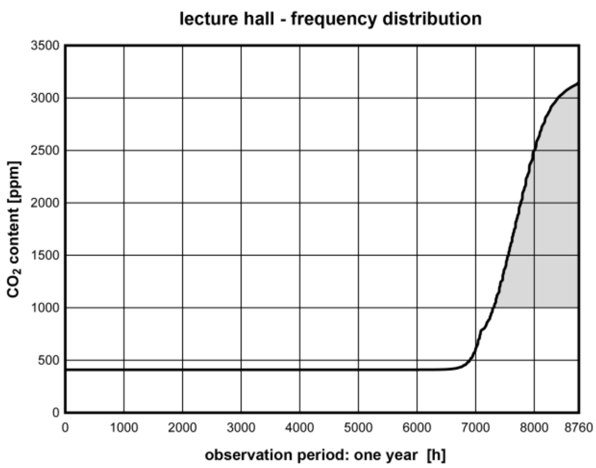

Figure 6. Frequency distribution of the CO_2-content within one year in the lecture hall. CO_2 hours above 1000 ppm are represented by the grey area.

It is much more practical to depict frequency distributions showing usage hours only (Figure 7). This kind of diagram provides a more realistic view of the real problems in the exemplary lecture hall with round about 80 % usage hours above 1000 ppm, 70 % usage hours above 1400 ppm and even 50 % usage hours above 2000 ppm.

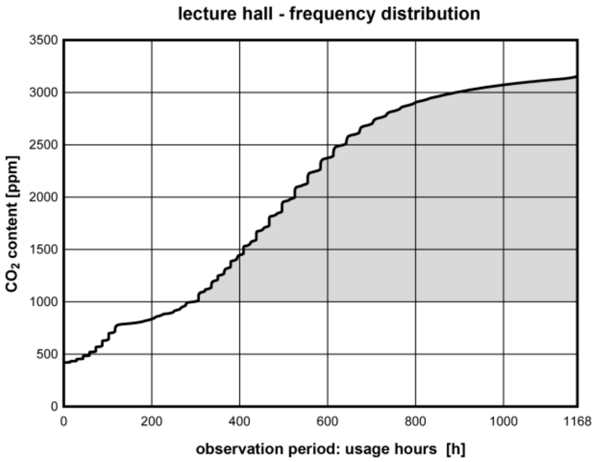

Figure 7. Frequency distribution of the CO_2-content within usage hours in the lecture hall. CO_2 hours above 1000 ppm are represented by the grey area.

The statistical evaluation of the duration of the prevailing CO_2 concentrations gives a first impression of the air-hygienic conditions of the room, but offers no precise assessment. For example, it can only be seen that 50% of the time the values are above 2000 ppm. It cannot be determined whether the values are far above the limit value of 2000 ppm or are near the limit value.

As long as average values of CO_2 concentrations over a whole year are used, misinterpretation is likely. Often the entire year is considered and no significant demand for action becomes evident, since the high concentrations within a lecture are getting compensated by hours without usage. In the case of the described lecture hall, this effect is especially severe due to the long holidays. The mean CO_2 concentration over one year is ~750 ppm, which is well below a critical concentration, ppm hours, however, reveal the severity of the problem. The focus has to lie on the hours of occupancy otherwise no significant demand for action seems to be necessary. Mean values over one whole year, often calculated with sophisticated dynamic building simulation tools are not helpful.

Even considering the mean value over just the period of occupancy often leads to misinterpretations. The differentiated distribution of the CO_2 concentrations is blurred to one value. However, it is particularly relevant how long which concentrations prevail.

CO_2 hours in categories of 100 ppm and the integration to ppm-hours during the lecture period, reveal the problem. In one year, the ppm hours during lecture period accumulate to 1 298 616 ppm·h, which is shown as the grey area in Figure 7. The ideal value would be zero, meaning at no time the CO_2 concentration exceeds the threshold of 1000 ppm. Roughly 874 hours are spent above this threshold value. Although the number of hours above the limit of 1000 ppm is five times higher than for the simulated classroom, ppm hours are almost 531 times higher, giving a clear indicator of insufficient air quality. During lectures, the CO_2 concentration rises up to more than 3100 ppm, which in many cases leads to severe health issues.

Here too, a calculation of only one estimated and unfortunately sometimes used category above 1000 ppm was carried out with limit values of 1000 ppm (lower limit) and 3200 ppm (upper limit). This results in 0 ppm, 1100 ppm, and 2200 ppm for recalculating ppm·h in terms of best, medium, and worst case scenarios to classify the integrated ppm hours. The results of 0 ppm·h, 961 400 ppm·h, and 1 922 800 ppm·h show that the precisely calculated integral of 1·298·616 ppm·h is oriented to the maximum possible ppm hours.

In the simulated classroom of the school building the number of ppm hours compared to the maximum value was quite small. The calculated ppm hours for the lecture hall resembles almost 70% of the maximum value, which is another indicator for overall bad air quality. Table 2 gives a quick overview of both use cases comparing percentages of CO_2 hours above 1000 ppm and the ppm-hours (threshold 1000 ppm) as well as the maximal, mean and minimal possible ppm-hours when more or less broad categories are used during the period of occupancy.

Table 2. CO_2-and ppm-hours above 1000 ppm of the use cases during the usage period.

use case	CO_2 hours above 1000 ppm [h]	ppm-hours [ppm·h]	max./ mean/ min. possible ppm-hours from category recalculation [ppm·h]
classroom	180	2447	max. 18 000
			mean 9000
			min. 0
lecture hall	874	1 298 616	max. 1 922 800
			mean 961 400
			min. 0

The presented values for CO_2 and ppm-hours will be more comparable once more buildings have been evaluated and more reference values are available. That could be summarized in tables for different scenarios and use cases, as it is the case for degree-hours in "ASHRAE: 2017".

RESULTS AND DISCUSSION

As the presented use cases show, the new method provides an easy understandable and applicable parameter given in ppm-hours for evaluating indoor air hygiene on the basis of CO_2 concentrations. In contrast to calculated mean values, high CO_2 contents are not compensated by low ones and cannot be summed up as CO_2-hours over a certain period of time only. For an accurate evaluation it is necessary to specify the period of occupancy and to focus only on those times.

There are still different threshold values for the evaluation of indoor air quality and the associated effects, such as headache "Pulimeno (2020)". Here, a general accepted and widely published threshold of 1000 ppm was used as basis for the considerations.

CONCLUSIONS AND FUTURE WORK

The CO_2 content is still a good indicator to represent the indoor air quality. A prerequisite therefore is that any CO_2 content inside a building higher than what is detected outdoors is mainly produced by human metabolism and generates accompanying volatile compounds. The latter are the main reasons for the sensation of bad air, concentration problems or health issues whereas CO_2 is an odorless and non-toxic gas as long as concentrations below 1 Vol.-% (10 000 ppm) occur. Manifold publications exist in which the CO_2 concentrations are analyzed and depicted in various diagrams. For a simple and easy applicable threshold value we suggest maximum ppm-hours of CO_2 over a certain period of time like lesson hours or office hours. Choosing the usage time and eliminating all other periods of time leads to a generally advantageous threshold value given in ppm·h.

This new unit may help to define a set of future limits which represent both (user) time dependency and intensity of higher CO_2-contents. For any kind of future standards it may be helpful to use ppm-hours during the usage hours as threshold values per working day or per working week. Moreover, the principle can be applied on any kind of measurements and thus, generate results that may lead to a better comparability and ranking.

Further improvements and specifications will only be possible together with practical tests in different use cases (schools, universities, office buildings, workshops and plants) and corresponding measurements of the CO_2-content over a usage time as well as precisely elaborated questionnaires to detect health issues and/or concentration problems. Further calculations like squared ppm-hours or new functions for ppm-hours, like exponential functions could be a first set of better modelling the perception and known health issues connected to high indoor CO_2 concentrations.

REFERENCES

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (2019). *Ventilation for Acceptable Indoor Air Quality*. (ANSI/ASHRAE 62.1-2019).

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.. (2017). *2017 ASHRAE® Handbook - Fundamentals (SI Edition).* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE).

Apte, M.G., Fisk, W.J. and Daisey, J.M. (2000). “Associations Between Indoor CO2 Concentrations and Sick Building Syndrome Symptoms in U.S.Office Buildings: An Analysis of the 1994–1996 BASE StudyData“. *Indoor Air*, 2000 (10), 245-257.

ASTM International (2018). *Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation* (ASTM D6245-18).

CO2levels.org (2021). *Real-time and historical CO2 levels - Atmospheric CO2 Levels Graph*, www.co2levels.org, Jan. 18th 2021.

Deutsches Institut für Normung, Europäische Norm (2007). *Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems* (DIN EN 13779-2007).

Erdmann, C. A. and Apte, M.G. (2004) “Mucous membrane and lower respiratory building related symptoms in relation to indoor carbon dioxide concentrations in the 100-building BASE dataset”. *Indoor Air*, 2004 (14), 127-134.

Fanger, P.O. (1988). “Olf and decipol: New units for perceived air quality”. *Building Services Engineering Research & Technology*, 9 (4), 155-157.

Federal Institute for Occupational Safety and Health (2012). *Technical rules for occupational health and safety – Ventilation* (available in German only) (ASR 3.6:2012).

Hellwig, R. T., Antretter, F., Holm, A., and Sedlbauer, K. (2009). “Investigations on indoor environmental conditions and natural ventilation in school buildings; Untersuchungen zum Raumklima und zur Fensterlueftung in Schulen”. *Bauphysik*, 31(2), 89-98. http://dx.doi.org/10.1002/bapi.200910013. Mar. 16th 2021.

Lederer, A. and Pampe, B. (2011). *Comparative study of selected guidelines in school construction* (available in German only). Montag Stiftung Urbane Räume gAG.

Macquarie University. *Property Design Guidelines: Lecture Room*. Macquarie University Sydney (Australia). http://property.mq.edu.au/space_types/teaching_spaces/lecture_room, Mar. 16th 2021.

Myhrvold, A. N., Olsen, E. and Lauridsen, O. (1996) "Indoor environment in Schools – Pupils health and performance in regard to CO_2 Concentrations". *Proceedings of 7th International Conference on Indoor Air Quality and Climate,* Nagoya (Japan), 21-26 July 1996.

Pettenkofer, M. (1858). *About the air change rate in residential buildings* (available in German only). Literarisch-Artistische Anstalt, Munich (Germany).

Pulimeno, M., Piscitelli, P., Colaazo, S., Colao, A. and Miani, A. (2020). "Indoor air quality at school and students' performance: Recommendations of the UNESCO Chair on Health Education and Sustainable Development & the Italian Society of Environmental Medicine (SIMA)". *Health Promotion Perspectives*, 10 (3), 169-174. doi: 10.34172/hpp.2020.29

Seppänen, O.A., Fisk, W.J. and Mendell, M.J. (1999). "Association of Ventilation Rates and CO_2 Concentrations with Health andOther Responses in Commercial and Institutional Buildings". *Indoor Air*, 1999 (9), 226-252.

Zhang, X., Wargocki, P., Lias, Z. and Thyregod, C. (2016). "Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance". *Indoor Air,* 2016. doi:10.1111/ina.12284