Guidance for standard evaluation procedures of indoor environmental parameters in schools

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A meta study "Fundamentals and concept development for the analysis of practice-oriented ventilation concepts for mechanical or window ventilation" shows with the focus on Germany an evaluative overview of the current state of research regarding to CO2-concentration during lessons in schools. For a systematised comparison of measurement results a number of options to the graphical presentation like Carpet-Plots, Box-Plots and scatter diagrams were examined. The analysis shows that caused by the different aims of the individual studies a direct comparison between different studies is hardly possible and many questions are still open. Future studies regarding this subject should be oriented towards the defined "ideal study" taking into consideration minimum requirements for the documented information and factors.

Keywords: ventilation, sustainable building, school, CO_2

Within the framework of the further development of the "Assessment System for Sustainable Building" (Bewertungssystem Nachhaltiges Bauen - short BNB) and the evaluation criteria profile for "indoor air hygiene" respectively, a number of parameters (CO_2 measurements, indoor climate, indoor thermal comfort, surveys on individual comfort experience) are evaluated for a number of field-tested ventilation solutions. With the focus on classrooms, recommendations for action for practice-oriented ventilation concepts as well as proposals for a well-argued evaluation approach in relation to the CO_2 requirements are established.

Background

The Federal Government of Germany has defined mandatory specifications for holistically improved buildings in the "Guideline for Sustainable Building" and the "Assessment System for Sustainable Building" (short BNB). Since October 2013, the BNB system is compulsory for the design and realisation of Federal Government buildings and was partially revised and updated in 2015. With regard to indoor air hygiene, particularly indoor air pollution by pollutants from building products and by carbon dioxide emissions from users are in focus.

Both the current normative requirement for outdoor air volume flow per person and the recommendations within the relevant workplace directive do not take into account all necessary parameters which govern the effectiveness of a suitable air exchange rate. From technical discussions and practical experience, it is known that poor ventilation leads to problems with respect to indoor air CO_2 concentration and, where appropriate, with respect to thermal comfort. This is especially true for rooms with high occupancy. It is also especially true for rooms with window ventilation but it affects also rooms with mechanical ventilation or a combination of both.

Concept

For the further development of BNB (evaluation system for sustainable buildings) the meta study "*Grundlagen- und Konzeptentwicklung für die Analyse von praxisgerechten Lüftungskonzepten bei mechanischer oder Fensterlüftung*" (fundamentals and concept development for the analysis of practice-oriented ventilation concepts for mechanical or window ventilation) shows with the focus on Germany an evaluative overview of the current (published) state of research regarding to CO_2-concentration during lessons in schools. 6 studies of the requested 15 studies could not be analysed, because no measurement values were available or no feedback was received. The raw data of the other 9 studies (see **Table 1**) could be prepared according to a standard procedure.

Table 1. Summary of the considered studies.

Considered studies	Brief description
Müller [Müller]	9 schools in Berlin were examined. They were different regarding to type of building, implemented restructuring measures and ventilation concepts. For a period of one day of class respectively one week of class random measurements in selected classrooms were done with regard to indoor air temperature, relative humidity, CO_2-concentration, sound pressure level and air velocity. Window ventilation as well as mechanical ventilation were considered.
Bischof [Bebersdorf, Bischof1, Bischof2]	10 schools in Erfurt were selected for this study. During the study the classrooms where not ventilated during the lessons, but only in the breaks in all classrooms for two days CO_2-concentrations, relative humidity and operative temperature and additionally in some classrooms the airborne germ rate was measured. The classrooms were ventilated by window ventilation, shaft ventilation and mechanical ventilation systems.
Fromme [Fromme1, Fromme2]	Schools located in Munich and in the District of Dachau were chosen for this study. During the measurement in the winter 46 schools (in total 62 days) and during the measurement in the summer 38 schools have been more closely analysed. CO_2-concentration, relative humidity, temperature and sometimes further air chemistry parameters were measured. So far as this is known, the classrooms were ventilated by window ventilation.
Lambertz [Lambertz]	This study took a closer look at a vocational college in Aachen after renovation. Different mechanical ventilation systems were compared among each other by measuring the CO_2-concentration, temperature, relative humidity, VOC emissions and energy consumption. For comparative purposes measurements with window ventilation were done bevor the renovation started.
Dietz/Sick [Dietz]	The primary school Hohen Neuendorf has been equipped with a hybrid ventilation (mechanical ventilation for the basic ventilation in combination with automatically opening windows and normal windows with a "ventilation signal light"). In two selected classrooms detailed parameters with regard to indoor air quality (CO_2-concentration, relative humidity, air temperature, radiation temperature and climate data) were recorded.
Bolsius [Bolsius]	The individual elements of the rehabilitation were assessed after the energy rehabilitation of the school complex in Olbersdorf. The energy-efficient school ventilation consists of supply box-type windows (windows with framed grounds) in combination with a CO_2 controlled exhaust ventilation system. For selected classrooms the CO_2-concentration, temperature, illuminance and outside climate were recorded.
Wargocki [Wargocki]	A Danish study took a closer look at two mechanically ventilated classrooms of a comprehensive school (age of pupils: 6 to 16 years). In a blind crossover design with new and soiled filters, high and low ventilation rates performance test, indoor air parameters (CO_2-concentration, temperature, relative humidity, etc.) and as well questionnaires were documented. The boundary conditions were defined for one week. The experiment was performed both in winter and in summer.
Lahrz [Lahrz]	A closer look at energetically rehabilitated schools in Berlin regarding the air quality during the heating period was taken in this study. Classrooms with window ventilation were considered as well as classrooms with mechanical ventilation. Parameters like carbon dioxide, temperature, relative humidity and diverse dust fractions were documented for a school week.
Birmili [Sinphonie]	Study to determine the „Leitfaden für die Innenraumhygiene in Schulgebäuden" (Guideline for Indoor Air Hygiene in schools) of the Federal Environmental Agency (UBA) as well as the EU joint project "Sinphonie" (further information are not available, because no publications are available)

To evaluate CO_2-concentrations measured over a longer period usefully, it is necessary to know the school hours. Studies where the school hours remained unknown are analysed by a VBA-based evaluation.

For a systematised comparison of measurement results a number of options to the graphical presentation like Carpet-Plots, Box-Plots and scatter diagrams were examined (see **Figure 1**). In this study the evaluation was carried out mainly with scatter diagrams for individual lessons or individual classrooms to avoid possible increased weighting caused of individual studies.

In the framework of this study the following measurements of CO_2-concentration exist:

- Window ventilation (5 studies): 652 lessons in 121 classrooms in at least 16 schools
- Hybrid ventilation (1 study): 375 lessons in 2 classrooms in 1 school
- Mechanical ventilation (5 studies): 513 lessons in 38 classrooms in 12 schools.

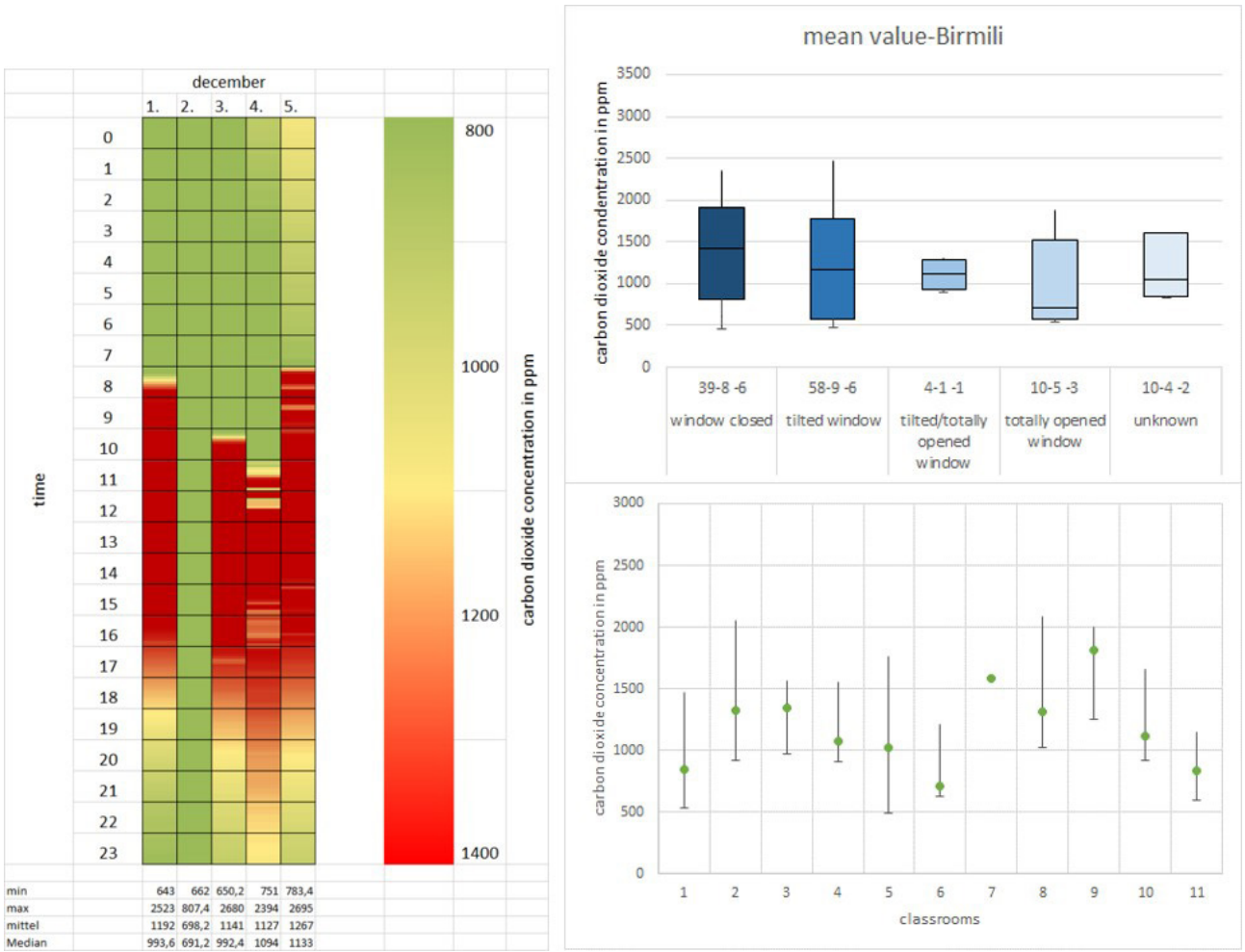

Figure 1. Exemplary presentation as Carpet-Plot (left) – Box-Plot (top right) – scatter diagram (on the bottom right).

Results

The following recommendations can be concluded for the individual ventilation concept due to the findings of the meta study as well as of the publications on individual studies and the participation in the AIVC-Workshop:

Window ventilation

Figure 2 shows that:

- 16% of the lessons have an arithmetic mean of the CO_2-concentration that meets the quality level 1 or 2 of BNB and comply with a positive BNB evaluation of the building and with the workplace regulation ASR A3.6. 35% of the lessons meet the quality level QN 0 (1000 ppm to 1400 ppm = 0 points according to BNB / non-compliance with ASR (workplace regulations)), 10% quality level QN 1 (800 to 1000 ppm) and 6% quality level QN 2 (< 800 ppm).
- The arithmetic mean of the CO_2-concentration depends clearly on time. In later hours of the day the probability that the arithmetic mean is under 1000 ppm decreases. (1. and 2. lesson with 23% and. 21% < 1000 ppm vs. 6. and 7. lesson with 7% respectively 3% < 1000 ppm).
- A clear dependence of the CO_2-concentration on the ventilation habits could not be shown. Lessons with tilted windows and closed windows lead to similar frequency of mean CO_2-concentrations under 1000 ppm (35% respectively 40%), whereas full opened windows lead to a decreased room air quality (only 15% of lessons with arithmetic mean < 1000 ppm). Causal should be that in the questionnaires the duration of ventilation processes was not documented.

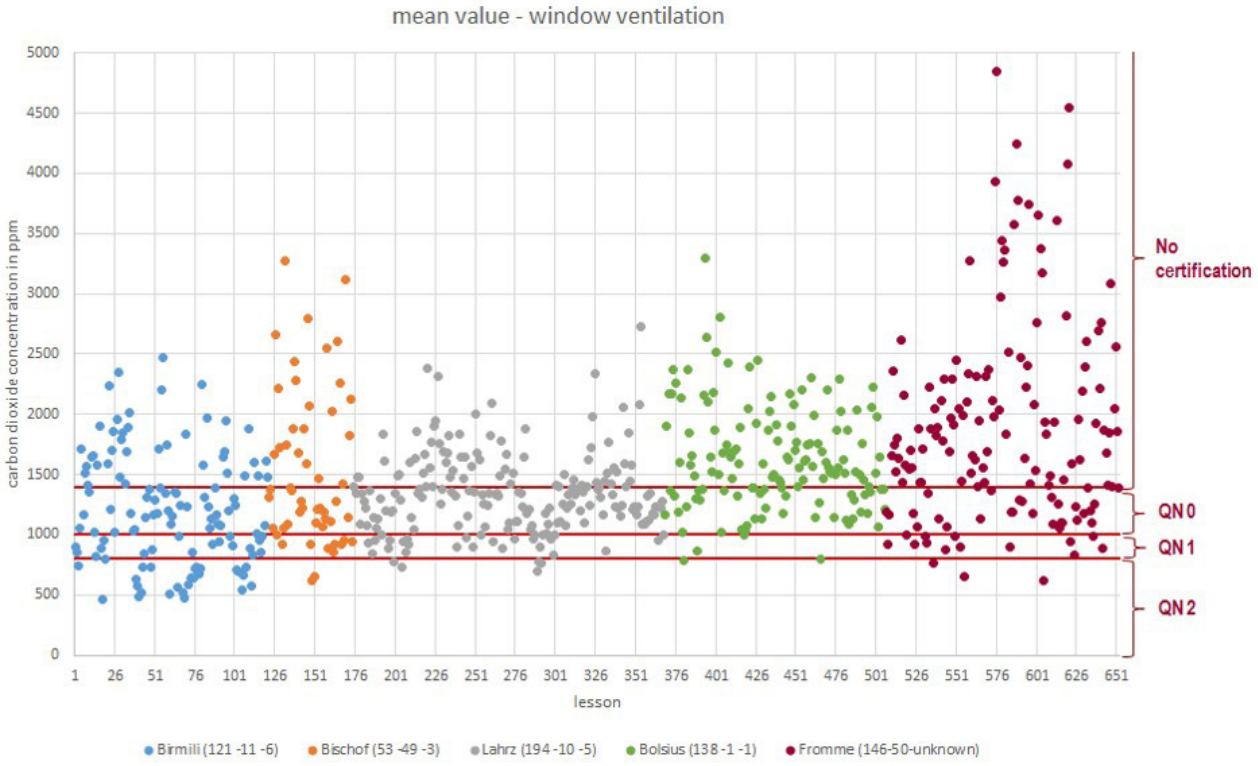

Figure 2. Scatter diagram of the arithmetic mean for window ventilation of the considered studies (lessons).

Hybrid ventilation

In the framework of this study hybrid ventilation is the combination of mechanical ventilation which is designed for the basic ventilation and a user-independent automatically window ventilation for example with servomotors at the windows.

Figure 3 shows that:

- 7% of the lessons have an arithmetic mean of the CO_2-concentration that meets the quality level 1 or 2 of BNB and comply with a positive BNB evaluation of the building and with the workplace regulation ASR A3.6. 42% of the lessons meet the quality level QN 0 (1000 ppm to 1400 ppm = 0 points according to BNB / non-compliance with ASR (workplace regulations)), 5% quality level QN 1 (800 to 1000 ppm) and 2% quality level QN 2 (< 800 ppm).
- The arithmetic mean of the CO_2-concentration depends clearly on time. In later hours of the day the probability that the arithmetic mean is under 1000 ppm decreases. (1. lesson with 52% < 1000 ppm vs. 5. lesson with 4% < 1000 ppm). The observed increase in the room air quality after the 5. lesson can be probably traced back to a change in use in the afternoon. Characteristic of elementary schools are also whole-day classes in smaller groups for example joint ventures or homework done under supervision.

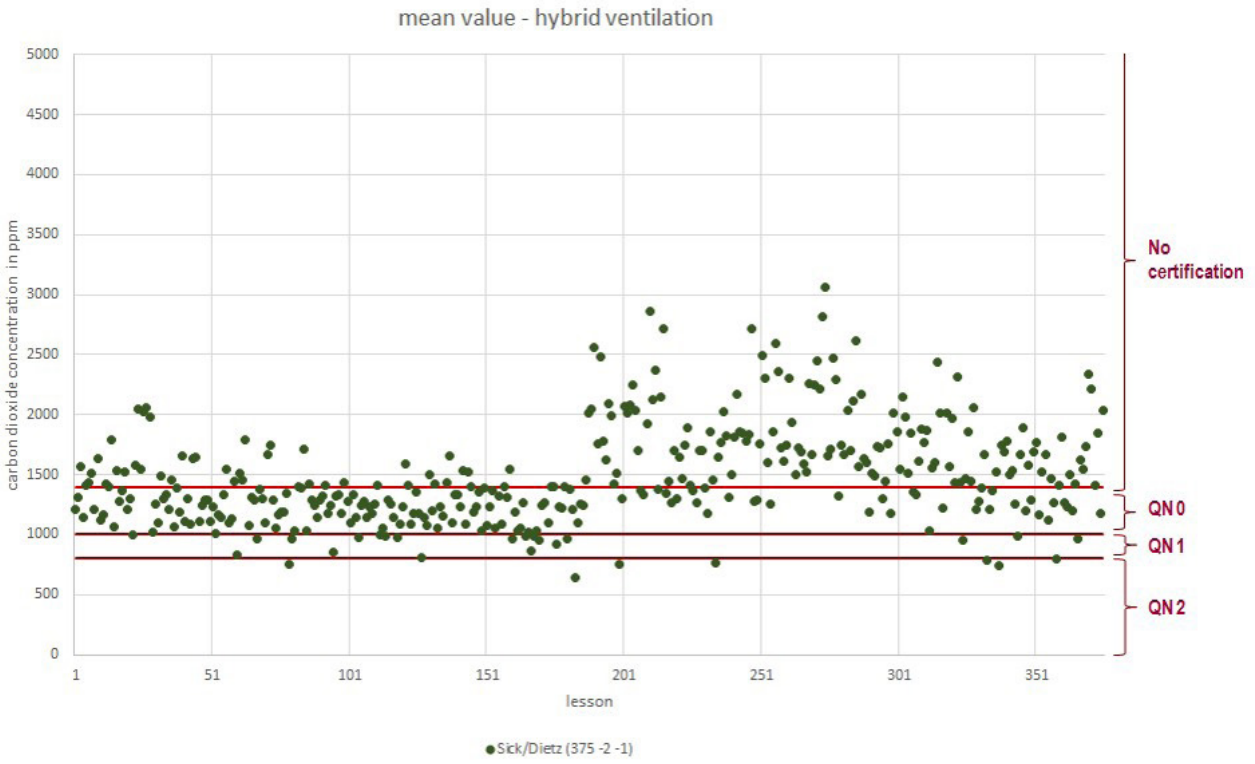

Figure 3. Scatter diagram of the arithmetic mean for hybrid ventilation of the considered studies (lessons)

Mechanical ventilation

Figure 4 shows that:

- 39% of the lessons have an arithmetic mean of the CO_2-concentration that meets the quality level 1 or 2 of BNB and earns a certification of the building according to BNB. 53% of the lessons meet the quality level QN 0 (1000 ppm to 1400 ppm = exclusion from building certification according to BNB / non-compliance with ASR (workplace regulations)), 27% quality level QN 1 (800 to 1000 ppm) and 12% quality level QN 2 (< 800 ppm).
- Based on arithmetic mean values and maximum values of the measured CO_2-concentration statistical parameters (median as well as 10. and 90. percentile) were determined for classrooms if there are measurement values for more than one lesson per classroom.

A comparative overview of the CO_2-concentrations shows that with mechanical ventilation 38% in the total of 513 considered lessons meet an average value under 1000 ppm, respectively under 1500 ppm are 94% of the lessons. The arithmetic mean of the CO_2-concentration of a lesson with window ventilation is under 1000 ppm in 16% of cases in the total of 652 considered lessons, 58% meet under 1500 ppm.

Regardless of the ventilation concept a reduction of number of students respectively an increase of classrooms, finally a larger area per person, results in lower CO_2-concentrations in classrooms.

Arithmetic mean values of the CO_2-concentration under 1000 ppm can be met for window ventilation and hybrid ventilation easiest in the early lessons. In the later lessons of the day a lower CO_2-concentration can

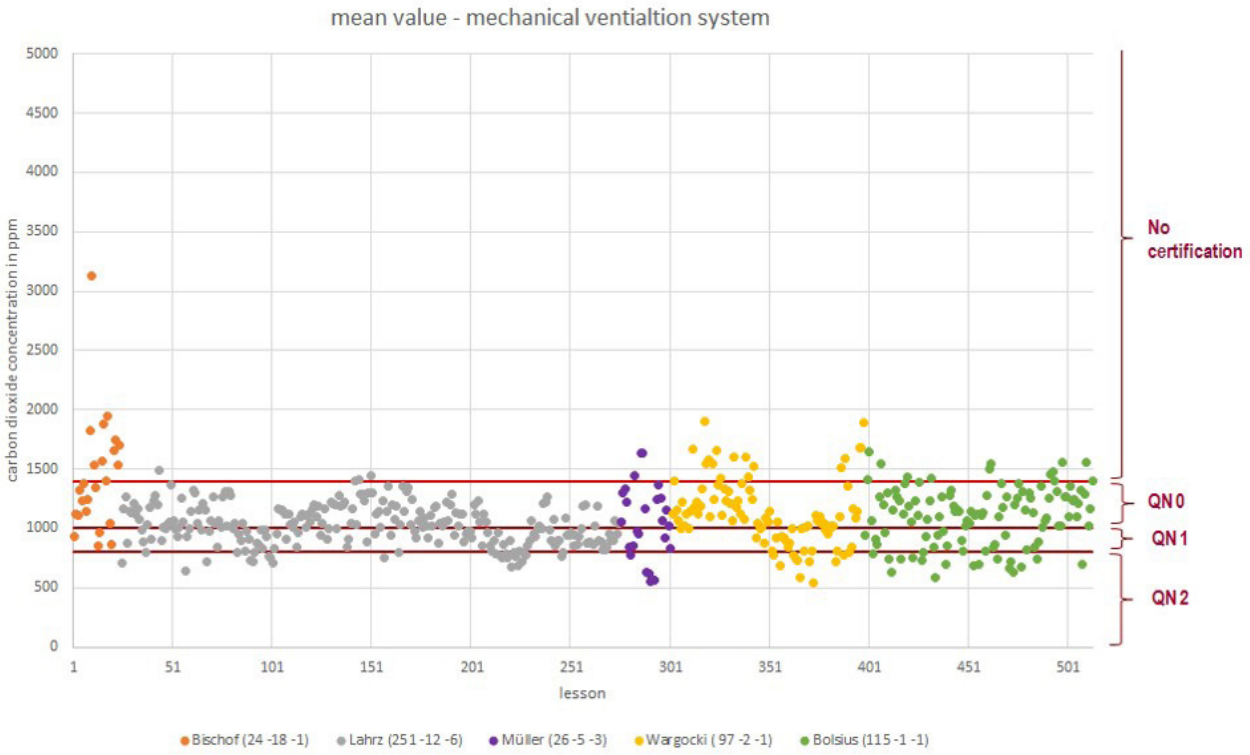

Figure 4. Scatter diagram of the arithmetic mean for mechanical ventilation of the considered studies (lessons).

only be reached taking into account certain boundary conditions like for example long break with intensive cross ventilation, a longer duration without teaching or smaller students per class.

Hybrid ventilation concepts combine mechanical ventilation with user-independent automatically window ventilation (for example motorised casements). The mechanical ventilation system provides a cost- and sound-optimised basic ventilation. This basic ventilation is supported by the automatically window ventilation in case of peak loads.

Ventilation systems should be designed for example according to DIN EN 13779 IDA 2, so no additional ventilation during the lesson is necessary. Organisational restrictions, discomfort of the persons in the room (temperature, draft risk) and disturbance through sound by window ventilation could be avoided with such a design. By optimising the control and operation mode of mechanical ventilation an improvement of the indoor air quality and an increase of acceptance can be reached.

In the current evaluation system BNB for school buildings the evaluation of the CO_2-concentration is made on the basis of requirements regarding to the (arithmetic) mean value and the maximum value of a lesson of 45 minutes. In future, the following extension options could be considered:

- Determination of maximum values based on the moving average over 5 minutes
- Determination of mean values based on the acceptable frequency of CO_2-values per lessons over a limit value (mathematical: percentile)
- Determination of a cumulative CO_2-exposure in ppmh (per lesson, school day, school week)
- Creation and if necessary BNB certification of a tool to classify according to BNB evaluation system

The analysis shows that caused by the different aims of the individual studies a direct comparison between different studies is hardly possible. For future studies, especially in the context of the evaluation and optimization of the BNB, the requirements for the parameters of an "ideal study" can be derived (see **Table 2**).

Table 2. Parameter of the „ideal study".

<table>
<tr><th colspan="2">General parameters</th></tr>
<tr><td colspan="2">– Ventilation system (window ventilation, mechanical ventilation, hybrid ventilation)
– Number of schools
– Type of school (primary school, secondary school)
– Number of classrooms (same number of ventilation system)
– Number of lessons (same number of lessons per classroom)
– Room occupancy (protocol)
– Age of pupils (class level)
– Area and volume of the classroom
– Lesson and break time
– Measurement period (for example one week in summer, winter, transition period) define minimum standards
– Measurement of outdoor air conditions where the school is located (wind, temperature, CO_2, etc.)
– Measurement of carbon dioxide in classrooms (one-minute interval)
– Logging of the situation in the breaks
– Uncertainty of the measurement technique, automation → Analysis not immediately after the commissioning, after all errors have been eliminated, stable running system
– Calibration of the measurement technique
– Measurement technique (arrangement, type, precision)
– Comfort (thermal comfort, sound…) as measurement or/and questionnaire</td></tr>
<tr><th>Additionally, with window ventilation</th><th>Additionally, with mechanical ventilation system</th></tr>
<tr><td>– Window profile (dimensions, number of casement, opening options [buttom hung, side-hung])
– documentation of ventilation with information about window position and duration of the ventilation for the lessons and the breaks including information which window is opened
– Kind of ventilation (one-sided or cross ventilation)
– Ventilation concept</td><td>– Information of the ventilation system (operating period, operating mode, contact switches at the windows, CO_2-control, combination of automatically casements etc.)
– Volume flow rate (development, actual state)
– Planned size (CO_2, temperature, volume flow etc.)</td></tr>
<tr><th colspan="2">Additionally, with hybrid ventilation</th></tr>
<tr><td colspan="2">Combination of the listed parameters of window ventilation and mechanical ventilation system
- planned volume flow rates (shares mechanical ventilation and window ventilation)</td></tr>
<tr><th colspan="2">Supplementary (optional) recommendations</th></tr>
<tr><td colspan="2">– Measurement of pollutants in classrooms (formaldehyde, radon, particulate matter etc.) (particulate matter PM based on the aerodynamic diameter 10 µm, 2,5 µm respectively 1 µm with PM10, PM2,5 and PM1classified)
– Performance tests</td></tr>
</table>

The research project shows that although so many different studies were implemented many questions are still open respectively have not been finally clarified yet. Answering these open questions should be tried in future studies. Such future studies regarding this subject should be oriented towards the defined "ideal study" taking into consideration minimum requirements for the documented information/factors. ■

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