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Assessment System for Sustainable Buildings of the German Government (BNB): Calculation tool for the ventilation rate and the resulting carbon dioxide concentration in the ambient air

Schütz H, Böttcher O

Federal Institute for Research on Building, Urban Affairs and Spatial Development
Straße des 17. Juni 112
10623 Berlin, Germany

Heidemarie.Schuetz@BBR.Bund.de, Olaf.Boettcher@BBR.Bund.de

Abstract. An important criterion for Assessment of the sustainability of buildings owned and occupied by the Federal Government is the indoor air quality. The stated aim is to avoid pollutants from construction products and unacceptable carbon dioxide concentrations. Regarding the limitation of the carbon dioxide concentration especially in rooms with high occupancy the challenge is to find a suitable ventilation concept. That concerns natural ventilation as well as mechanical ventilation or the combination of both.

Although there are normative rules for the required air change it is hardly verifiable during building planning whether the proportion of natural ventilation is sufficient in practice. Various evaluation reports in the past have shown that natural ventilation comparability mostly did not work, especially in rooms with high occupancy. In addition, it was also shown that comparability of the test results was usually not given and therefore no conclusions could be drawn on functioning ventilation concepts.

To be able to determine and evaluate the air exchange (in case of natural ventilation) and the resulting development of the carbon dioxide concentration in a room, the development of a calculation tool is part of a recent research project. The tool is used to calculate the outdoor air volume flow with natural ventilation depending on multiple parameters (as examples: wind, temperature, window size, window opening). In the same step CO_2 concentration for a certain number of CO_2 sources in the room will be determined automatically. Thereby the tool will be very helpful in an early stage of planning to find a proper ventilation concept. In addition to its use as a planning aid, the tool offers two different applications for assessing carbon dioxide concentration in a room: The calculation under specified conditions provides the opportunity to classify the expected carbon dioxide emissions as part of the assessment of sustainable buildings. The tool is also suitable for checking the air exchange under extreme climatic or other individually selectable conditions. At the end the calculation results of each individual constellation are shown in graphical diagrams.

1. Introduction

For many years sustainable building has been a natural part of the planning and construction processes for Buildings which are owned and used by the Federal Government. In order to achieve future requirements for holistically optimized buildings the Federal Building Ministry has set up binding quality requirements and quality criteria which are described and constantly being developed in the Sustainable Building Guide and the Sustainable Building Assessment System (BNB). The Division

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Sustainable Buildings in the Federal Institute of Research on Building, Urban Affairs and Spatial Development (BBSR) has the task to support the Federal Building Ministry in questions of sustainable construction. Therefor it elaborates the basics, is responsible for the continuation of the BNB and supervises corresponding research projects.

The BNB, which has been mandatory for federal building since October 2013, describes the building qualities in a transparent, comprehensible and verifiable manner. On the one hand it is an essential assessment system for defining the goals in the sustainability of a building and the integration of sustainability aspects into the planning process. On the other hand, the final assessment of sustainability after building completion leads to a certificate, which summarizes the evaluation of 46 individual criteria into an overall grade.

As human beings and their needs are an integral and important part of sustainable construction, equivalent to environmental and economic goals, the BNB also includes a number of criteria relating to the health and comfort of building users. The most important criterion in this regard is the indoor air quality [1] which assesses the pollutants from construction products and carbon dioxide emissions caused by room users. Failure to keep the boundary valuewill result in the exclusion of the BNB certification.

To ensure that the carbon dioxide concentration does not exceed the level of occupational health and safety regulations (max. 1000 ppm CO_2 in the interior – see also Table 1.) a sufficient air exchange is required.

Table 1. CO_2 concentration in the indoor air according to ASR [2] A3.6 and AIR [3].

CO_2 Concentration [ppm]	Hygienic Valuation	Measures
<1000	Hygienic inoffensive	• No further measures (as long as the room use causes no increase in concentration over 1000 ppm).
1000-2000	Hygienic conspicuous	• Check and improvement of airing habits • Preparing an airing plan (e.g.. to determine responsibilities) • Airing measures (e.g. outdoor air volume flow or raising air exchange)
>2000	Hygienic unacceptable	• Further measures necessary (z. B. enhanced airing, reduction of the number of people in the room)

2. Need for research / Purpose

Various evaluation reports in the past have shown that natural ventilation mostly did not work, especially in rooms with high occupancy. Nevertheless, for example school buildings in Germany are usually still built without a mechanical ventilation system. On the basis of this insight, existing measurement studies in German schools were analyzed on behalf of the BBSR according to the respective spatial conditions and the corresponding ventilation behavior. The aim was to draw conclusions about the practicability of various concepts of natural ventilation for rooms with difficult conditions [4]. The result of this investigation has shown that, although the measurements series presented the CO_2 concentrations, various determining boundary conditions of the respective room situation were not documented. Therefore, neither comparability nor evaluability were given and the desired conclusions impossible. But yet, it has been shown that a basic supply via a mechanical ventilation system in combination with natural ventilation seems quite practicable. Even with such so-called hybrid ventilation concepts, however, considering natural ventilation in planning is a particular challenge.

Although there are normative rules for the required outdoor air volume flow and for the calculation of required window opening area, in natural ventilation it is hardly verifiable during building planning whether the proportion of natural ventilation is sufficient in practice. By developing ventilation concepts

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the ventilation scenarios as well as the local spatial and climatic conditions (e.g. speed and direction of the wind, temperature difference inside / outside, internal thermal loads) are critical parameters for the calculation of volume flows achieved by natural ventilation and the resulting CO2 concentration in the room.

Therefore, such evidence is usually provided indirectly in compliance with the requirements of the standard. So far suitable tools for the development of effective ventilation concepts in the planning phase are missing. This results in a need for corresponding specialist information and a transparent tool for calculation carbon dioxide concentrations in the interior as an approximate planning assessment tool according to sustainable building.

The research project „Entwicklung von Handlungsempfehlungen für praxisgerechte Lüftungskonzepte und Entwicklung eines CO_2-Berechnungstools“[5] presented below is intended to develope instruments for planning the CO_2 concentrations during the phase of use and for verifying the functionality of different ventilation concepts. Furthermore, the possibility of an automated BNB assessment should be created. In detail, the following goals are to be achieved:

a) Identification of opportunities and limitations of natural, hybrid and mechanical ventilation under clearly defined parameters at different use scenarios and under considering all aspects of thermal comfort.

b) Development of a valuation tool through which both the required outside air volume flows and the resulting CO_2 concentrations can be determined especially for window ventilation and in combination with mechanical ventilation according to the respective framework conditions.

c) Drafting of descriptive recommendations for different ventilation concepts and room constellations which can be published within the framework of the BBSR.

3. Concept and method

The possibilities and limitations of natural ventilation in rooms with high occupancy are studied in an experimental test station under laboratory conditions. Through that the numerous factors influencing natural ventilation can be better controlled and logged. The test station simulates a typical classroom situation.The study series includes stationary and transient experiments.

3.1 Experimental test station

The basic structure of the test station (Figure 1) consists of two areas: The climate area 1 simulates the outdoor area and the climate area 2 forms the section of a typical classroom with a need for space of about 2 m²/ child. This area is equipped with rows of tables and people simulators which generate the heat load and CO_2 emissions per person. Both areas are separated by a wall in which the windows to be examined are installed. The selected depth of the test station allows the installation of up to 2 windows allowing experiments with openings of only one or both window axes can be performed.

Adjustable radiators are arranged below the windows. Through a decentralized ventilation system, the climatic area 2 can also be mechanically ventilated. The vertical ventilation system installed on the external wall has two ventilation openings in the parapet area and one exhaust opening in the ceiling area of the facade. Radiators and decentralized ventilation are not shown in Figure 1.

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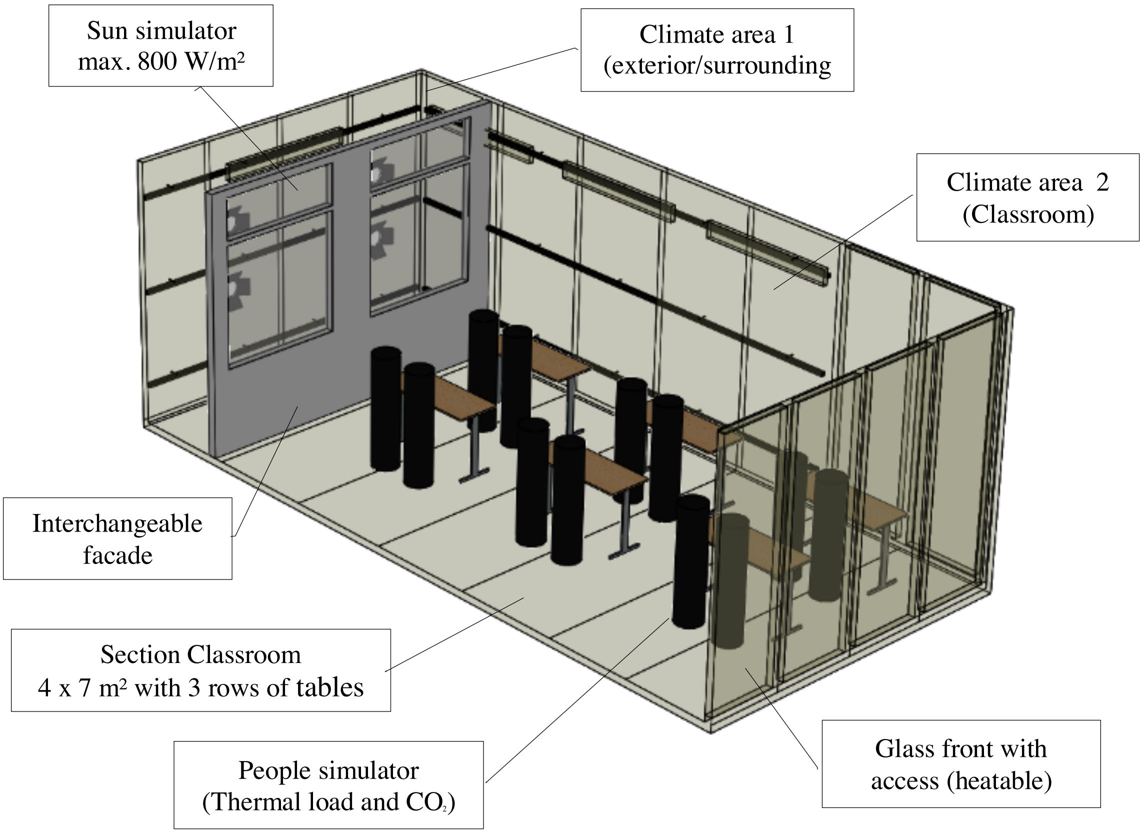

Figure 1. Basic setup of the test station.

The following data are recorded through these measurements:

- Temperature distribution in the classroom distributed up to 27 different points horizontally and vertically
- CO_2 distribution in space at up to 4 positions horizontally and in 2-3 levels at 4-6 positions each
- Thermal comfort at a defined measurement point (operating temperature, air velocity, CO_2)

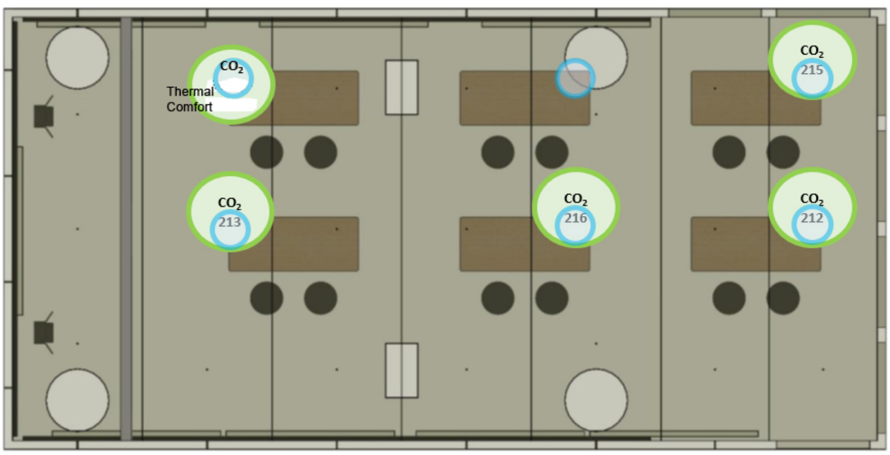

Figure 2. Measurement points ground plan.

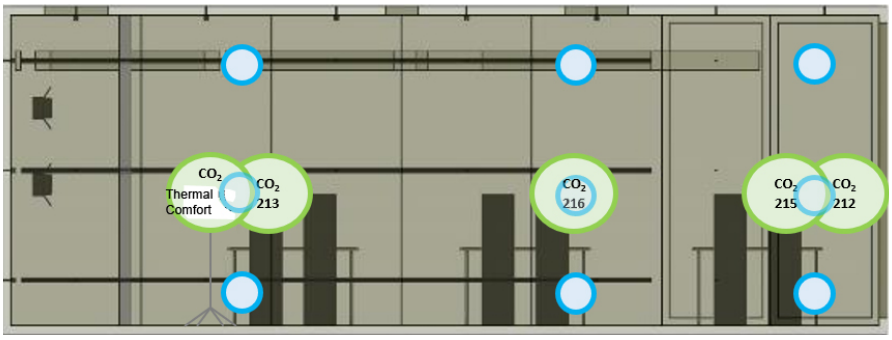

Figure 3. Measurement points sectional drawing.

In the studies on natural ventilation, the resulting volume flows were not measured directly, but indirectly determined by the tracer gas method via the decay of the CO_2 concentration in the indoor air.

3.2 Stationary test

The stationary tests are concerned with the effectiveness of different ventilation scenarios (natural ventilation, mechanical ventilation, hybrid ventilation) under constant conditions to determine the actual outside air volume flows and the resulting CO2-concentrations in the room.

The focus of these studies is initially on windows with turn and tilt wings, as this type of window is the most widespread. As a next step, other types of windows will be examined. In the test series, different boundary conditions vary, such as outside temperature (0 °C, 13 °C, 26 °C), solar heat input (with / without), wind speed (0 m/s, 3 m/s) and window opening positions.

The results for the outside air volume flows in the stationary tests with focus on natural ventilation are the base for the comparison which calculation approach is best suited for the calculation tool. The standards listed below are generally suitable for the calculation of volume flows from natural ventilation:

DIN EN 15242 [6]
DIN EN 16798-7 [7]
DIN SPEC 4108-4 (draft) [8]

Within the BNB assessment the calculation of the volume flow according to DIN EN 15242 [6] is mandatory. For the closer examination of the carbon dioxide concentration in the course of the day with freely selectable parameters no calculation rule has been defined yet in the BNB. For this purpose, prospectively the calculation formula which comes closest to the measurement results should be selected.

3.3 Transients tests

The series of measurements under transient conditions should provide insights about the spatial distribution and development of the CO_2 concentration over a longer period under certain ventilation scenarios and operating conditions. The results of the measurements are also used to evaluate the CO_2 tool which is used to calculate CO_2 developments over longer periods of time. Table 2 shows an example of a corresponding daily profile.

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Table 2. Usage profile of a lesson day for a transient test.

Time-Start	Time-End		Presence of Children	Occupancy	Window Position
08:00 am	08:45 am	1. period	yes	100%	all closed
08:45 am	08:50 am	5-min-break	yes	100%	upper part tilted, lower part 140 mm
08:50 am	09:35 am	2. period	yes	100%	all closed
09:35 am	09:55 am	20-min-break	yes	50%	upper part tilted, lower part 140 mm
09:55 am	10:40 am	3. period	yes	100%	all closed
10:40 am	10:45 am	5-min-break	yes	100%	upper part tilted, lower part 140 mm
10:45 am	11:30 am	4. period	yes	100%	all closed
11:30 am	12:00 am	30-min-break	no	0%	upper part tilted, lower part opened 90°
12:00 am	12:45 am	5. period	yes	100%	all closed
12:45 am	12:50 am	5-min-break	yes	100%	upper part tilted, lower part 140 mm
12:50 am	01:35 pm	6. period	yes	100%	all closed
01:35 pm	01:45 pm	10-min-break	yes	50%	upper part tilted, lower part 140 mm
01:45 pm	02:30 pm	7. period	yes	100%	all closed
02:30 pm	03:15 pm	8. period	yes	100%	all closed

The results lead to planning and action recommendations for the creation and implementation of ventilation concepts.

3.4 Tool development

The new CO_2 tool is based on Excel and serves as an instrument through which both the outside air volume flows and the CO_2 concentration in the indoor air can be determined. Particularly the contribution of pure natural ventilation is of interest, but also their contribution in combination with mechanical ventilation according to the respective framework. The tool has two modes:

a) Calculation of the CO_2 concentration according to BNB-criteria 3.1.3 (V2015) under fixed conditions
b) Calculation of the CO_2 concentration during the day under free conditions

Case a) serves to demonstrate the indoor CO2 concentration within a ventilation interval in accordance to the requirements of the corresponding BNB assessment criterion under following conditions.

- Intensive airing for 5 min. once after 60 Min. or during lessons once after 45 Min.
- Temperature difference inside / outside: 7 K
- Outside CO_2 concentration: 400 ppm
- One-sided room ventilation
- Average wind speed 3 m/s

The case of application b) also allows the CO2 concentration profile to be determined via a self-selected daily profile and / or under changed climatic conditions in order to be able to check different usage scenarios under different conditions.

4. Summary of the results

In the studies on the effectiveness of natural ventilation through windows with turn / tilt wings, 28 different configurations of the relevant variables were considered. In addition, 8 hybrid and 2 mechanical ventilation scenarios were examined. The number of experiments with mechanical ventilation could be kept low since the expected decrease in concentration occurred. To ensure result transferability to other types of windows corresponding series of tests are currently in progress.

4.1 Algorithm for the calculation of volume flows in natural ventilation

An essential aim of the studies on natural ventilation was to find out which of the existing calculation rules in the standards best reflects the results of the experiments. Therefore the experimentally determined volume flow of a test series was compared with the calculated volume flows of the three considered standards.

The summarized results in Table 3 show that the use of the calculation regulation from DIN SPEC 4108-8 (draft)[8] gives the smallest deviations from the experimental volume flows. The calculation of this standard is therefore used calculating the air volume flows for window ventilation in the CO_2 tool.

Table 3. Summary of the results with regard to frequency of deviations as well as the absolute and percentage deviation of the measured values from the calculated values.

Standards	Number of lowest Deviation total	Up from that	Down from that	Absolute Average Deviation in m³/h	Relative Average Deviation in %
DIN EN 15242	7	4	3	84	16
DIN EN 16498-7	5	3	2	266	54
DIN SPEC 4108-8 (draft)	16	2	14	20	15

4.2 CO_2 Tool

For natural ventilation, the calculation tool considers the algorithm for determining the volumetric flow chosen in Section 4.1. The volume flows of the mechanical ventilation are entered directly into the tool. The CO_2 concentration of the indoor air can be determined by a pollutant balance of the considered area at any point in time. The tool is separated into three sections:

- **Input section:** In this part all relevant parameters for every room, which has to be considered, are entered (e.g. climate, room geometry, windows, users, usage profile).
- **Calculation section:** The calculation of the respective carbon dioxide concertation curves for all individual rooms occurs after the completed data entry.
- **Result section:** Graphical representations of the carbon dioxide concentration profiles are shown (see Figure 4). In addition the BNB assessment is shown for the use case a).

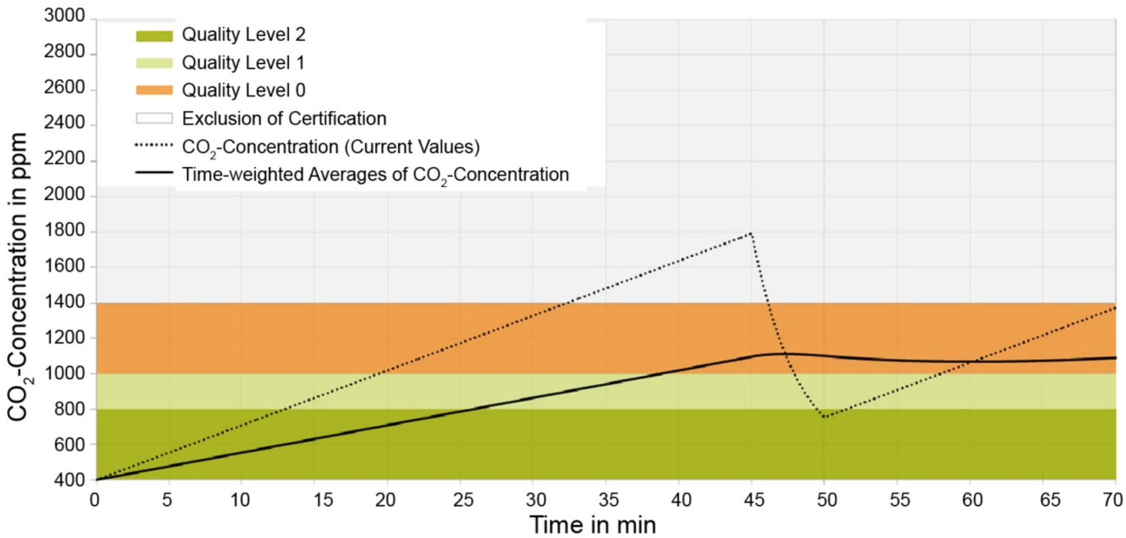

Figure 4. Graphical representation of the carbon dioxide trend and assignment of quality levels according to BNB 3.1.3 version 2015.

4.3 Results of the transient investigations during the course of the day
The CO_2 concentration developments during the day are represented very well based on the different studied usage and ventilation scenarios. Therefor any ventilation concepts can already be modelled in early planning phases and simultaneously its effectiveness is assessable. The exemplified ventilation concept, shown in Figure 5, illustrates that neither ventilation during breaks nor permanently tilted windows – over the entire teaching period – are sufficient to keep the hygienic CO_2 concentrations of max. 1000 ppm on average. Longer periods of intensive airing during lunch break causes a clear subsidence, but this is insufficient for lesson units over several hours.

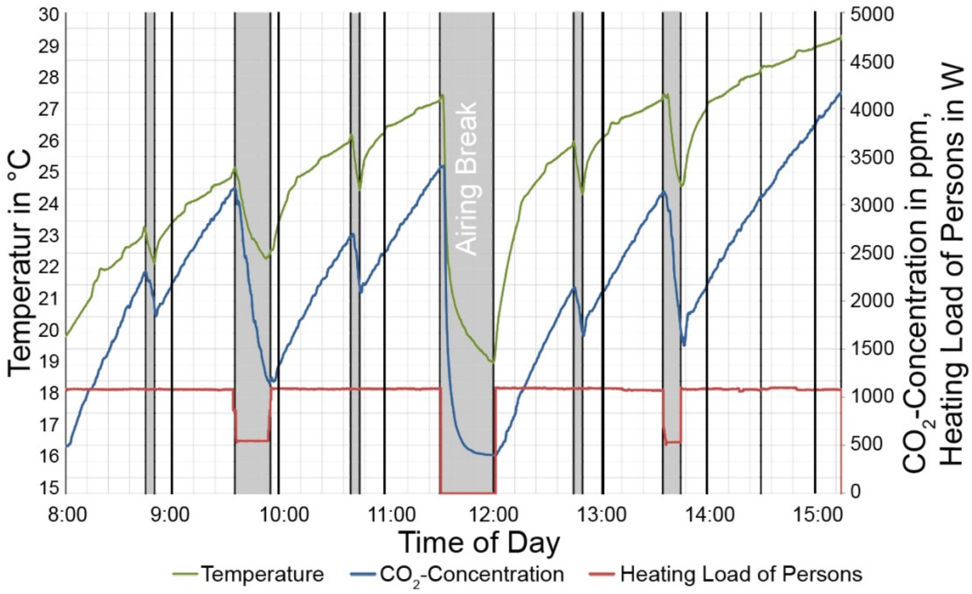

Figure 5. Average temperature and CO_2 concentration curve – transient test at 13 °C outside air temperature (see also Table 3.).

5. Conclusion and outlook

The result of the research project reveals for the first time a tool with user-friendly and intuitive applications, which can already be used during the planning phase and is also suitable for the proof of the expected carbon dioxide content in interiors within the framework of the BNB assessment. The advantage of this procedure of furnishing proof lies in the clarity, comparability and traceability due to its graphic and tabular evaluation. Furthermore, the assessment result is calculated automatically for each individual room and for the entire building at the same time.

All results of the project lead to a manual in the form of a BBSR brochure. Both basics and indicators for functioning ventilation concepts are presented and case studies are used to show which parameters influence the course of the CO2 concentration. Thereby the most problematic spatial constellations with a high occupancy rate are discussed in the example of typical school situations and possible solutions are shown with the help of the tool application.

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