Improving Air Quality in Schools (ImpAQS): a longitudinal study of ventilation and indoor air quality in Austrian classrooms – final report

Eds. Robert Scot McLeod, Christina Johanna Hopfe

Funding acknowledgement

The funding for this project was provided by the Austrian Federal Ministry for Education, Science and Research (Bundesministerium für Bildung, Wissenschaft und Forschung (BMBWF) in 2023. This ministry has since been restructured and the Austrian Federal Ministry of Education (Bundesministerium für Bildung) (BMB) was formed in 2025. We are grateful to the BMB and its predecessor the BMBWF for supporting this research study, which was conducted in line with its initiative #TruSD: 'Trust in Science and Democracy'.

Disclaimer

Bundesministerium
Bildung, Wissenschaft
und Forschung

Bundesministerium
Bildung

Improving Air Quality in Schools (ImpAQS): a longitudinal study of ventilation and indoor air quality in Austrian classrooms – final report

version v 1.0 (28th May 2025)

Cite this final report as:

McLeod, R.S., Hopfe, C.J., Villanova, L., Pollozhani, F., Gustin, M., Perkovic, T., Aznira, M. (2025) Improving Air Quality in Schools (ImpAQS): a longitudinal study of ventilation and indoor air quality in Austrian classrooms – executive summary. Graz, Austria: Graz University of Technology. ISBN 978-3-99161-055-7, DOI 10.3217/978-3-99161-055-7. Available at https://www.tugraz.at/en/institutes/ibpsc/research/research-projects/completed-projects

Editors:	Robert Scot McLeod, ORCID 0000-0001-7204-6268 Christina Johanna Hopfe, ORCID 0000-0002-8921-2098
Editorial support:	Fatos Pollozhani
Authors:	Robert S McLeod, Christina J Hopfe, Laura Villanova, Fatos Pollozhani, Matej Gustin, Tijana Perkovic, Meita Aznira
Layout:	Robert Scot McLeod,
Cover picture:	Shutterstock ID: 466062413, Ground Picture, serial number: US-071A032A5-1

2025 Verlag der Technischen Universität Graz
www.tugraz-verlag.at

ISBN 978-3-99161-055-7
DOI 10.3217/978-3-99161-055-7

Executive Summary

ImpAQS (**Imp**roving **A**ir **Q**uality in **S**chools) investigated CO_2 concentrations, ventilation rates, and indoor and outdoor environmental data in 1200 Austrian classrooms spread over the 9 federal regions of Austria, across the 2023–24 school year. The study also evaluated the benefit of installing CO_2 monitors in classrooms as a means of improving ventilation practices and reducing the risk of airborne disease transmission. The study was funded by the BMBWF and is one of the largest and most comprehensive studies of ventilation and air quality carried out in Austrian schools to date.

The CO_2 data recorded by the ImpAQS project indicates *a widespread failure to comply with existing European and Austrian ventilation guidelines in schools*. The results showed that less than 25% of the schools are able to maintain an annual daily mean CO_2 concentration below the existing 1000 ppm (BMK, 2024) guideline threshold. Whilst for more than a quarter of the school year the recommended minimum outdoor airflow rate of 4 l/(s·person) (ÖNORM EN 16798-1:2024) is not met. During the winter season, the situation is even worse with less than 12% of schools maintaining a daily mean CO_2 concentration below the 1000 ppm threshold.

Significant disparities exist between schools where the daily mean difference between the 10 best and 10 worst performing schools is more than 1000 ppm in winter-time. Significant differences were also found on the basis of school type, federal state, and ventilation type. Notably, there is not a single school that performed consistently within the existing guidelines all-year around. In the worst cases hourly mean CO_2 values were found to be nearly 7-times higher than the guideline threshold (exceeding 6900 ppm) over some teaching periods (with even higher values recorded over shorter time intervals).

Qualitative surveys, carried out alongside the quantitative monitoring, showed that ventilation practices are strongly influenced by two main factors: the room air temperature and external noise. In many cases, physical obstructions were found to hinder appropriate natural ventilation (including window restrictors or unsecured inward-opening windows colliding with desks). Factors that influence compliance with CO_2 targets include the occupant density (number of students per classroom), external and internal air temperatures, and the ventilation method (mechanical or natural). For example, when the outside air temperatures are 10 °C or below, mechanically ventilated classrooms have on average 450–600 ppm lower daily mean CO_2 concentrations than naturally ventilated schools. Whilst mechanically ventilated schools performed better overall, three naturally ventilated schools ranked amongst the top 10 best-performing schools. Their low CO_2 readings can be traced back to the occupants' diligent window opening behaviour, higher than average spatial densities in classrooms (more than 3.2 m^2 per child) and well-designed window openings. It should also be noted that in some cases, mechanical ventilation systems were permanently switched-off, due to high running costs, highlighting a major barrier to their use in financially constrained schools.

Four key outdoor air pollutants ($PM_{2.5}$, PM_{10}, NO_2, O_3) were assessed in proximity to the ImpAQS schools using data from the Federal Environment Agency (UBA). The results show that the majority of measurement stations exceed the World Health Organisation (WHO) air quality guidelines reference levels for each pollutant, with some locations having mean values above thresholds which should not be breached more than 3 times per year. Despite these findings, teachers did not identify outdoor pollution to be a major hindrance to opening windows.

This situation suggests that the use of mechanical ventilation with appropriate particulate and/or activated carbon filters should be recommended to help safeguard the health of students and staff in the worst affected schools.

Analytical infection risk modelling of the SARS-CoV-2 virus showed that classrooms with lower annual mean CO_2 rates (and correspondingly higher airflow rates) have a much lower year-around infection risk. The results showed that increasing the ventilation rate from 7.4 l/(s·person), the annual mean of daily ventilation rates in the sample, to 14 l/(s·person) could reduce the risk of at least one person in a classroom being infected during the school day by approximately 30%. That risk could be further reduced by about 45% using higher 'health-based' ventilation rates (such as those advocated by ASHRAE Standard: 241) with a minimum equivalent airflow rate of 20 l/(s·person), wherein a component of that airflow can also be sourced from recirculating air cleaned by HEPA filters. These calculations assume one infected person in a classroom of 25 people, a worst-case scenario that would only occur under certain conditions, such as during a peak of a COVID-19 wave. As such, these estimates represent potential risks rather than daily in-situ probabilities. Pearson correlation analysis revealed a moderate association between infection risk and absenteeism (0.554) across the school year. This finding may have been influenced by the reduced absenteeism dataset (wherein only 40% of schools submitted information) and by the fact that only associations with SARS-CoV-2 were investigated, but not other circulating airborne viruses.

The use of visible CO_2 monitors and ventilation guidance made a significant difference to the ventilation practices in naturally ventilated classrooms compared to similar classrooms without any visible information. In January, a quarter of naturally ventilated classes with visible CO_2 monitors reported CO_2 concentrations that were 500 ppm lower than the corresponding classrooms without visible monitors. This finding demonstrates the value of using CO_2 sensors (with visual alerting systems), particularly during the colder months, in naturally ventilated classrooms.

Generally, the installation of CO_2 monitors was perceived very positively by the majority of classroom teachers and school directors. An increase in the number of classroom CO_2 champions (students alerting teachers to ventilate on a regular basis) was seen over the project duration. It should be noted that no additional training was provided to the participating classes in relation to the correct use of the CO_2 sensor or ventilation strategies. Therefore, it is anticipated that with appropriate training, the full benefit of students and teachers engaging in the ventilation process is likely to be much greater than demonstrated in the outcomes of this study.

The findings of the ImpAQS study have national and European significance in raising awareness of the urgent need to improve ventilation and air quality in schools. The results provide actionable information that should be used to improve learning outcomes, health and well-being of school students and staff across Austria. Compliance with existing guidelines and standards should be seen as the first step towards a future where 'health-based' ventilation practices become the norm. To avoid further inequities in existing ventilation practices, the authors believe that responsibility for this transition cannot be delegated to individual schools but must be part of a nationally coordinated process.

DOI 10.3217/978-3-99161-055-7-001

Table of Contents

Abbreviations, symbols and nomenclature

List of Abbreviations

Abbreviation	Definition
ACH	Air changes per hour
ACR	Air change rate
AER	Air exchange rate[1]
AHU	Air handling unit
AQG	Air quality guideline
BMB	Federal Ministry of Education
BMBWF	Federal Ministry of Education, Science and Research
BMK	Ministry of Climate Action and Energy
BMR	Basal metabolic rate
BMSGPK	Federal Ministry for Social Affairs, Health, Care and Consumer Protection
C	Control classroom
CI	Confidence interval
COVID-19	Coronavirus disease 2019
DCV	Demand controlled ventilation
ECA_i	Equivalent clean airflow rate for infection risk mitigation
EEA	European Environment Agency
EPA	Environmental protection agency(EPA, 2024)
Eq.	Equation
Fig.	Figure
GDPR	General Data Protection Regulations
IA	Illness absence
IAQ	Indoor air quality
IEQ	Indoor environmental quality
ImpAQS	Improving Air Quality in Schools research project
IQS	Federal Institute for Quality Assurance in Austrian Education
IRMM	Infection risk management model
HEPA	High-efficiency particulate air
MEMS	Micro-electromechanical systems
MPIC	Max Planck Institute for Chemistry
MV	Mechanical ventilation
MVHR	Mechanical ventilation with heat recovery
NADR	Non-infectious Air Delivery Rates
NDIR	Nondispersive infrared
NFC	Near-field communication
NV	Natural ventilation
ODA	Outdoor air quality
p.l.	Personal load
PNC	Particle number concentration
PM	Particulate matter

[1] Note: air exchange rate (AER) is a potentially misleading term as it implies that air is simply transferred between the outdoors and the occupied space, when in fact air can pass through unconditioned spaces, wall cavities, etc. Air change rate (ACR) is a better term to use for this reason.

RAG	Red, Amber, Green (visual alerting system)
REGIONS 1. BUR 2. CAR 3. LOA 4. UPA 5. SAL 6. STY 7. TYR 8. VOR 9. VIE	 1. Burgenland 2. Carinthia 3. Lower Austria 4. Upper Austria 5. Salzburg 6. Styria 7. Tyrol 8. Vorarlberg 9. Vienna
RH	Relative humidity
RNA	Ribonucleic acid
RR	Relative risk
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SCHOOL TYPES: 1. ABHS 2. KMS 3. MS 4. SS 5. TGS 6. VS 7. WS	 1. General secondary school 2. Commercial middle or higher school 3. Middle school 4. Special school 5. Technical and commercial middle or higher school 6. Elementary school 7. Business vocational middle or higher school
SBS	Sick building syndrome
T	Test classroom
Tbl.	Table
TVOCs	Total volatile organic compounds
UFP	Ultra fine particles
USD	United States dollar
UV	Ultra-violet
VOC	Volatile organic compound
VR	Ventilation rate

List of chemical nomenclature

Abbreviation	Definition
CO_2	Carbon dioxide
NO_2	Nitrogen dioxide
O_3	Ozone
PM_1	Particulate matter ≤ 1 micron diameter
$PM_{2.5}$	Particulate matter ≤ 2.5 microns diameter
PM_{10}	Particulate matter ≤ 10 microns diameter

List of symbols and nomenclature

Symbols and nomenclature	Definition
±	Plus or minus
Δ	Difference between two values
∫	Integral
∑	Sum
·	Multiplication
C	CO_2 concentration in the space
$\mathrm{C_{out}}$	Ambient outdoor CO_2 concentration
$\mathrm{C_{ss}}$	Steady state indoor CO_2 concentration
$\mathrm{c_v}$	Viral load
d	The derivative
D_{50}	Infective dose [-]
ε_v	Ventilation effectiveness [-]
G	Human CO_2 generation rate [l/s]
vol%	Percentage by volume
$\mathrm{P_{RNA}}$	Infection risk for a single viral particle [-]
Q	Supply airflow rate [l/s]
t	Time [h]
$\mathrm{t_{virus}}$	Virus lifetime (e-folding time) in aerosol [h]
V	Volume of a space [l]

List of units

Unit	Parameter
°C	Degrees Celsius
Genome copies per person/day·10^6	Genome copies (in millions) per inhabitant per day
hPa	Air pressure in hectopascals
l/(h·person)	CO_2 production in litres per hour per person
l/(s·m^2)	Ventilation airflow rate in litres per second per square meter
l/(s·person)	Ventilation airflow rate in litres per second per person
l/(m^2·h)	CO_2 production in litres per square meter per hour
m^2/person	Occupancy in square meters per person
m^3/h	Airflow rate in cubic meters per hour
ppb	Concentration in parts per billion
ppm	Concentration in parts per million
µm	Micrometer
µg/m^3	Concentration in micrograms per cubic meter
µmol/mol	Volume fraction in micromoles per mole

1 Introduction

There are many reasons why it is important to gain a better understanding of the air quality, ventilation and indoor environmental conditions in schools. In combination these factors significantly influence the quality of the learning environment as well as impacting on the health, wellbeing, and performance of students and staff. By monitored and analysing data from a large number of schools, spread throughout the whole of Austria, the ImpAQS study set out to provide a better understanding of these issues at a national and regional level. Coupling this environmental data with the personal insights of school directors and teachers provides a more nuanced and rounded understanding of the complex social factors influencing the data. Evaluating these social and technical perspectives in tandem brings a deeper understanding of the causes and potential solutions to these complex challenges. This evidence-based approach provides information essential to the development of informed responses, which is vital for the realisation of successful long-term outcomes.

1.1 Purpose and scope of this report

This report marks the final stage of the ImpAQS (Improving Air Quality in Schools) research study which was funded by the former Ministry of Education, Science and Research (BMBWF) now Ministry of Education (BMB). The report consciously avoids naming the individual schools which participated in the study, a point which was confirmed to the participating schools before the study began. Creating unnecessary debate about which schools scored 'better' or 'worse' than others would serve little purpose, whilst potentially alienating schools from participating in further research and undertaking remedial actions. The participating school directors will subsequently receive bespoke reports, from the BMB, informing them of their school's results and advising them of any recommended actions. The main purpose of this research study is to draw useful conclusions at the national and regional level and to make general recommendations on the air quality and ventilation practices in Austrian schools. This information is needed to design effective policies and programmes that will support the transition towards the provision of uniformly high air quality in all Austrian schools.

ImpAQS is the first longitudinal study to investigate ventilation and indoor air quality (IAQ) in a large sample of Austrian school classrooms. The project involved monitoring carbon dioxide (CO_2) concentrations, air temperatures, and relative humidity (RH) over a 12 month period (from September 2023 to September 2024) in 1,200 classrooms, and outdoor areas in 120 schools, spread across the 9 federal regions of Austria. This represents approximately 240,000 school days of data and over 570 million individual data points. To supplement this information, analysis of outdoor air pollutants in proximity to the schools was carried out based on the analysis of four important contaminants (PM2.5, PM10, O_3, and NO_2) using data provided by the Austrian Environment Agency (UBA). Additional anonymised data, regarding school absenteeism was gathered to gain a better understanding of the relationship between indoor air quality, ventilation and attendance at the school and classroom level. The empirical data was further evaluated using analytical and numerical models to derive secondary variables, including the ventilation airflow rates in each classroom and information concerning the relative risk of infectious airborne disease transmission. In addition to the quantitative data, described above, qualitative data was gathered through four focused surveys (involving school directors and classroom teachers) in order to incorporate end-user perspectives.

This report is primarily targeted at relevant policy makers at the Austrian federal level and their European counterparts, as well as the regional and local authorities responsible for managing air quality in the individual school districts. At the individual school level, school facility managers (responsible for the day-to-day maintenance and operation of ventilation systems and IAQ monitoring) as well as school directors/headteachers and teachers (responsible for the health and wellbeing of their staff and students) should take a keen interest in this report, as well as their subsequent individual school reports. A further target group, that may benefit from the findings and recommendations of this study, includes school owners, building designers and managers (responsible for the design, construction, renovation and upkeep of school buildings and their associated ventilation systems). Finally, this report should be of interest to the students, who spend a large percentage of their waking lives in school buildings, as well as their parents and guardians.

The scope of work addressed here covers work packages AP3 – AP6 (Appendix A1) as outlined in the ImpAQS project proposal. For completeness and comprehension there is some minor duplication of reporting between this report and the ImpAQS interim project report (McLeod et al., 2023) in relation to the description of the project planning, equipment calibration and quality assurance processes. This is intentional and was designed such that the final report could be read independently of the interim report. The key phases of the project are described in Section 3 and illustrated in Fig. 3-2.

1.2 Drivers and barriers to improving indoor air quality in schools

Schools are designed to create an optimal environment for the intellectual, emotional and physical development of children and adolescents. Pupils and staff typically spend around 12–15% of their lives inside a school building (EPA, 2009; Parinduri, 2014) which is more than in any other place other than their home. It is well known that good indoor air quality (IAQ) influences the short and long-term performance, concentration, academic attainment, health and comfort of school pupils and staff (Mendell and Heath, 2005; Sadrizadeh et al., 2022). Despite this awareness, the provision of good IAQ remains elusive in many classrooms. In part this may be because classrooms are more densely occupied than almost any other workplace, with occupant densities around four times higher than a typical office building (Katafygiotou and Serghides, 2014). An additional challenge lies in the fact that the majority of European schools are naturally ventilated (Csobod et al., 2014), and therefore typically lacking any automated means of regulating or monitoring the incoming fresh-air supply. Moreover, guidance on the provision of good air quality in schools is scant and often inconsistent; alongside which, there is an absence of regulatory mechanisms by which to ensure best practice is maintained.

Numerous studies have attempted to quantify the negative impact of poor IAQ on human health, wellbeing, and productivity in the built environment (Seppänen et al., 2006; Morawska, Marks, and Monty 2022; LBNL 2024). The importance of air quality and ventilation in school buildings, in relation to child health and academic performance has also been extensively studied (Mendell, 2005; Mendell et al., 2013; Csobod, 2014; Haverinen-Shaughnessy et al. 2015; Petersen et al., 2016; Wargocki et al., 2020). Summarising the findings of more than 20 peer reviewed studies, investigating associations between health, performance, and absenteeism with ventilation rates and/or carbon dioxide concentrations, Fisk (2017, p1040) concluded that, "*There is compelling evidence, from both cross-sectional and intervention studies, of an association of increased student performance with increased ventilation rates.*" Fisk also noted that, "*There is evidence that reduced respiratory health effects and reduced student absence are associated with increased ventilation rates.*"

Since the COVID-19 pandemic began, in 2019, there have been recurrent waves of the disease across Europe, and most of the world. Despite suggestions that the Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) virus would eventually take on a seasonal pattern (much like influenza) and diminish in intensity this has not occurred to date, and the virus has continued to mutate and evolve. Whilst the majority of recurrent SARS-CoV-2 infections remain "mild" or asymptomatic, some children may develop severe disease after infection with COVID-19, including multi-system inflammatory syndrome in children (MIS-C) (ECDC, 2023). Post-COVID conditions (i.e. long-COVID) can also affect people of all ages, and the prevalence of those reporting one or more symptoms 18-months after a SARS-CoV-2 infection is estimated at around 10% (Hastie et al., 2023). Moreover, the long term health impacts associated with repeated SARS-CoV-2 infections, which include increased risk of chronic respiratory, cardiovascular, neuropsychiatric, and autoimmune diseases (Greer et al., 2022; Wrona and Skrypnik, 2022; Heidemann et al., 2023) suggest that caution is warranted to try and minimise repeated infections. Evidence from the Austrian Federal wastewater monitoring system (BSGPK, 2024) currently indicates that, on average, two or more waves occur per year, with the highest peak to date having occurred in late 2023 (Figure 1-1).

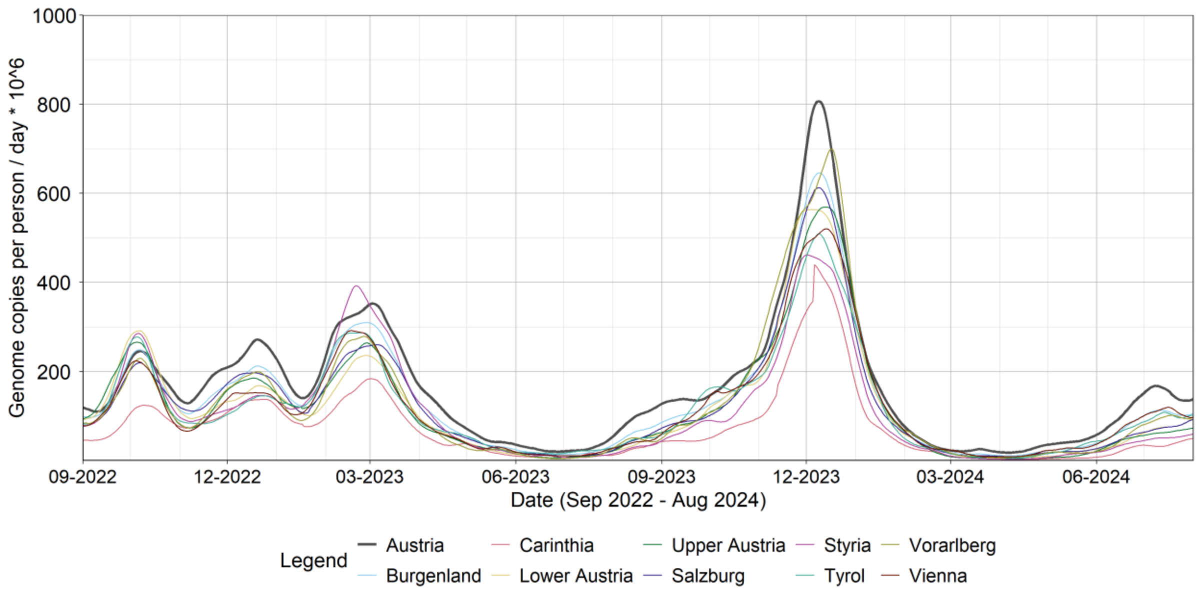


Figure 1-1. Person-weighted trends in Austrian SARS-CoV-2 wastewater concentrations (Sept. 2022–Sept. 2024) (BSGPK, 2024)

According to Barcellini et al., (2021), the level of SARS-CoV-2 infection in school students and teaching staff closely reflects the overall level of transmission in the wider community. The European Centre for Disease Prevention and Control (ECDC) acknowledges that, "*Transmission of SARS-CoV-2 in schools appears to be affected by how widespread the virus is in the broader community as well as the measures introduced in schools to mitigate SARS-CoV-2 transmission*"(ECDC, 2024). However, mathematical modelling suggests that schools may actually be a key driver of community transmission (Johnson et al., 2021) and that the rapid kinetics of SARS-CoV-2 transmission may explain why school and community prevalence quickly converge (White et al., 2022).

The concentration of an airborne pathogen indoors can be reduced by three principle measures: (i) *source control* – reducing the number of occupants and/or by wearing filtering face protection (i.e. FFP rated masks) (ii) *dilution* – through the provision of fresh air at high air exchange rates, and (iii) *purification* – the use of filtration and sterilisation devices (i.e. devices that filter pathogens out of the air or have a virucidal effect) (Uhde et al., 2022). However, single measures used in isolation are often insufficient to prevent the spread of airborne disease (McLeod et al., 2022). In the context of a fitness gymnasium, Blocken et al., (2021) showed that neither ventilation (at 2.2 h^{-1}) nor air filtration (in isolation) could sufficiently reduce the spread of viral aerosols, however when used in combination ventilation and air cleaning could reduce aerosol particle concentrations by 80 to 90%.

In respect to airborne infection prophylaxis in schools, several large scale studies have confirmed that ventilation and air cleaning can play a key role in helping to contain the spread of disease. In a study involving more than 10,000 Italian classrooms (Buonanno et al., 2022), inferred that the relative risk (RR) of SARS-CoV-2 infection, decreased as a function of the ventilation rate, with a maximum RR reduction of 80% attained in mechanically ventilated classrooms with ventilation rates greater than 10 l/(s·person). A similar finding was confirmed in a Swiss study involving 150 primary school classrooms, which found that significantly more individuals were infected with SARS-CoV-2 in poorly ventilated classrooms (EMPA, 2021).

More recently transient computational fluid dynamics (CFD) modelling has shown that the ventilation system design itself, and not simply the air exchange rate (AER), plays a pivotal role in the effective removal of respiratory particles from the room air. Using an enhanced ventilation design, involving underfloor and ceiling displacement (UFAD-CDR) ventilation for a university classroom Zabihi et al., (2024) showed that at the same airflow rate, the maximum density of respiratory particles could be reduced by up to 85% according to the specific design of the ventilation system. Similar findings were demonstrated experimentally in relation to a low cost mechanical extract ventilation system developed by the Max Planck Institute for Chemistry (MPIC), Germany, which was designed to enhance the removal of aerosols from classroom room air without recirculating them (Klimach et al., 2021).

Despite the well documented health and academic benefits of good ventilation and IAQ, the quality of classroom air in European schools remains largely unmonitored and unregulated. It is often left to the discretion of individual schools and classroom teachers to manage their own ventilation practices. In Austria most schools are naturally ventilated (via manual window airing) but school staff receive little or no training regarding appropriate ventilation practices. To date only a small number of IAQ monitoring studies have taken place and there is no regional or national level reporting of IAQ or ventilation in schools. As a result very little quantitative or qualitative longitudinal data exists regarding IAQ and ventilation practices in Austrian schools.

In the context of naturally ventilated classrooms, IAQ is influenced by a number of interacting factors (Fig.1-2). Some of these factors include physical constraints (e.g. the type of ventilation system and the level of external air pollutants) but many can be controlled, or at least influenced, by design and operational decisions (regarding the building services and the opening of windows). At the same time there are numerous barriers facing individual school directors, classroom teachers and other end-users in achieving the goal of providing optimal air quality and ventilation. These challenges range from a lack of knowledge of good ventilation practices, to practical issue regarding the regulation of window openings whilst attempting to maintain acceptable levels of thermal comfort. In many cases there are other conflicting factors which must also be addressed, including school policies (regarding energy consumption and room temperatures) as well as external factors (including noise and air pollution).

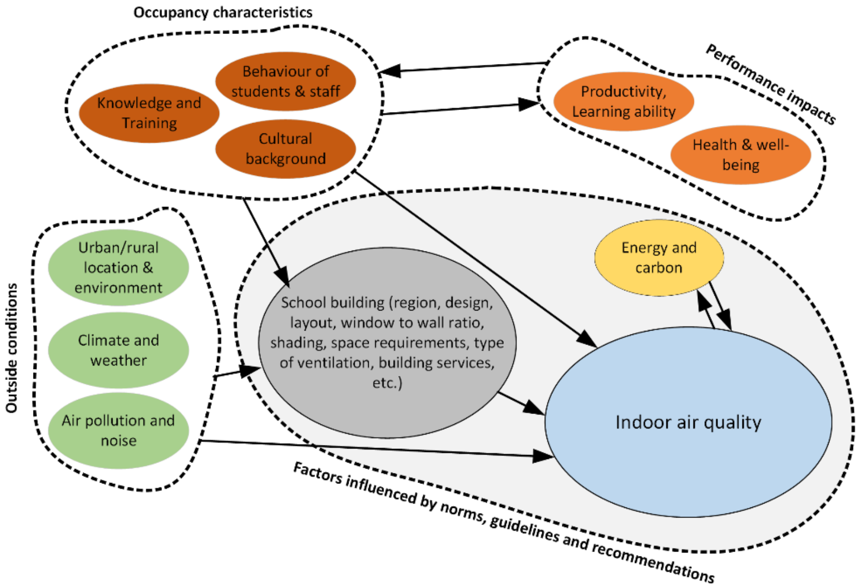


Figure 1-2. Factors influencing ventilation and IAQ in schools

It is important to note that indoor air pollution and airborne disease transmission in schools does not only affect the pupils but also the staff that work in them (and who are often exposed for longer periods of time). Analysis of cohort data has shown that school teachers have elevated risks of asthma and other respiratory illnesses (Tak et al., 2011; Csobod, 2014; Burge et al., 2021) as well as one of the highest COVID-19 case rates of any occupational group (Rhodes et al., 2022; Kvalsvig et al., 2023). It is worth noting that teachers' satisfaction with their working environment has also been shown to be influenced by the indoor environmental quality (IEQ) of their school, of which air quality is considered to be a key parameter (Sadick and Issa, 2018).

1.3 Overarching aims of the ImpAQS study

The overarching aim of the ImpAQS study is to understand the efficacy of current ventilation practices in Austrian schools and to evaluate the benefit of installing CO_2 monitors in classrooms as a means of improving ventilation practices, enhancing indoor air quality, and reducing the risk of airborne disease transmission.

It is hypothesised that the use of CO_2 monitors (with RAG visual alerts), together with basic instruction on appropriate ventilation procedures, can reduce the mean CO_2 concentration and quantifiably improve the air quality in classrooms. However, it is not known whether such an intervention can deliver appreciable benefits in terms of the IAQ and ventilation rate, and nor is the human acceptance of such interventions well documented.

1.4 Research questions

In order to fulfil the overarching aims of this project a series of research questions were formulated, which provide the basis of the primary research:

1. *What percentage of Austrian classrooms are adequately/inadequately ventilated according to existing norms and emerging 'health-based' ventilation guidance?*
   → This question is answered in Section 4.2.

2. *Are classroom CO_2 concentrations and ventilation practices dependent upon the season and/or other local environmental factors (e.g. thermal comfort, external air pollution etc)?*
   → This question is answered in Sections 4.2, 4.3, and 5.0.

3. *Do classrooms equipped with CO_2 monitors, and basic ventilation guidance, achieve better ventilation outcomes (reduced CO_2 concentrations) than those without monitors?*
   → This question is answered in Section 4.4.

4. *Does improving the indoor air quality in classrooms provide a statistically significant advantage in terms of reducing the risk of airborne disease infection?*
   → This question is answered in Section 4.5.

5. *Do teachers perceive the installation and use of CO_2 sensors positively, negatively, or indifferently? And if positively or negatively, what are the greatest drivers and barriers to the use of CO_2 monitors and achieving appropriate ventilation practices in classrooms?*
   → This question is answered in Section 5.0.

These questions, and a number of inter-related questions, are comprehensively investigated from a socio-technical research perspective using the combined evidence from the quantitative measurements and analytical investigations (Section 4) and the qualitative survey responses (Section 5). A summary of the consolidated analysis findings of the quantitative analysis is presented in Section 4.6 and of the qualitative analysis in Section 5.3.

2 Literature review – normative standards and studies of ventilation and IAQ in schools

This section of the report provides important background information which sets the context for the ImpAQS study. It draws together diverse literature informing current practices regarding indoor air quality and ventilation in schools. This includes relevant information from normative guidance documents, legislation, and standards, as well as the findings of similar research studies conducted elsewhere. Additional information describing the scientific basis for assessing indoor air quality and its relationship to health, wellbeing, and scholastic attainment is presented when it has relevance to the interpretation of the research findings. In addition, case studies of best practice from other European countries and the implications of emerging 'health-based' ventilation standards are discussed.

This review aims to summarise current knowledge as well as indicating places where there are still significant gaps in the existing knowledge base. Due to the enormous quantity of emerging research in this field, it is not intended as a comprehensive review of the literature.

Use of ISO and ÖNORM content in this report is provided with the kind permission of Austrian Standards plus GmbH, a subsidiary of the ISO member Austrian Standards International, Vienna.

2.1 Austrian school studies and related research

To date only a few studies have investigated current practices and outcomes in relation to ventilation and indoor air quality in Austrian schools and educational buildings. Of the documented empirical studies most have examined only a relatively small number of classrooms and/or carried out short-term studies, from which it is difficult to generalise more widely. Other studies have touched on this topic from a policy perspective but without presenting primary evidence regarding the existing situation. None-the-less, the findings of these preceding studies serve as a valuable frame of reference for the ImpAQS study, as well as highlighting pre-existing issues specific to the Austrian context.

Brandl et al., 2001 – Prior to this study, data on the ventilation and indoor pollutant situation in Austrian schools was very sparse. The few measurements of the indoor environment that were carried out before this time indicated that, "*the fresh air ventilation rate was often more than an order of magnitude below the required level*" (Brandl, 2001). Although there were no specific regulations regarding the air quality required by schoolchildren at this time, the Austrian Workplace Ordinance (AST-VO 1998) (Republik Österreich, 1998) regulations applied to school staff.

In this study the authors monitored the IAQ in 20 classrooms (in 4 primary schools, 4 secondary schools, and 2 general secondary schools) wherein formaldehyde and total volatile organic compounds (TVOCs) were sampled, and CO_2 was continuously recorded during several teaching lessons. The results show that whilst formaldehyde was mostly within the limits set by the WHO guidelines (at that time), elevated TVOCs levels (mean 830 µg/m³, median 250 µg/m³) were present in many classrooms and in 3 classrooms TVOC values exceeded 1000 µg/m³. The average concentrations of CO_2 in all classrooms were found to exceed 1000 ppm (0.1 vol%) and in many cases this value was surpassed for extended periods. A maximum CO_2 concentration of 6700 ppm (0.67 vol%) was measured in one classroom. The authors observed that "*when windows were tilted in classrooms where cross ventilation was possible, a significant reduction in the increase or a constant level of* CO_2

concentration was observed. In classrooms where cross ventilation was not possible, tilted windows only reduced the increase slightly" (Brandl, 2001, p10).

Hohenblum, 2008 – this report summarises the findings of the "LUKI: Air and children - Influence of indoor air on the health of children in all-day school" project. The study aimed to comprehensively examine the extent to which children (6 to 10 years) are exposed to various environmental factors in their school. A total of 9 schools participated in the study (including 7 all-day schools in Vienna, St. Pölten, and Graz, as well as two schools with all-day care in Klagenfurt and Villach). A total of 252 gaseous and particle-bound air pollutants were measured (in samples of house dust, fine dust and the air), as well as the CO_2 concentration. Additional tests included the analyses of heavy metals, based on hair and tooth samples, taken from the students. A standardised cognitive test was carried out to determine the influences of pollutants on the students' mental performance. In addition, the living environment and the health status of the children (especially their respiratory systems) were recorded using a parent questionnaire and lung function tests.

The results showed that fine dust measurements in classrooms (or adjacent rooms) were partly influenced by the outside air (i.e. by ventilation) and this was also reflected in the measured NO_2 concentrations. However, larger particles including PM_{10} pollution mainly originated form internal sources (e.g. chalk dust, student activity). Numerous toxic VOC compounds were regularly detected in both house dust (PM_{10}) and fine dust ($PM_{2.5}$). Elevated concentrations of specific pollutants (including (ethylbenzene, xylene, formaldehyde, benzyl butyl phthalate, PBDE 196, and the trisphosphate TDCPP) showed a correlation with a decrease in lung function. The findings of the lung function and cognitive performance tests indicated that the children's wider environment is likely to have had an influence on these two factors. In particular, mould in the home and (passive) smoking were found to be associated with decreased lung function.

NO_2 values are commonly used as a tracer for traffic emission and were found to be in a relatively narrow range of 8.7 to 28 $\mu g/m^3$ (as an average over 4–14 days of exposure) in this study. These values are well within the guideline values established by the ad hoc working group of the Indoor Air Commission (of 60 $\mu g/m^3$) at that time (Hohenblum, 2008). It is notable however, that the WHO reduced the daily threshold value (assessed at the 99^{th} percentile of the daily mean) to 25 $\mu g/m^3$ in their 2021 guidelines and recommended an annual (daily mean) nitrogen dioxide air quality guideline (AQG) level of 10 $\mu g/m^3$ (WHO, 2021b).

In the classrooms examined, significantly increased CO_2 concentrations were reported. A maximum moving hourly average of 1,400 ppm CO_2 was exceeded in 16 of the 18 classes studied, whilst absolute maximum values above 1,900 ppm were reported in 15 of the 18 classes examined. In only one of the 18 classes examined were all of the guideline requirements for assessing CO_2 met, indicating that in the vast majority of classrooms fresh air was not supplied in sufficient quantities to maintain hygienic conditions (Hohenblum, 2008).

Altrichter and Helm, 2022 – this paper reports on COVID-related educational research in Austria and provides a comprehensive overview of Austrian pandemic management measures in the school sector from 2020 to early 2022. The study (Altrichter, 2022) focuses primarily on the effects of school closures and COVID-19 prevention measures on the learning and well-being of children and young people. Whilst the study outlines the key prophylaxis strategies set-out in the ministries '4-point plan' (BMBWF, 2021) (which included waste-water monitoring, PCR and antigen testing in schools, vaccination buses, and funding to support the purchase of room air cleaners) it does not attempt to evaluate the success of these policies in relation to improving the health and safety of students and school staff or the mitigation of SARS-CoV-2 in Austrian schools.

Pollozhani et al., 2024 – investigated the effect of different ventilation strategies on energy performance, indoor environmental quality and SARS-Cov-2 viral transmission in an Austrian university seminar room. This computational and analytical study (Pollozhani, 2024) concluded that that although higher ventilation rates, from hybrid and mechanical ventilation systems, significantly reduced the risk of long range airborne viral transmission the risk could not be eliminated without additional prophylactic measures (e.g. masking). Overall, hybrid ventilation and room-based mechanical ventilation with heat recovery were found to provide the best compromise between final energy consumption, thermal comfort, indoor air quality and infection risk.

2.2 European school studies and related research

Whilst a number of studies have investigated the effectiveness of current policies and practices in relation to the long-term provision of adequate ventilation and indoor air quality in European schools, only a small sub-set of these have taken place at sufficient scale to make reliable inferences at the national and/or European level. Common limitations with many studies include small sample sizes, and sampling procedures which typically fail to account for the heterogeneity of school types and ventilation system characteristics; as well as the short duration of many studies (which fail to capture the year-round performance of naturally ventilated schools). None-the-less, a number of studies are included here since they provide findings which are particularly informative, in relation to the deployment of CO_2 sensors, improved ventilation practices in different seasons and school types, as well as the influence of ventilation rates on learning outcomes and attendance.

Geelen et al., 2008 – studied the efficacy of using CO_2 sensors as a means of improving ventilation outcomes in 20 Dutch primary schools over a 9 week period. Only classrooms with natural ventilation (e.g., windows, ventilation grilles) were included, so that airflow was dependant on ventilation behaviour. The authors reported that the use of a CO_2 warning device and an accompanying information package appeared to be effective tools in improving ventilation behaviour and IAQ in classrooms. Conversely, they found that giving class-specific ventilation advice without any supporting means was ineffective. Notably, the authors of this study point out that whilst ventilation was significantly improved (through behavioural change and the use of a CO_2 sensor) classroom CO_2 concentrations still exceeded 1000 ppm for more than 40% of the school day. As a consequence, the study concluded that whilst a CO_2 warning device and teaching information package are useful interim tools for improving ventilation behaviour and IAQ in classrooms, ultimately the ventilation facilities needed to be upgraded (Geelen, 2008).

Wargocki and Wyon, 2013 – summarise the results of a series of experiments on the effects of poor indoor environmental quality and ventilation on school children's performance. They conclude that classroom temperatures above 20–22 °C are sub-optimal (from a learning perspective). The authors also estimate that attempts to save heating energy in schools, by reducing ventilation rates, may be reducing children's academic performance by up to 30% (Wargocki & Wyon, 2013).

Csobod, 2014 – The SINPHONIE study is considered to be a landmark study of IAQ in European schools and childcare centres. The study had three main objectives, to: (i) contribute to the better characterisation of IAQ in EU schools; (ii) produce recommendations on remedial measures (iii) disseminate guidelines to policy makers. The study measured a wide range of physical and comfort parameters (including temperature, relative humidity and ventilation rate) alongside key chemical and biological pollutants (including priority compounds recognised by the WHO and EC) in 114 schools and childcare centres across 23 participating countries.

The results showed that more than 85% of schoolchildren were exposed to $PM_{2.5}$ at concentrations above 10 µg/m^3 (the WHO guideline annual mean value at that time, now reduced to 5 µg/m^3). The threshold exposure limits for numerous other key pollutants including radon, benzene, and formaldehyde were exceeded by a significant percentage. Notably, 50% of children and teachers were also exposed to high levels of endotoxins and microbes (typically found in damp poorly ventilated buildings) at levels higher than those found outdoors. The levels of traffic-related pollutants ($PM_{2.5}$, NO_2 and O_3) were elevated in the vicinity of many schools and 58% of the schools were exposed to road noise.

Mean and median levels of CO_2 were found to be higher than 1,000 ppm in both primary schools and kindergartens, with schools located in Central, Eastern and Southern Europe having mean levels above 1,500 ppm. The majority (86%) of classroom ventilation rates were found to be lower than the recommended target value (at that time) of 4 l/(s·person), a level which is significantly lower than the current EN standard 16798-1 (Tbl. 2-9) and ÖNORM H 6039 (Tbl. 2-3) recommend. The report attributes this finding to the high occupation density in many classrooms (20% of classrooms were found to provide floor areas of less than 2 m^2/child); and the inappropriate way in which ventilation rates were often expressed (i.e. in terms of air changes per hour (ACH) rather than litres per second per person).

In terms of the health impacts associated with air pollution, it was found that children in schools with elevated levels of chemical air pollutants were at a higher risk of suffering from recent symptoms related to multiple respiratory illnesses, with 3.6% of the schoolchildren having had asthma attacks in school. The findings of the SINPHONIE project indicate that asthma at school may affect around 100,000 children in Europe. Teachers also had respiratory issues with 17% reporting suffering from coughing or phlegm, 27% from a nasal allergy (at some point in their life), and 9% having received a medical diagnosis of asthma. Despite the extensive guidelines produced by the SINPHONIE study, and their relevance to the planning, design, construction and operational phases of new and existing schools, it is not known to what extent these guidelines have been implemented (Csobod, 2014).

<u>Wargocki and Da Silva, 2015</u> – used CO_2 sensors with visual displays in classrooms during normal school operation. During 2-week periods, teachers and students were instructed to open the windows in response to visual CO_2 feedback for 1 week and then open them as they would normally do, without visual feedback, in the other week. The results showed that providing visual CO_2 feedback reduced classroom CO_2 levels, as more windows were opened, with the effect of increasing the energy use for heating in winter and reducing the cooling requirement in summertime (Wargocki and Da Silva 2015).

<u>Canha et al., 2016</u> – characterized the relationship between ventilation and IAQ in 51 French classrooms in 17 schools by monitoring a number of parameters (including CO_2, volatile organic compounds (VOCs), aldehydes, and particulate matter as well as temperature and relative humidity). The study examined the influence of the season (heating or non-heating), type of school, and ventilation rate on the IAQ. Based on the minimum value of 4.2 l/(s·person) required by the French legislation (at that time) for mechanically ventilated classrooms, 91% of the classrooms were found to have insufficient ventilation. The ventilation rate (VR) was significantly higher in mechanically ventilated classrooms than in naturally ventilated rooms. The correlations between IAQ and ventilation were found to vary according to the location of the primary source of each pollutant (i.e. outdoors vs. indoors), and for indoor sources, whether they were associated with occupant activities or from continuous emissions (Canha, 2016).

Petersen et al., 2016 – investigated the effect of increased classroom ventilation rates on the performance of children aged 10-12 years. A double-blind 2 × 2 crossover study was carried out using four classrooms at two different schools located in the same area (1 km apart) near Aarhus, Denmark. Four different tests were carried out in order to assess short-term concentration and logical thinking at different ventilation rates. Analysis of the results showed that the number of correct answers improved significantly when the outdoor airflow rate was increased from an average of 1.7 to 6.6 l/(s·person) in four out of four performance tests: addition (6.3%), number comparison (4.8%), grammatical reasoning (3.2%), and reading and comprehension (7.4%), (Petersen, 2016).

Stabile et al., 2017 – analysed the IAQ (based on CO_2 and particulate matter concentration) in 5 naturally ventilated classrooms in 3 schools in Central Italy. Measurements were conducted in both the heating period and non-heating period. The results showed that indoor-generated pollutants (e.g. CO_2) were significantly higher at cold times than at warm times of the year. This was attributed to the shorter ventilation periods used in winter. In a selected class, when measurements were performed under different ventilation strategies, longer ventilation durations reduced indoor CO_2 concentrations as well as other gaseous pollutants generated indoors. Conversely, higher levels of ultrafine particles (and other vehicle-related pollutants) were recorded indoors due to the longer ventilation duration. The study (Stabile et al., 2017) highlights the challenges of manually airing rooms in cold weather and the limitations of natural ventilation in specific environments where high levels of external pollutants are present.

Carrer et al., 2018 – summarise the results of the HealthVent project (Seppänen et al., 2012), whose aim was to develop health-based ventilation guidelines for public and residential buildings and through this process contribute to the advancement of indoor air quality (IAQ) policies and guidelines. The HealthVent framework is based on three principles: (i) Adopting criteria for permissible concentrations of specific air pollutants set by health authorities, which must be respected; (ii) Ventilation strategies must be preceded by source control methods to limit the release of harmful contaminants; (iii) Base ventilation rates must be sufficient to remove occupant emissions (i.e. bio-effluents). HealthVent thresholds were derived on the assumption that the outside air complies with Word Health Organisation (WHO) air quality guidelines, wherein it is proposed that the base ventilation rate should be set at 4 l/(s·person). However in numerous European locations that assumption is not routinely met, in such cases the HealthVent guidance specifies that higher ventilation rates are to be used. In terms of the interpretation of the HealthVent framework in relation to health-based ventilation outcomes it is worth noting that this guidance pre-dates the COVID-19 pandemic. Moreover, in relation to the practical application of the framework the authors recommended that, "studies are also needed to examine the effectiveness of the approach and to validate its use" (Carrer, 2018).

Greenpeace, 2018 – in collaboration with the engineering company Buro Blauw, and project partners, Greenpeace Belgium carried out air quality monitoring in 222 primary schools in Belgium (46% of the schools were located in rural areas and 54% in urban or urbanised areas). The study focused on monitoring NO_2 and CO_2 to assess the impact of roads adjacent to schools. Air samples were taken in the school playground (outside the school) inside the school entrance, and in a representative classroom. In relation to NO_2 the study found that there was little difference between the street and the playground (regardless of whether the playground was located at the front or rear of the school). The annual mean NO_2 values measured in classrooms were elevated, and in the majority of schools exceeded 20 µg/m³, with 5 schools exceeding the EU statutory limit of 40 µg/m³. Pollutant levels were most pronounced in schools which were sited in an "urban canyon" (i.e. in a street lined by tall buildings where air pollution cannot easily be dispersed). An interesting finding of this study is that classrooms with mechanical ventilation reported higher NO_2 concentrations than naturally ventilated classrooms (suggesting that the mechanical ventilation systems drew in polluted air from the adjacent street). Although naturally ventilated classrooms had lower NO_2 concentrations than were recorded in the street, this finding may simply reflect the fact that the naturally ventilated classrooms were generally poorly ventilated (this finding was confirmed by comparative CO_2 measurement). The CO_2 concentration in the classrooms studied averaged 1250 ppm, whilst for a two hour period, the average concentration values were between 1500 and 1700 ppm. It should be noted that this study took place over a 3 week period in November to December 2017, at a time when classroom windows were often observed to be closed due to cold external temperatures (Greenpeace, 2018).

Wargocki et al., 2020 – reviewed the literature on ventilation, academic performance and school absenteeism (prior to the COVID-19 pandemic), using CO_2 as a metric of ventilation. The results suggest that increasing the ventilation rate in classrooms in the range from 2 l/(s·person) up to 10 l/(s·person) can bring significant performance improvements, in relation to the outcome of psychological tests and the speed at which tasks are performed, as well as improving attendance. However, no data was available to explore the benefits of higher ventilation rates (Wargocki, 2020).

Avella et al., 2021 – conducted a 3 week-long monitoring study in four schools, in the South Tyrol, to investigate the impact of using a CO_2 based visual alerting system to improve the IAQ in historic school classrooms. The results suggest that a visual alerting system, indicating when windows should be opened, can reduce the average classroom CO_2 concentration by up to 42%. With the best results being achieved during mild outdoor conditions (Avella, 2021).

Di Gilio et al., 2021 – conducted real-time monitoring of CO_2 levels (as a proxy for SARS-CoV-2 transmission risk) in 11 classrooms, in 9 schools, located in the Apulia Region (South of Italy) following the COVID-19 lockdown. They showed that implementing detailed ventilation protocols, based on specific measures and simultaneous real-time visualisation of CO_2 levels, led to an overall improvement in the indoor CO_2 concentrations, however the majority of classrooms recorded mean CO_2 values exceeding 1000 ppm, despite a recommended limit of 700 ppm (Di Gilio, 2021).

EMPA, 2021 – the Swiss Federal Laboratories for Materials Science and Technology (EMPA) monitored the CO_2 concentration in 150 classrooms in 59 schools and found that CO_2 concentrations of 2000 ppm were exceeded in 60% of classrooms. Moreover a statistical correlation between the number of weekly COVID-19 cases and the measured CO_2 concentration was observed, with the result that significantly more students were infected with SARS-CoV-2 in insufficiently ventilated classrooms (EMPA, 2021).

Buonanno et al., 2022 – demonstrated the positive impact of higher air change rates achieved by mechanical ventilation systems (MVS) on the risk of infection with SARS-CoV-2 in 1,419 schools in the La Marche region of Italy, by monitoring a total of 10,411 classrooms over the period from September 2021 to the end of January 2022. The probability of SARS-CoV-2 infection in mechanically ventilated classrooms was reduced by at least 74% compared to classrooms with natural ventilation. With mechanical ventilation rates above 10 l/(s·person) the airborne transmission risk was estimated to be reduced by as much as 80% (Buonanno, 2022).

Zhang, Ding, and Bluyssen, 2022 – conducted a laboratory and field study showing the influence of different CO_2 sensor locations in a classroom under different ventilation regimes. By monitoring the CO_2 concentration in 18 locations in an experimental classroom, it was shown that the concentration varied greatly between different locations in the same room, particularly with natural ventilation. The results indicate the necessity to monitor CO_2 concentrations at multiple locations in a classroom to reduce measurement uncertainty. However, in well mixed conditions (e.g. in mechanically ventilated classrooms) a single measurement position appeared to be sufficient. It was also found that the most representative location for monitoring CO_2 concentration was on the wall opposite the windows and on the front wall (near the teacher) (Zhang, 2022).

<u>Rowe et al., 2022</u> – derived the temporal evolution of the quantum concentration of the SARS-CoV-2 virus in air under steady state conditions for a well-mixed room and then linked this with the monitored concentration of CO_2 in the room to determine risk probabilities for airborne transmission. Using a dose-response model the authors illustrated that the difference in quantum production rates between different viral variants plays an enormous role in the dose concentration, and hence in the probability of infection. They also highlight that the duration of exposure and the ventilation rate (per person) have a significant effect on the probability of airborne viral transmission. On this basis they carried out a risk analysis for a variety of situations based on monitored CO_2 time-series observations. As a result of this monitoring they conclude that present norms are "insufficient and not respected" in relation to the CO_2 thresholds needed to minimise airborne transmission risks. They point out that indoor CO_2 concentrations alone are an unreliable indicator of infection risk and that the communication of CO_2 threshold limits as a single deterministic value (e.g. 1000 ppm) is misleading as it ignores the critical issue of exposure duration. On this basis they recommend that a much lower threshold limit of 600 ppm is needed to further reduce risks in unmasked settings, including schools (Rowe, 2022), however little evidence is provided to support this claim.

<u>Schwarzbauer, 2022</u> – compared the effect of different ventilation methods in 244 classrooms over a one-year period (representing a total of 37,000 school days) in the Bayern region of Germany. Multiple ventilation methods (including natural ventilation - also combined with mobile air cleaners, fan-assisted window ventilation as well as central and decentralised mechanical air handling units (AHUs)) were investigated. CO_2 concentrations were found to be above 1000 ppm 24% of the time with natural ventilation, 16% with fan-assisted window ventilation, 11% with decentral AHUs, and 21% with central AHUs. Median CO_2 concentrations of 776 ppm were reported with centralised AHUs, 764 ppm with window ventilation in combination with mobile air purifiers, 750 ppm with window ventilation, 710 ppm with (hybrid) fan-assisted window ventilation and 706 ppm with decentralised (room based) AHUs. These relatively low median values may be somewhat influenced by the heightened ventilation vigilance occurring during the early phase of the COVID-19 pandemic.

A dependence on the time of year was also observed, with lower CO_2 concentrations being measured in the warm season than in the cold season, which was due to the longer ventilation times at warmer temperatures. By defining a reference classroom a standardised virus dose factor (VDF) was created for the airborne transmission of SARS-CoV-2 and Influenza A (using analytical equations to determine the inhaled virus dose for a standard classroom, assuming well-mixed air exchange at the rate of 3 ACH). The VDF reference value (of 1) was exceeded for 40% of the total teaching time and was least favourable in classrooms with natural ventilation. By combining free window ventilation with mobile air purifiers, the VDF could be significantly reduced, but the exceedances of the CO_2 thresholds remained unchanged (Schwarzbauer, 2022).

<u>Uhde et al., 2022</u> – investigated the effectiveness of various air purifying measures (including window ventilation and air cleaners) to reduce the exposure to bioaerosols in school classrooms. Bacteriophages (type MS2) were used to test a number of interventions including: increasing air exchange rates (using window fans and mechanical ventilation with heat recovery), mobile air purifiers, and disinfection by introducing active agents into the indoor air of classrooms. The authors provide evidence that increased ventilation (e.g. through window ventilation) and the use of portable air purifiers are both effective in reducing the number of viable viruses in the room. However, in

contrast to a study by Blocken et al. (2021) it was found that the combination of the two measures did not reliably lead to further improvement in air quality (Uhde, 2022).

Burridge et al., 2023 – Studied variations in classroom ventilation during the COVID-19 pandemic. They monitored CO_2 concentrations and air temperature in 36 naturally ventilated classrooms, at two primary schools and two secondary schools, in England during 2021. The authors noted that compared to UK school air quality guidance (Education and Skills Funding Agency, 2018), the CO_2 levels within classrooms remained relatively low during periods of warmer weather, but with elevated CO_2 levels being evident during the colder seasons. The researchers also observed that CO_2 data varied significantly between schools and between classrooms in the same school, noting that further research is required to ascertain the drivers of differing classroom ventilation behaviours. They also noted from the cold period during the latter part of 2021, that ventilation rates were significantly lower than those achieved during a similarly cold period earlier in the year. This finding was contrary to what the researchers had expected following a year of significant public messaging regarding COVID-19 (Burridge, 2023).

Helleis et al., 2023 – researchers at the Max Planck Institute for Chemistry in Mainz report on the development of hybrid mechanical extract ventilation (MEV) system. They extensively compared the effectiveness, energy efficiency and sustainability of different ventilation methods for increasing air quality and infection control in classrooms and demonstrate that window ventilation with simple technical support such as exhaust fans and CO_2 sensors provides a cost-effective method of improving indoor air quality and reducing the aerosol transmission of infectious diseases, such as COVID 19 or influenza (Helleis, 2023).

Haddrell et al., 2024 – analysed the physicochemical properties of respiratory aerosols that influence viral stability and infectivity. They showed that a significant increase in SARS-CoV-2 aerostability results from only a moderate increase in the atmospheric CO_2 concentration (e.g. from 500 ppm to 800 ppm). Regardless of RH, they show that increasing the CO_2 will drive the pH of an alkaline respiratory droplet towards pH neutral to some degree. As a result, at an RH of 80% and below, moderate increases in CO_2 are shown to increase viral aerostability. This finding provides prima facie evidence that CO_2 is not simply a marker of poor ventilation but may also play a direct role in viral infectivity. The study highlights the critical importance of fresh air and the need to maintain low CO_2 concentrations in indoor environments in order to mitigate airborne viral disease transmission (Haddrell, 2024).

Wood et al., 2024 – reported on the per-person ventilation rates derived from CO_2 data measured in 322 UK schools (throughout the Autumn term, 2023) as part of the citizen science School's Air Quality Monitoring for Health and Education (SAMHE) project. They confirmed that daily adherence to existing UK school CO_2 guidelines (Education and Skills Funding Agency, 2018) depends strongly on the average outdoor temperature. More specifically they found that the overall mean ventilation rate was 5.3 l/s.(person); rising to 6.8 l/s.(person) during warmer weather and falling to 3.8 l/s.(person) during colder weather. They also found that classroom CO_2 levels were on average lower in private (fee-paying) schools and schools located in more affluent areas. Classrooms with pupils under the age of eleven years were found to have lower CO_2 levels, despite similar ventilation rates to older classes. Unsurprisingly, schools with more pupils than they were originally designed for experienced higher classroom CO_2 levels (Wood, 2024).

2.3 International school studies and related research

Shendell et al., 2004 – studied the associations between classroom CO_2 concentrations and student attendance. Absenteeism and CO_2 data were collected from 409 traditional and 25 portable classrooms from 22 schools located in six school districts in the states of Washington and Idaho. The study classrooms had individual heating, ventilation, and air conditioning (HVAC) systems, with the exception of two classrooms (which were naturally ventilated). Forty-five percent of classrooms studied had short-term indoor CO_2 concentrations above 1000 ppm. The study found that a 1000 ppm increase in CO_2 was associated ($p<0.05$) with a 0.5–0.9% decrease in annual average daily attendance (ADA), corresponding to a relative increase of 10–20% in student absences. Based on these findings the authors recommend that "Adequate or enhanced ventilation may be achieved, for example, with educational training programs for teachers and facilities staff on ventilation system operation and maintenance" they also advised that, "technological interventions such as improved automated control systems could provide continuous ventilation during occupied times, regardless of occupant thermal comfort demands."

Mendell et al., 2013 – investigated relationships between VRs and illness absence (IA) in 162 (3rd–5th grade) classrooms in 28 Californian elementary schools in 3 school districts over a two year period. The relationship between daily IA and VR was estimated from real-time CO_2 measurements in each classroom. It was found that all school districts had median VRs below the 7.1 l/(s·person) minimum value, specified in the California Title 24 standard (California Energy Commission, 2012). For each additional 1 l/(s·person)) increase in the VR, IA was reduced by 1.6% in models for the combined districts ($p < 0.05$). This finding follows the same trend shown in the earlier work of Shendell et al. (2004) above, although the effect reported by the earlier study is 2–5 times larger than the findings reported by Mendell et al., (2013). The study also compared IAQ benefits and energy costs of increased VRs, showing that increasing classroom VRs from the current Californian school average (4 l/(s·person)) to the California Title 24 standard (7.1 l/(s·person)) would decrease IA by 3.4%, thereby increasing attendance-linked funding to schools by $33 million (USD) annually, whilst increasing operating costs by only $4 million (USD). The findings (whilst requiring confirmation) indicate that increasing classroom VRs above the Californian state standard would substantially decrease illness absence rates whilst providing substantial economic benefits (Mendell, 2013).

Laiman et al., 2014 – investigated changes in particle number concentration (PNC) arising from local sources (either within or adjacent to classrooms) over a 2 week-long period in naturally ventilated primary school classrooms in 25 schools in Brisbane, Australia. Measurements of PNC and CO_2 were taken both outdoors and in two selected classrooms. The air exchange rates (AERs) in each classroom were estimated using an exponential decay model for the CO_2 concentration from a peak decay concentration occurring before and during the lunch break period. This method relies on the assumption that window airing patterns during the lunch break are similar to the patterns occurring during the occupied period. Based on this method, the median AER during the occupied school hours was estimated to be 1.0 h^{-1}, with the warmer months being higher than the colder months. This value was stated to be approximately 43% higher than the applicable ANSI/ASHRAE Standard 62.1 (2013) at that time. The median indoor CO_2 concentrations during school hours was 430 ppm, relative to an outdoor mean of 373 ppm. This value is extremely low (in comparison to other studies) although it would correspond to a median indoor value of 480 ppm in 2024 (relative to a median outdoor value of 423 ppm). Short term exceedances of the 1000ppm threshold were reported in a few classrooms, and these were attributed to higher than average occupant densities in those rooms. The study also found that particles were removed by both air exchange and deposition; chiefly by ventilation when

AER > 0.7 h^{-1} and by deposition when AER < 0.7 h^{-1}, showing that higher ventilation rates can play an important role in the removal of internally generated fine particles (Laiman, 2014).

Andamon et al., 2023 – monitored the IAQ in 10 primary and secondary school classrooms in Victoria, Australia, for a whole year. The classrooms were naturally ventilated, with additional air-conditioning units providing heating and cooling. All 10 classrooms in the study exceeded the Australian recommended median CO_2 limit of 850 ppm, with 70% of the classrooms having median values above 1000 ppm. Using average peak CO_2 concentrations from year-long measurements, the estimated mean VR was 4.08 l/(s·person), around 60% lower than the 10–12 l/(s·person) recommended by Australian guidelines (Andamon, 2023).

Bruns, 2023 – carried out a cost benefit analysis comparing the costs of operating a range of different building types under normal operational conditions versus under the ASHRAE Standard 241 'Control of Infectious Aerosols' (ASHRAE, 2023) infection risk management model (IRMM). The analysis was carried out under the assumption that the respiratory virus season lasts 112 days/year and that each day 1% of the population is infectious. The calculation of monetised benefits was based on using the Wells-Riley model to estimate the change in infection probability, in each space, as a result of changes in the equivalent clean airflow rate (ECA_i). A United States dollar (USD) value was placed on the infection reduction using the US Department of Health and Human Services' methodology (which values each life-year gained at about $500,000 (USD), whilst the value of preventing a death was estimated at $4 million (USD). Based on these assumptions and using room geometry and occupancy data sourced from ASHRAE standards (62.1, 62.2 and 170) the estimated costs and monetised COVID-19 reduction benefits were calculated for a variety of building and room types. For school classrooms (based on a default occupancy of 30 people) the number of infections prevented is estimated as 3.8 with monetised value of $7,000 (USD) and an implementation cost of $820 (USD), whilst for a lecture hall (with an occupancy of 150) the monetised value is estimated as $25,000 (USD) and the cost $7,500 (USD). Based on the assumptions used there is a clear financial and human benefit to implementing the ASHRAE 241 standard during the respiratory virus season. It is not clear however, how the risk of short range transmission was addressed (in relation to the total risk reduction modelled).

Kurnitski et al., 2023 – developed a new methodology for post-COVID 'health-based' ventilation design. The methodology in this paper underpins the REHVA 'Health-based target ventilation rates and design method for reducing exposure to airborne respiratory infectious diseases' (REHVA, 2022). The authors point to the limitations in current 'health-based' ventilation guidance with respect to viral load data, risk control methods and incomplete air mixing, which they claim have resulted in recommendations which omit consideration of room activity and room specific viral loads as well as actual air distribution systems which deviate from full-mixing. To overcome these limitations a new infection risk-based ventilation design method operating with room category specific target ventilation rates and point source ventilation effectiveness is proposed. Their analytical findings suggest that in classrooms and offices existing EN 16798-1 category 1 flow rates are sufficient in most cases, but higher airflow rates are needed in meeting rooms, restaurants, and gyms (Kurnitski, 2023).

Zhang et al., 2023 – investigated the indoor environmental conditions in a university lecture room in Beijing, China. They recorded the indoor temperature, relative humidity, CO_2, and VOC concentrations whilst the room was occupied. Temperatures were recorded in the range from (21.2 ± 0.8 °C to 26.8 ± 0.7 °C). They reported mean CO_2 concentrations in the range of 1,291–1,833 ppm and total volatile organic compounds (TVOCs) in the range of 159–1,178 ppb. They reported that the subjective evaluation of the indoor air quality was worse at 27 °C than at 24 °C. They also determined that the occupant CO_2 emission rate from the students increased by 0.54 l/(h·person) for every 1 °C rise in the room temperature. They calculated that to control the room CO_2 concentration to not exceed 1,000 ppm the outdoor supply airflow rate would need to increase by 0.25 l/(s·person) to offset the temperature increase (Zhang, 2023).

Mendell et al., 2024 – reviewed the literature for guidelines regarding the use of CO_2 as an indicator of IAQ and the supportive evidence provided. Of the 43 guidelines identified in the study, 35 set single CO_2 concentration limits and eight set multi-tiered limits. Indoor CO_2 thresholds varied from 550 ppm to 1750 ppm with the most common limit being 1000 ppm. Thirteen guidelines specified maximum CO_2 limits as time-weighted averages, but none provided evidence linking averaged limits to occupant effects. 18 guidelines cited evidence to support the limits set, but this was only considered to be persuasive for eight. Among these eight guidelines, seven set limits to control odour perception, whilst one provided 17 scientifically-based CO_2 limits (ranging from 486–1535 ppm) for specific example space uses and occupancies (Afshari et al., 2023) with the intention of controlling the long-range transmission of SARS-CoV-2 indoors. The authors argue that, "No scientific basis is apparent for setting one CO_2 limit for IAQ across all buildings, setting a CO_2 limit for IAQ as an extended time-weighted average, or using any arbitrary one-time CO_2 measurement to verify a desired VR" (Mendell, 2024, p1). To address the issues with current CO_2 guidance the authors recommend producing specific CO_2 guidelines for different space uses as needed, e.g., based on expected occupancy and activity levels, as in current ASHRAE and European VR standards as well as referencing the scientific support and uncertainties for the CO_2 limits set. As a good example of this, they recommend the guidance produced by the Nordic Ventilation Group (Afshari, 2023) and the REHVA airborne infection guidelines (REHVA, 2021; REHVA, 2022; Kurnitski, 2023).

Morawska et al., 2024 – summarised the lessons learnt from the COVID-19 pandemic for ventilation and indoor air quality based on a review of the literature and expert opinions. They point out that one of the consequences of neglecting IAQ is the presence of pathogenic viruses in indoor air, including local outbreaks of the common cold and seasonal influenza, as well as epidemics and pandemics caused by novel viruses. In order to address this widespread problem the authors identified seven lessons of particular importance (Tbl. 2-1).

Table 2-1. Key lessons from the COVID-19 pandemic regarding ventilation in the indoor environment (Morawska, 2024)

Lesson number	Key findings and lessons (summarised)
1	Interdisciplinary expert knowledge should be the guiding factor in infection risk control and IAQ management.
2	Ventilation must go far beyond advice to "open the windows".
3	Better building designs that optimize ventilation performance, with IAQ as the focus, should be the guiding principle behind the constriction of future buildings.
4	Equivalent ventilation (e.g. HEPA filters or UV-C devices) is useful as a supplement in spaces without adequate ventilation.
5	Ventilation control guided by risk assessment tools, have a role in building design.
6	Ventilation performance should be monitored at all times when buildings are occupied.
7	IAQ must be regulated to protect human health in public spaces.

The importance of ventilation (in relation to human health and other priorities) remains poorly understood according to the authors, who remark that, "*Even in the middle of the pandemic, there were controversial discussions in Central and Northern Europe, for example, about whether ventilation* *makes sense given possible heat loss and the risk of colds"* (Morawska, 2024a, p1) . This failure to "follow the science" is attributed to the definition of "expert knowledge". Although the WHO affirmed that they had experts advising them during the pandemic, these were predominantly public health experts, whilst the value of physical, chemical, engineering and other related expertise was seen as less relevant.

The author's cite numerous reasons (including thermal comfort, external noise and air pollution) why relying on window opening as the primary means of ventilation often fails in practice. They claim that one of the key lessons learned from the recent pandemic is that, "*modern society cannot rely solely on natural ventilation in buildings that are not designed to provide sufficient and effective air supply under all meteorological conditions*" (Morawska, 2024a, p2).

Regardless of the ventilation system used the authors advocate that ventilation performance should be monitored whenever a building is occupied, to dynamically inform ventilation control in response to building occupancy and use. Acknowledging that there are various suggestions for what CO_2 values are indicative of excessive contaminant concentrations, the authors suggest that a limit of less than 800 ppm has been recommended by scientific consensus (Morawska et al., 2024b). However, as Mendell et al.,(2024) point out there are numerous limitations to the use of a single CO_2 limit in all room types and across diverse usage contexts.

2.4 Summary of the main findings from the scientific literature review

The literature documenting associations between classroom CO_2 concentrations and ventilation and their resultant impact on IAQ, health and absenteeism spans every continent and more than two decades of research. Whilst certain findings are context dependent (for example whether increased ventilation improves IAQ in externally polluted environments), and some findings require further confirmation (such as the strength of the association between ventilation rates and illness related absences), there is overwhelming evidence that most classrooms are under-ventilated. Moreover, numerous studies show that there is an association between under-ventilated classrooms (with elevated CO_2 levels) and impaired academic performance, and in some cases increased absenteeism. Whether this is caused indirectly, by an increase in harmful pollutants (such as VOCs or particulates), or the increased CO_2 concentration (or some combination thereof) is yet to be fully determined.

Moreover, increased room temperatures are associated with poorer air quality (and are often correlated with increased CO_2 and VOC emission rates) with temperatures above 20–22 °C being identified as sub-optimal from a learning perspective. The specific design of hybrid and mechanical ventilation systems can also play a key role in the effectiveness of ventilation systems. The way the air enters and is removed from a room significantly influences the resultant IAQ, thereby potentially influencing infection risks as well as the academic performance of the occupants. Thus, it is not simply the volumetric airflow rate which matters but also the design of the ventilation system, wherein vertical displacement systems typically achieve better ventilation effectiveness.

It is also important to acknowledge that many of the findings documented in the literature were valid when compared to the norms and standards in place at the time these studies were undertaken. In relation to modern (i.e. post 2020) "health-based" ventilation guidance the disparities would be even more striking in most cases. With new knowledge (including the explosion of research and guidance which has emerged since the COVID-19 pandemic began) there is an even greater awareness of both the direct and indirect role which CO_2 plays as an indicator of air quality, as well as its limitations. Whilst CO_2 remains a very useful indicator of ventilation rates under normal operating conditions (e.g.

in a classroom where only one person is speaking) it is significantly less precise as an indicator of IAQ (in relation to airborne pathogen transmission) in rooms where significant aerosol generating activities take place (e.g. singing and sport). Despite these limitations, the vast majority of Austrian classrooms are naturally ventilated and in this context the measurement of CO_2 remains one of the simplest and most cost effective means of assessing the ventilation rate and freshness of the indoor air.

The COVID-19 pandemic has driven greater awareness of the role of clean air in reducing the transmission of airborne pathogens. Three findings are particularly important in this regard:

i) Lower classroom CO_2 concentrations are associated with reduced illness related absenteeism.
ii) The time duration of exposure, the activity taking place in the room, and the occupant density in a space all play a key role in the probability of airborne infections. Therefore appropriate CO_2 targets must consider all of these issues in combination.
iii) Moderate increases in room air CO_2 concentrations are shown to increase the viral aerostability of SARS-CoV-2 and other viruses, meaning that CO_2 plays both an indirect and a direct role in influencing the risk of airborne disease transmission.

2.5 Indoor air quality and ventilation – normative standards, guidance documents and laws

2.5.1 Austrian standards, guidelines and official acts

Austria has specific legislature mandating the control of external air pollution which is set out in in the Air Pollution Control Act (Republik Österreich, 1997) and documented in subsequent amendments to that act (BMK, 2024a). In terms of indoor air quality and occupational health and safety (OHS) in the workplace, the Austrian Workplace Ordinance and the Austrian Guidelines (Arbeitsinspektion, 2020) provide some guidance on the provision of acceptable ventilation rates. In addition, a series of position papers (on topics related to ventilation, indoor air quality and infection risks) have been commissioned by the Indoor Air Working Group at the Austrian Federal Ministry for Climate Protection, Environment, Energy, Mobility, Innovation and Technology (BMK) (BMK, 2024c). A number of these documents concern the provision of acceptable ventilation and IAQ in schools and/or the workplace. In relation to this study the most relevant documents are summarised as follows:

Air Pollution Control Act (German: Immissionsschutzgesetz-Luft IG-L) – (Republik Österreich, 1997)

This legislation aims to achieve the preservation of good air quality and/or the improvement of air quality via the preventive reduction of external air pollutants. To achieve this goal an Austria-wide measuring network, for the continuous monitoring of air pollutants, is operated via the Federal Environment Agency (UBA), and exceedances of limit and/or target values are identified and reported. To protect human health, emission limit values for the air pollutants CO, NOx, SO_2, lead, benzene, particulate matter ($PM_{2.5}$ and PM_{10}) and benzo(a)pyrene are stipulated in the IG-L; alarm values are also set for SO_2 and NO_2, and target values for particulate matter and NOx. Furthermore, target values were introduced for arsenic, cadmium and nickel. For particulate matter $PM_{2.5}$, an obligation and a target were introduced in addition to the limit value in order to reduce the average exposure of the population to fine particulate matter.

Austrian Workplace Regulations (German: Rechtsvorschrift für Arbeitsstättenverordnung AStV) – (RIS, 2024a)

The Austrian Workplace Regulations (AStV) are a federal act which includes information regarding air quality in the Austrian workplace and as well as limits for the protection of human health which are valid throughout the entire federal territory. Whilst the complete consolidated federal law (RIS, 2024b) also includes provisions defining the adequacy of both natural and mechanical ventilation.

Wherein, for naturally ventilated spaces, § 26. states that the following conditions must be fulfilled:

(i) Rooms used as *workspaces must have a supply of sufficient fresh air, as free as possible from impurities, and the used air must be removed*. The ventilation must ensure that the rooms are ventilated as evenly as possible. Fixed workplaces must be arranged in such a way that employees are not exposed to harmful draughts.
(ii) Workspaces that are exclusively ventilated naturally must have ventilation openings leading directly to the outside. These ventilation openings must: have an effective ventilation cross-section of at least 2% of the room's floor area in total and, If the room depth exceeds 10 m, be arranged to allow for cross-ventilation.

Whilst for spaces with mechanical ventilation and extract ventilation, § 27. states that the provisions of § 26 paragraph also apply to mechanical ventilation and in addition *workspaces must be mechanically ventilated if natural ventilation is insufficient*, particularly if:

(i) The ventilation cross-sections required under § 26, item (ii) are not met, or despite meeting the required ventilation cross-sections:
a) Sufficient air quality cannot be guaranteed (e.g., under aggravating conditions such as increased heat, smoke, or steam exposure, or air contamination by hazardous substances), or
b) Natural ventilation would cause unacceptable noise disturbance for the employees.

If a workspace is exclusively ventilated mechanically, the AStV (RIS, 2024a) specifies the minimum airflow rates which apply according to the type of activity carried out in the workplace (Tbl. 2-2).

Table 2-2. Minimum airflow rates in mechanically ventilated rooms according to activity type (RIS, 2024b)

Minimum airflow rate [m^3/(h·person)]	Type of work activity
35	If the work involves only light physical activity
50	If the work involves normal physical activity
70	If the work involves heavy physical activity

In relation to mechanical ventilation, the precise activity level corresponding to ‘light’, ‘normal’ and ‘heavy’ physical activity are not described (Tbl. 2-2). Assuming that teaching is considered a ‘light’ physical activity then the act states that a minimum airflow rate of 35 m^3/(h·person) (9.7 l/(s·person)) would be needed in classrooms, and all similar rooms occupied by school staff. Moreover, the mechanical recirculation of air is only permitted under very limited circumstances wherein the proportion of the outside air volume supplied per hour may be reduced linearly to a value of 50% at outside temperatures between 26 °C and 32 °C and between 0 °C and -12 °C (RIS, 2024b).

Whilst the requirements for natural ventilation are somewhat loosely defined, it is clear the intent of this act is to ensure that employees have an adequate supply of fresh air, that is as free as possible from pollutants, and that the ventilation must ensure that the rooms are ventilated as uniformly (and therefore as continuously) as possible. The act also states that "workspaces must be mechanically ventilated if natural ventilation is insufficient" (RIS, 2024b, §27(2)).

ÖNORM EN 16798-1:2024 – Energy performance of buildings – Ventilation for buildings – Part 1 (German: Energetische Bewertung von Gebäuden Lüftung von Gebäuden **– Teil 1** – (CEN, 2024)

It should be noted that ÖNORM EN 16798-1 is both a CEN standard and an Austrian standard. It is described in Section 2.5.2. to distinguish it from standards that have purely a national scope.

ÖNORM H 6039:2023 - Ventilation systems (German: Lüftungstechnische Anlagen) – (ASI, 2023)

This ÖNORM regulates the planning of fresh air requirements, including the design, operation and maintenance of controlled mechanical ventilation of classrooms and group rooms as well as rooms with similar purposes (e.g. seminar or training rooms). This ÖNORM does not address air cleaning units that operate in recirculation mode in conjunction with chemical or radiation treatments (e.g. UV-C radiation, ozone, hydrogen peroxide, chemical treatment, etc.). Nor does it address the requirements of special classrooms (e.g. training workshops or teaching kitchens, gymnasiums, or laboratories). This ÖNORM recommends a maximum CO_2 threshold of 1000 ppm for classrooms and 1400 ppm for subordinate areas with mechanical ventilation (based on the arithmetic mean value over one lesson) (ASI, 2023, p6).

In relation to VRs, ÖNORM H 6039:2023 recommends the following values according to the age range of the pupils:

Table 2-3. Recommended airflow rates by age according to ÖNORM H 6039:2023 (ASI, 2023)

Pupil age range	Airflow rate [m³/(h·person)]	Airflow rate [l/(s·person)]
< 10 yr	28	7.8
11–18 yr	33	9.2
> 19 yr	36	10

Guideline for the assessment of indoor air - carbon dioxide as a ventilation parameter (German: Richtlinie zur Bewertung der Innenraumluft - Kohlenstoffdioxid als Lüftungsparameter) – (BMK, 2024d)

This BMK guideline states that CO_2 should be regarded as a key parameter for the air pollution caused by humans, since the increase in the CO_2 concentration indoors correlates well with the increase in odour intensity caused by human metabolism. The relationship between the percentage of people dissatisfied in a space and the CO_2 concentration (above the ambient level) is defined by Eq. 2-1 (Beinfait et al., 1992).

$$PPD = 395 \cdot \exp\left(-15.15 \cdot \Delta CO_2^{\,-0.25}\right) \quad [2\text{-}1]$$

Where,

PPD = Percentage of persons dissatisfied with the indoor air quality [%]
ΔCO_2 = Increase in CO_2 concentration [ppm] above the outdoor air concentration

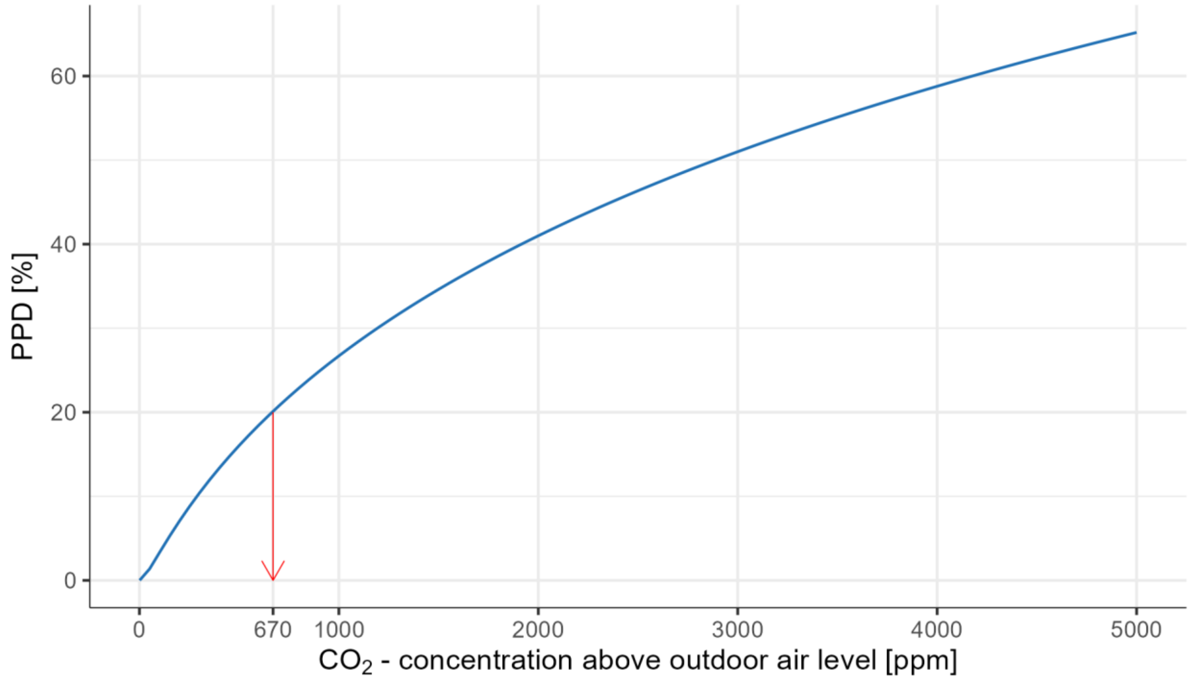


Figure 2-1. Room CO_2 concentration above ambient and the corresponding percentage of persons dissatisfied [PPD]

It can be seen (Fig. 2-1) that at circa 1,100 ppm (i.e. ambient level plus 670 ppm) around 20% of the occupants will find the indoor air unsatisfactory (BUWAL, 1997). The classification of rooms according to the CO_2 concentration has become an established practice for rooms in which contamination is mainly caused by human metabolism (see, for example, ÖNORM H 60391 for schools). With respect to CO_2 emission rates from humans the BMK guideline points out that, there are sometimes widely differing values cited in the literature.

With respect to new schools the guideline reports that, for energy-saving reasons, many schools have extremely airtight windows in which the air exchange rate (i.e. infiltration rate) is below 0.05 h^{-1}. Moreover, these windows often cannot (or must not) be opened during breaks for safety reasons. This results in extremely high CO_2 levels and affects schools both in the city and in rural areas. Under unfavourable circumstances, this can result in very high CO_2 concentrations (in the range of 5,000 ppm and beyond). These figures suggest that the schools concerned are operated for extended periods without any form of purposeful ventilation.

The BMK guideline states that "CO_2 is a good measure of the breathing activity of the room users. In the case situations that come close to the standard situation described in Müller et al. with regard to speech activity (4% speakers, i.e. one in 25 people), CO_2 measuring devices can therefore provide a relatively good indication of the risk of infection" (BMK, 2024d, p28). Compliance and target threshold values for a range of different school rooms are set out in the guideline, as shown in Table 2-4.

Table 2-4. Specifications of the BMK guideline for the assessment of indoor air with regard to CO_2 (BMK, 2024d, p47)

Room class	Description	Arithmetic mean of instantaneous CO_2 [ppm]*
Class A+	Target value	≤ 800
Class A	Compliance value – for rooms in which intellectual work is carried out (e.g. classrooms)	≤ 1000
Class B	Compliance value – for other indoor rooms (e.g. dining areas, assembly halls, gymnasiums)	≤ 1400
Class C	Compliance value – for ancillary rooms (e.g. corridors, bathrooms)	≤ 5000
Outside of class	Rooms not used or occupied by people	> 5000

*** Note:** assessed as the arithmetic mean value over the assessment period (<u>usually 1 hour, or longer</u>).

The above guidance (Tbl. 2-4) is adapted from information set out in ISO 16000-41, wherein assessment takes place according to the arithmetic mean of the CO_2 concentration in the respective assessment period. These assessment periods are defined by the length of school classes during teaching time which can span from a 'school hour' (i.e. 1–2 h) up to a 'school day' (i.e. 6–8 h) (ISO, 2023).

Four different functional room classes are defined in Table 2-4, and according to this classification classrooms would be considered as Class A (≤ 1000 ppm CO_2) for compliance assessment purposes or Class A+ (≤ 800 ppm CO_2) in relation to setting target values. Corridors and bathrooms (i.e. indoor spaces with low usage time) would be considered as Class C[2] (≤ 5000 ppm CO_2). In this regard allowing up to 5000 ppm in communal corridors and toilets would appear to engender unnecessary risks (on account of the very low air change rates this would imply) and the fact that stale corridor air can easily migrate into adjacent classrooms . Moreover, whilst the majority of student time is spent in classrooms, it is estimated that students can spend up to an hour each day using the corridors between classes, as well as for school-related and extracurricular activities. This is partly because school corridors are also often used for day-to-day storage, which is less common in office buildings (Ng and Mills, 2024). Because of these unique requirements, the most recent version of ASHRAE Standard 62.1-2022 defines school corridors as a separate space type, with specific outdoor air ventilation requirements that are different from general corridors. Increasing ventilation in school corridors serves to reduce exposure to airborne contaminants in corridors but can also improve the overall IAQ in school buildings, since internal classroom doors are frequently opened and are sometimes left open for extended periods to promote cross ventilation of rooms (although this is not recommended unless ventilation or room temperature targets cannot otherwise be met).

In this context it is also important to note that studies show that SARS-CoV-2 can remain infectious in an aerosolised state for up to 16 hours (Fears et al., 2020) and as long as 4-days in poorly ventilated washrooms (X. Li et al., 2022). Moreover, evidence showing that SARS-CoV-2 aerostability is directly linked to the room-air CO_2 concentration (Haddrell, 2024), which challenges the logic of standards

[2] BMK (2024d, p48) states, "For indoor spaces with limited usage duration by people (e.g., hallways, wet rooms, auxiliary rooms, rarely used rooms), the arithmetic mean of the momentary values during the assessment period should not exceed 5,000 ppm CO_2 (Room Class C, MAK value according to the limit value regulation). Limited usage duration is defined as when a room is used by the same person for no more than half an hour per day." However in relation to the transmission of SARS-CoV-2 ventilation is important even in rooms with brief usage since according to Alsved et al., (2023) dependent on the viral emission rate "a susceptible person would inhale an infectious dose within 6 to 37 min in a room with normal ventilation".

that permit significantly elevated CO_2 thresholds, even in intermittently occupied spaces, particularly when such spaces are adjacent to continuously occupied rooms.

Position paper on ventilation requirements in educational institutions (German: Positionspapier zu Lüftungserfordernissen in Bildungseinrichtungen) – (BMK, 2024)

This paper is based on the “position paper on ventilation requirements in buildings” (German: “Positionspapier zur Bewertung von Innenräumen in Hinblick auf das Infektionsrisiko durch SARS-CoV-2”) (BMK, 2021) and the (now withdrawn) 2020 “position paper on school and classroom ventilation – SARS-CoV-2” (German: “Positionspapier zur Lüftung von Schul- und Unterrichtsräumen – SARS-CoV-2”). The updated publication makes the statement that, “intensively used school and classroom rooms or similar facilities such as kindergartens cannot usually be ventilated all year round by window ventilation alone” particularly in colder weather but also on busy streets where background noise conflicts with the requirement to provide fresh air (BMK 2024, pp 5-6). It goes on to state that, “if ventilation is sufficient with regard to the CO_2 parameter, it can generally be assumed that anthropogenically (man-made) air constituents and odours, pathogens, pollutants from building materials, furnishings and everyday objects as well as from the soil (radon) are efficiently removed.” However, it should be noted that this unreferenced assumption is contradicted by scientific evidence from in-situ studies in schools which show that acceptable CO_2 levels do not guarantee that other contaminants remain within safe limits (Csobod, 2014; McLeod et al., 2022).

In relation to defining acceptable limits for CO_2 the document refers to guidelines on CO_2 set out in the Directive on the Assessment of the Indoor Air of the BMK (2024d) (Tbl. 2.4).

Position paper on ventilation support measures for infection prevention (German: Positionspapier zu lüftungsunterstützenden Maßnahmen zur Infektionsprophylaxe) – (BMK, 2022)

This position paper from the ‘Indoor Air Working Group’ addresses the use of air purifiers and the introduction of active substances into indoor air. In relation to ventilation rates, the paper advises that, “The decisive factor is the volume of outside air supplied, often referred to as "fresh air". As a guideline, the respective room should be supplied with an outside air volume of around 35 m^3 per adult person present in the room per hour.” This figure corresponds to the requirements for workplaces for work with low physical strain, as defined in the Austrian Workplace Ordinance and the Austrian Guidelines for Cultural Activities (above), which are largely based on EU-directives (Arbeitsinspektion, 2020). The position paper also makes the unreferenced statement that, “For children, lower [airflow] values should be used depending on their age”, however, no specific values are provided and the scientific basis for this statement is not provided (BMK, 2022, p8). In regard to this assertion, it is worth noting that young children are known to be more vulnerable to air pollution than adults (Selgrade et al., 2008; Zhang et al., 2013; Cai et al., 2021). Moreover, Bakó-Biró et al., (2012) showed that the outcomes of tasks such as picture memory and word recognition could by increased by 8% and 15% respectively in school children when higher airflow rates (of 8 l/(s·person)) were provided. Similarly, Wargocki and Wyon (2017) reported that school-related performance can be reduced by up to 30% when indoor air quality is reduced.

In relation to the limitations of air purifiers the position paper notes that they cannot replace the sufficient hygienic provision of fresh air. Moreover in relation to airborne pandemics it is noted that air purifiers can be used to complement, but by no means replace, risk minimisation by a series of other measures (including the wearing of FFP2 masks, increasing natural or mechanical ventilation and reducing room occupant densities) (BMK, 2022, p26).

Position paper on the assessment of indoor spaces with regard to the risk of infection by SARS-CoV-2 (German: Positionspapier zur Bewertung von Innenräumen in Hinblick auf das Infektionsrisiko durch SARS-CoV-2) – (BMK, 2021)

The paper points out that the risk of infection with SARS-CoV-2 is related to the activities of the people in the building (speaking, shouting, singing and physical activity) and that the presence of many people in a confined space increases the risk. As a result, comparatively high risks arise in school rooms which are solely reliant upon window ventilation, and the paper recommends that suitable air purification devices can significantly reduce the risks in this context.

The paper advises that determining the absolute risk of infection transmission is a complex task, which also entails a high degree of uncertainty (e.g. due to constantly changing infection numbers, limited knowledge of the infectious viral quanta released by an individual as well as individual immunological risk factors). Therefore, the paper advocates that the calculation of the relative risk (i.e. the risk in a given room compared to a reference situation) can be more informative and more easily understood, particularly by laypersons (BMK, 2021, pp8–9). Relative risk assessments can also be helpful enablers of decisions at a political and building management level, since they can provide information regarding which rooms require additional precautions to protect against infection. At the same time the paper acknowledges the limitations of simplified airborne infection risk models, for example in situations where close-range effects (such as sneezing, coughing, or speaking in close proximity) outweigh the effects of long-range aerosol transmission.

In relation to CO_2 and the use of CO_2 monitors, the paper suggests that CO_2 measuring devices or "ventilation traffic lights" (i.e. RAG visual alerting systems) can give a relatively good indication of the risk of infection by SARS-CoV-2 and other viruses (particularly in the case of situations that are close to the standard situation described in terms of speech activity (4% speakers, i.e. one in 25 people), citing a white paper by Müller et al. (2020). The paper notes however, that the association between CO_2 and airborne infection risk breaks down in environments were multiple people are speaking or singing, or conversely when additional filtration measures (masks, room air cleaners etc) are used.

2.5.2 European (CEN) standards

EN 16798-1:2019. Energy performance of buildings – Ventilation for buildings – Part 1 – (CEN, 2019)

It should be noted that EN 16798-1 is both a CEN standard (CEN, 2019) and an Austrian standard (ÖNORM EN 16798-1) (CEN, 2024) but is described here to distinguish it from standards that have purely a national scope. EN 16798-1 provides criteria for assessing the ventilation and energetic performance of buildings in relation to the indoor environment. A number of performance guidelines are specified in the standard, including threshold CO_2 concentrations and ventilation airflow rates. This guidance is intended primarily for offices and spaces with a similar type of activity, including classrooms, and as such it assumes that the activities occurring in such spaces are sedentary (≈ 1.2 met).

In order to interpret the guidance provided in EN 16798-1 it is first necessary to define the category of indoor environmental quality (IEQ) appropriate to the level of expectation suitable for the occupants of the building (Tbl. 2-5). According to the standard "a normal level would be 'Medium' (which corresponds to IEQ_{II}), whilst a 'High' level (which corresponds to IEQ_{I}) may be selected for 'occupants with special needs (children, elderly, persons with disabilities, etc.)'" (CEN, 2019, p18). Since schools are predominantly occupied by children and some school occupants will also have disabilities and additional special needs (or be in high risk groups for asthma or airborne diseases etc.) the category IEQ_I ('High') offers the most appropriate category for the safe and inclusive operation of classrooms. This is particularly so in the context of dynamic occupancy, where the precise age and health status of all the room occupants is typically unknown. In this context it should be noted, however, that the guidance in EN 16798-1:2024 is not intended as 'health-based' guidance per-se. Notably, the ventilation rates specified are unchanged since the previous version of the standard (EN 16798-1:2019) was issued, prior to the COVID-19 pandemic. The values provided should not therefore be interpreted 'a priori' as being prophylactic or health-based, from the perspective of mitigating the spread of airborne disease.

Table 2-5. EN 16798-1 Categories of indoor environmental quality (CEN, 2019)

Category	Level of expectation
IEQ_I	High
IEQ_{II}	Medium
IEQ_{III}	Moderate
IEQ_{IV}	Low

In relation to acceptable CO_2 concentrations EN16798-1 stipulates that the following values (Tbl. 2-6) are appropriate, assuming a standard CO_2 emission rate[3] of 20 l/(h·person) for non-adapted persons[4]. On the basis that classrooms should be designed for an occupancy type which corresponds to IEQ_I it can be seen (Tbl. 2-6) that 975 ppm (or approximately 1000 ppm in urban areas) should be used as the upper threshold limiting value for the indoor CO_2 concentration in accordance with this normative standard.

Table 2-6. EN 16798-1 Default design CO_2 concentrations above outdoor concentration (CEN, 2024)

Category	Corresponding CO_2 [ppm] concentration above outdoors	Indoor CO_2 [ppm] threshold concentration (2024)[5]
IEQ_I	550	975
IEQ_{II}	800	1225
IEQ_{III}	1350	1775
IEQ_{IV}	1350	1775

In relation to determining the minimum airflow rate during occupied periods EN 16798-1 advises that due to health reasons the total minimum airflow rate during occupancy, expressed as l/s per person, should never be below 4 l/(s·person). This is because a minimum airflow rate of 4 l/(s·person is needed to dilute human bio-effluents, with an additional component required for building and activity related emissions (CEN, 2019, p51). The design ventilation airflow rate is therefore always comprised

[3] The CO_2 emission rate for children depends on their age, sex, and activity level. For sedentary activities across the age range of 5–18 years Wu et al., (2023) report a mean value of 0.00367 l/(s·person) or 13.2 l/(h·person).
[4] A 'non-adapted person' is defined as a person who has not occupied the space for more than 15 minutes and adapted to the odour level of bio-effluent from the occupants (Olesen, 2015). Non-adapted criteria are generally used for assessing the performance of non-residential buildings such as schools and offices.
[5] Assumes a mean background CO_2 concentration of 425 ppm (Ludewig, 2024) note that a higher background concentrations (e.g. circa 450 ppm) may be applicable for buildings located in dense urban areas where the European continental background value is increased by localised CO_2 emission sources.

of two parts (a) ventilation to dilute/remove pollution from the occupants (i.e. bio effluents) and (b) ventilation to remove/dilute pollution from the building fabric and systems.

Three methods are provided in EN 16798-1 to specify appropriate airflow rates. These methods assume complete mixing of the fresh supply air in the room (i.e. the concentration of pollutants at the exhaust location is equal to that in the occupied zone). For non-residential buildings, ventilation rates should be adjusted by the ventilation effectiveness (Ɛ) in accordance with EN 16798-3 if the air distribution differs from that of complete mixing.

EN 16798-1 method 1: based on perceived air quality

This method combines two components, the first is the design ventilation rates for sedentary adults (Tbl. 2-7) (which assumes non-adapted persons) for diluting emissions (i.e. bio effluents) from people, which are stated as per person airflow rates according to the respective IEQ category (Tbl. 2-5). These values are in turn defined by estimates of the expected percentage of persons dissatisfied (with the room odour) (Fig. 2-1) at the given airflow rate, wherein category IEQ_I would correspond to a dissatisfied vote of 15% (CEN, 2019).

Table 2-7. Design ventilation rates for diluting emissions (bio effluents) from people (CEN, 2024)

Category	Expected Percentage Dissatisfied	Airflow per non-adapted person [l/(s·person)]
IEQ_I	15	10
IEQ_{II}	20	7
IEQ_{III}	30	4
IEQ_{IV}	40	2.5

Depending on the IEQ category, and whether the building is considered to be a "very low", "low", or "non-low" polluting building[6], an additional airflow is then added to the per person ventilation rates.

Table 2-8. Design ventilation rates for diluting emissions from different types of buildings (CEN, 2024)

Category	Very low polluting building LPB-1 [l/(s·m²)]	Low polluting building LPB-2 [l/(s·m²)]	Non low polluting building LPB-3 [l/(s·m²)]
IEQ_I	0.5	1.0	2.0
IEQ_{II}	0.35	0.7	1.4
IEQ_{III}	0.2	0.4	0.8
IEQ_{IV}	0.15	0.3	0.6

By combining the bio-effluent dilution rate (Tbl. 2-7) with the building emission dilution rate (Tbl. 2-8) the design ventilation flow rate can be determined for a specific room. In the following example it is assumed that 24 students and one teacher occupy a 50 m^2 low polluting classroom, as non-adapted persons with a 'High' level of expectation (i.e. IEQ_I).

[6] The building is considered low or very low polluting if the majority of the interior materials are low or very low emitting. Detailed criteria for the different building types are set out in EN 16798-1 Section B.4 and Tbl. B.17.

Table 2-9. Example: EN 16798-1 method 1 ventilation air flow rate calculation for a low polluting building (LPB-2)

Category	Low polluting building LPB-2 [l/(s·m^2)]	Airflow per non-adapted person [l/(s·person)]	Total design ventilation air flow [l/(s·person)]
IEQ_I	1.0	10	12
IEQ_{II}	0.7	7	8.4
IEQ_{III}	0.4	4	4.8
IEQ_{IV}*	0.3	2.5	3.1

* Note: The design air flow for IEQ_{IV} is below the threshold of 4 l/s per person, so cannot be used in this case

The above example (Tbl. 2-9) illustrates the calculation of the total design ventilation flow rate using EN 16798-1 (2019) according to the building type, room size, occupancy number, and IEQ category. In this particular example, a total design airflow rate of 12 l/(s·person) is needed to comply with the standard. However, in practice, since it is not always possible to know whether the building will always be operated as a 'low polluting' building or whether the room occupancy will at some point increase, the system should be designed with some additional capacity to cope with these eventualities.

EN 16798-1 method 2: based on limit values of a substance concentration

This method uses a mass balance formula based on the steady state substance concentration in the space (e.g. CO_2) taking into account the outdoor concentration, using Eq. 2-2.

$$Q_h = \frac{G_h}{C_{h,i} - C_{h,o}} \cdot \frac{1}{\varepsilon_v} \qquad [2\text{-}2]$$

Where,
Q_h is the ventilation rate required for dilution, in m^3 per second;
G_h is the generation rate of the substance, in micrograms per second (or l/s);
$C_{h,i}$ is the guideline value of the substance, in micrograms per m^3 (or ppm*10^{-3});
$C_{h,o}$ is the concentration of the substance of the supply air, in micrograms per m^3 (or ppm*10^{-3});
ε_v is the ventilation effectiveness (1 for complete mixing, default values in EN 16798-3 (CEN, 2022)).

If CO_2 is used as a tracer of human occupancy, the default design values are provided in Table 2-6. This method is typically used for demand controlled (DC) mechanical ventilation but can also be used in naturally ventilated rooms in conjunction with one (or more) appropriately sited CO_2 sensors. Once again, consideration needs to be given to the appropriate selection of health-based CO_2 thresholds (Section 2.5.6) in schools, since the threshold values specified in EN 16798-1 (Tbl. 2-6) (i.e. IEQ_I = 975 ppm) were not intended as thresholds suitable for airborne pathogen mitigation and nor do they guarantee optimal learning outcomes.

EN 16798-1 method 3: based on predefined ventilation flow rates

The total design ventilation air flow rate can be either expressed as a required airflow rate per person (l/(s·person)) or as a required rate per m^2 of floor area (l/(s·m^2). An illustration is provided below (Tbl. 2-10), based on the previous example (for a 50 m^2 classroom with 25 occupants) used in method 1 (above).

Table 2-10. Example: EN 16798-1 method 3 - applied to an example classroom

Category	Total design ventilation air flow rate for room	
	[l/(s·person)]	[l/(s·m²)]
IEQ_I	12	6
IEQ_{II}	8.4	4.2
IEQ_{III}	4.8	2.4
IEQ_{IV}*	3.1	1.55

* Note: The design air flow for IEQ_{IV} is below the threshold of 4 l/(s·person), so cannot be used in this case

<u>EN 16798-2:2019. Energy performance of buildings – Ventilation for buildings – Part 2</u> – (CEN, 2019a)

The European standard EN 16798-2 explains how to interpret and apply the information in EN 16798-1. The document specifies methods for the long term evaluation of the indoor environment based on calculations or room based measurements. The standard also provides criteria which can be used, if required, to measure compliance during inspections. It also identifies the key parameters to be used when monitoring and displaying indoor environmental parameters in existing buildings. The standard also explains how the different IEQ category criteria for the indoor environment (Tbl. 2-5) can be applied in practice.

EN 16798-2 emphasises the importance of source control (i.e. limiting the release of harmful contaminants) in any ventilation strategy, since air pollutants are often generated indoors. Stating that *"source control should as often as possible be the primary strategy for controlling the level of air substances"* (CEN, 2019a, p17) whilst pollution remaining after source control should be dealt with by dilution or displacement at appropriate air flow rates.

Source control in the context of schools implies careful specification of materials used in the both the construction and finishes within a building as well as limiting the introduction of potential contaminants through furniture office equipment, disposable materials and cleaning products. In relation to airborne pathogens it means that reduced occupancy (i.e. staying home when sick and/or reducing class sizes during pandemics) and masking can play an important role in reducing the concentration of infectious particles in a space.

2.5.3 Examples of best practice in other European nations

Air quality initiatives, standards and directives are rapidly evolving in a number of European countries in relation to the operation of public buildings, including schools. Prompted by the COVID-19 pandemic a number of countries have recently tightened their policies and/or developed new legislation to provide stricter control of indoor air quality in schools. In addition many governments and regional governments have provided funding for CO_2 sensors, ventilation systems and air cleaning devices to support the delivery of such targets. Listing every example of emerging best practice would be too numerous to describe, so two key examples are drawn here to illustrate recent developments in Belgium and France.

Belgium

Belgium was the first European country to mandate CO_2 measurement in all closed spaces accessible to the public (Morawska, 2024a). "The Belgium Clean Air Law: A Law to Improve Indoor Air Quality in Enclosed Spaces Open to the Public" was enacted on the 6th November, 2022 (Belgian statutes, 2022). This law entered into force ten days after its publication, however the obligations set out in this statute will take force in stages. The requirement to use at least one CO_2 meter; draw up a risk analysis; and draw up an action plan (if the risk analysis shows that this is necessary) will become mandatory from 1 January 2027. Initially, these obligations will only apply to certain closed spaces accessible to the public. The scope will then be extended to cover all spaces by the end of 2037.

In a second phase, spaces that have met the initial provisions will be able to implement the following points (apply for certification of the space; display the certification label awarded; and continue to operate the space under technical conditions at least equivalent to those existing at the time of certification). This will be carried out on a voluntary basis initially, once the certification process has been set up. These provisions will then become mandatory, at the earliest on 1 January 2038 (i.e. once all closed spaces accessible to the public are covered by the first obligations).

This legislation means that, as of 1 January 2027, all specified public spaces (including schools) in Belgium will be required to commence measuring the IAQ and abide by the obligations set out in the act. The act (article 3, paragraph 1) describes two reference levels for CO_2 monitoring:

(i) Reference level A corresponds to a CO_2 concentration in the premises that is generally *less than 900 ppm or a minimum ventilation and air purification rate of 40 m^3 per hour per person* (of which at least 25 m^3 per hour per person is ventilation with outside air).
(ii) Reference level B is a CO_2 concentration in the premises that is generally less than 1200 ppm or a minimum ventilation rate with outside air of 25 m^3 per hour per person.

It should be noted that the law does not obligate those responsible for the spaces to meet these specific targets, rather these references provide benchmark indicators which enable the quality of the air present to be assessed.

One of the key obligations (for any space open to the public) is “the provision and communication of the label by display or any other means as soon as the certification (referred to in point 4 of the Article) has been obtained” (Belgian statutes, 2022). Each space will be assigned a label that must be displayed at the location, this will inform the public that the IAQ is being measured and controlled in order to minimise the negative impact the air could have on people's health. The law also creates a platform and database for IAQ, which will serve to broaden the existing scientific knowledge base as well as advising policymakers, and raising public awareness (HFCSE, 2024).

France

Since 2012 there have been statutory requirements (Decree No. 2012-14) to evaluate the means of ventilation in all teaching rooms in middle schools and high schools in France (as well as rooms used for sports, canteens and dormitories). In addition reception rooms housing children under the age of six years and also leisure centres are obliged to comply with this law. This decree was revised in December 2022 (Decree 2022-1690), amongst the amendments the new statute defines the direct measurement of the CO_2 concentration as a requisite step in the annual assessment of the means of aeration. It also provides thresholds for triggering pollutant measurement campaigns and their implementation deadlines (République Française, 2022a) (Nous aérons, 2023).

A further ordinance (JORF No. 0301), which entered into force on 1 January 2023 (République Française, 2022b), sets out the conditions for carrying out direct-reading measurements of CO_2 concentrations in indoor air as part of the annual assessment of ventilation systems. As well as specifying the required measurement precision, positioning of the sensor in the room, length of the measurement period and the required occupancy conditions, the ordinance also sets out the correct interpretation of the measurements. *According to the ordinance a CO_2 concentration of less than*

800 ppm indicates satisfactory air renewal in occupied premises. If this value is exceeded, action must be taken to restore satisfactory air quality. Conversely, a CO_2 concentration exceeding 1500 ppm indicates inadequate air renewal. If this value is exceeded, immediate action must be taken to address the causes of the exceedance and restore satisfactory air renewal quality (République Française, 2022b).

2.5.4 International standards

ASTM D6245-18 – Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation – (ASTM, 2024)

The American Society for Testing and Materials (ASTM) is a developer of international voluntary standards which govern environmental and engineering services. ASTM D6245 includes guidelines on using indoor CO_2 concentrations to determine outdoor air ventilation rates, using an approach based on the work of Persily and de Jonge (2017). This approach is referred to as an equilibrium analysis and is based on a steady-state, single-zone mass balance calculation of CO_2 in the building (see Eq. 2-2).

ASTM D6245-24 (ASTM, 2024) cautions that mass-balance calculations are sometimes presented with little or no discussion of their limitations or the assumptions on which they are based, and as a result the technique has been misused and indoor CO_2 concentrations may have been misinterpreted. Paradoxically, the standard itself offers potential for misinterpretation in this respect since it states that, "One approach to estimating the air change rate of a zone involves tracking the amount of time it takes for the CO_2 concentration to decrease from one concentration value to a lower one after the occupants have left a space" (ASTM, 2024, p16). Without further precision this statement is potentially misleading since what is being measured by such a decay test is likely to be the background infiltration rate, or more precisely the residual air change rate (ACR) in a multi-room building. This is because the CO_2 decay profile in a given room is influenced not only by the infiltration and exfiltration of outdoor air but also by the ingress and egress of air to and from adjacent rooms. This point is particularly pertinent in classrooms where windows are likely to be closed, and ventilation systems set-back or turned off when the occupants leave the building.

The guide also describes the determination of more precise CO_2 generation rates from people as a function of body size and their level of physical activity (Li et al., 2024). In addition, ASTM D6245 describes how measured values of indoor carbon dioxide (CO_2) concentrations can be used in evaluations of indoor air quality and building ventilation.

ISO 16000-26:2012. Indoor air – Part 26: Sampling strategy for carbon dioxide (CO_2) – (ISO, 2012)

ISO 16000-26:2012 emphasises the importance of careful planning in relation to indoor pollution measurements based on the measurement of CO_2. In the case of indoor air measurements, the sampling and measurement strategy are of particular significance since the results of such measurement campaigns can have far-reaching consequences, for example, with regard to ascertaining the need for remedial action or the viability of existing ventilation methods.

In terms of the measurement location ISO 16000-26 recommends that for rooms of a surface area of up to 50 m^2 it is generally sufficient to have one sampling point per room, that should be at a height of 1.5 m and should be at a distance of at least 1 m to 2 m from the walls. For larger rooms, more sampling sites should be provided to ensure that any concentration gradients are determined. In the case of school classrooms locating sensors 1–2m away from a wall is likely to be impractical (as it would conflict with seating layouts) and is likely to mean that the sensor would not be attached to a permanently fixed surface. Moreover, since school pupils are generally seated in classrooms measurement of the CO_2 concentration at breathing height (i.e. 1.1–1.2m above floor level) is more indicative of the actual concentration inhaled by the students.

The standard advises that measurement uncertainty should be considered in the context of measurement planning, and that measurement uncertainty should be appropriately described. In the measurement results, it is suggested that numerical data are usually reported so that the last decimal place (significant figure) reflects the order of magnitude of the measurement uncertainty. In relation to quality assurance the standard recommends that the calibration procedures used (including how often, and how extensively, measurement devices are calibrated) should be clarified prior to any monitoring campaign. Table B.1 in Appendix B of ISO 16000-26 provides a summary of the general classification of IAQ and CO_2 concentrations indoors, based on EN 13779, however since that standard is now withdrawn the values have not been included here.

ISO 16000-41:2023 – Indoor air – Part 41: Assessment and classification – (ISO, 2023)

ISO 16000-41:2023 defines a procedure for the assessment of IAQ that is valid for all interior rooms in both residential and non-residential buildings, using either natural or mechanical ventilation. The standard points out that the concentrations of substances in the room air can fluctuate significantly across a space, over time, and in relation to usage-specific activities. This underscores the importance of longitudinal studies that span the full operating cycle of the building being studied.

For the assessment of IAQ the ISO 16000-41:2023 standard classifies the room air into three quality classes A (High), B (Medium), and C (Low), based on the evaluation of key IAQ parameters (Tbl. 2-11). If any of the main criteria do not permanently fulfil quality class C, the indoor air is considered to be "outside all quality classes" (ISO, 2023).

Table 2-11. Overall indoor air quality classes (ISO 16000-41)

Quality class	Designation	Description
A	High room air quality	Low substance concentrations
B	Medium room air quality	Average substance concentrations
C	Low room air quality	Above-average substance concentrations
Lowest air quality class not fulfilled		Concentrations above class C limits

The main prescribed parameters that must be included for a complete assessment of the IAQ are listed as follows: formaldehyde, volatile organic compounds (VOCs), radon, carbon dioxide, mould (microbial infestation), odour, fine dust (PM_1, $PM_{2.5}$, PM_{10}) and ultrafine particles (UFPs) in accordance with the respective limiting values provided.

In relation to the assessment of CO_2 in school classrooms the standard recommends restricting the assessment period to the time of most intensive, but still common usage, whereby the duration of breaks before or after a class are also included. In this respect the daily monitoring period for a typical school might last from the beginning of instruction to the end of instruction (i.e. 6–8 hours), or for the duration of an individual lesson (i.e. 1-2 hours) (ISO, 2023).

Table 2-12. Indoor air quality classes for CO_2 (ISO 16000-41) (ISO, 2023)

Quality class	Description	Arithmetic mean of instantaneous CO_2 [ppm]
A	Requirements for indoors rooms for the continuous stay of persons in which intellectual activities are carried out or which are used for regeneration	≤ 1000
B	General requirements for indoor rooms for the continuous stay of persons	> 1000 ≤ 1400
C	Requirements for indoor rooms with brief use by persons	> 1400 ≤ 5000
Outside of class	Not acceptable for use by persons	> 5000

The ISO 16000-41:2023 standard underpins the CO_2 targets and compliance values prescribed in the "Positionspapier zu Lüftungserfordernissen in Bildungseinrichtungen" (BMK 2024) according to specific room usage types. It should be noted that there are some discrepancies between the adaptation of Tbl. 2-12 in the ISO standard and its implementation in the BMK position paper (Tbl. 2-4), wherein the target class A+ in the BMK guidance does not form part of the ISO classification. Moreover, in the BMK guidance (Tbl. 2-4) it is indicated that class C is appropriate for bathroom and corridor spaces, whilst the precise interpretation of the ISO standard is unclear in this regard since the meaning of the term "brief use" is undefined. In this respect it should also be noted that the ISO standard only considers the direct health and wellbeing consequences of exposure to individual pollutants (e.g. bioeffluent or CO_2), and not for example the consequential risk of airborne disease transmission, which has been shown to be indirectly associated with the CO_2 concentration.

ISO 17772-1 – Energy performance of buildings – Indoor environmental quality Part 1: Indoor environmental input parameters for the design and assessment of energy performance of buildings – (ISO, 2017)

ISO 17772-1 addresses the energy consumption of buildings and the indoor environment including heating, cooling, ventilation, and lighting as well as the design and operation of buildings and their systems. The standard adopts the concept of using four different categories of indoor environmental quality ranging from 'High' to 'Low' in common with EN 16798-1 (Tbl. 2-5). Similarly to EN 16798-1, ISO 17772-1 states that, "a higher level might be selected for occupants with special needs (children, elderly, handicapped, etc.)". Whilst at the same time making the unreferenced statement that "a lower level will not provide any health risk but might decrease comfort" (ISO, 2017, p7). However, when such a concept is applied to the room CO_2 concentration or ventilation rate there may be significant indirect health implications associated with the choice of IEQ category, as evidenced in a number of recent studies (Schwarzbauer, 2021; Buonanno, 2022; Pollozhani, 2024).

The methods of sizing ventilation airflow rates described in ISO 17772-1 (ISO, 2017) are based on the dilution of human bio effluents and background emissions (from the building fabric and usage type), which are identical to the methods described in EN 16798-1 (Tbls. 2-7, 2-8). Similarly, the method of using limit values of a substance concentration, such as CO_2, to define ventilation threshold limits are identical to method 2 of EN 16798-1. Therefore, from a ventilation sizing and CO_2 threshold concentration perspective the two standards can be considered as being identical.

<u>ASHRAE 62-1 – Ventilation and Acceptable Indoor Air Quality</u> – (ASHRAE, 2022)

ASHRAE 62-1 is part of a suit of building performance standards developed by the American Society of Heating Refrigeration and Air conditioning Engineers (ASHRAE). Standard 62.1 (covering commercial, institutional and high-rise residential buildings) specifies minimum ventilation rates and other measures intended to provide IAQ acceptable to human occupants and to minimise adverse health effects. The standard was updated in 2022 and is widely used as a default design standard for the sizing of ventilation systems in North America and in many other countries worldwide.

According to ASHRAE 62.1 the outdoor air quality must be investigated prior to completing a ventilation system design. This investigation requires documentation of the outdoor air quality at both the regional and local level. At the local level this includes identification of potential contaminant sources on the site and from adjoining properties including any that operate only seasonally (ASHRAE, 2022). It is notable that such a comprehensive assessment of the outdoor air quality, during the planning stage, is not mandated in equivalent European ventilation standards.

In relation to minimum ventilation rates, the revised standard states that school classrooms must be operated at or above a minimum ventilation rate of 5 l/(s·person) with an additional area weighted component of 0.6 l/(s·m^2) (to account for building related emissions). Therefore, assuming a minimum classroom occupant density of 3 m^2/person, the combined minimum ventilation rate would be 6.8 l/(s·person). This value is well below the corresponding level indicated by EN 16798-1 at IEQ_I and is also lower than the IEQ_{II} value (Tbl. 2-7) and the values stated in ÖNORM H 6039:2023 (Tbl. 2-3).

When applied in 'real-world' contexts the application of such standards need to consider the 'performance-gap' occurring between the values stated in design standards and the measured in-situ performance of ventilation systems. Haverinen-Shaughnessy et al., (2011) point out that a significant percentage of US schools were found to be under-ventilated relative to the version of ASHRAE 62.1 in place at the time they were designed. Research by Persily (2021), confirms that there are numerous reasons why actual ventilation performance often fails to match the design intent.

2.5.5 Summary of European and international normative standards and guidelines

It is important to emphasise that the fresh airflow ventilation rates prescribed in EN 16798-1:2019, ISO 17772-1:2017 and ASHRAE 62.1 originate largely from studies that investigated the effects of indoor air pollutants from the perspective of human perceptions of air quality. In other words they are derived from laboratory and field-tests carried out on individuals whose olfactory systems were either 'adapted' or 'non-adapted' to various bio-effluents and building-related pollutants (both separately and in combination) (Fanger and Berg-Munch, 1983; Berg-Munch et al., 1986; Gunnarsen and Ole Fanger, 1992; Wargocki, 2004; Wargocki and Kostyrko, 2022). The airflow rates prescribed by these standards are therefore primarily based on the 'perceived air quality' as opposed to the actual 'air quality' (from a toxicological or health-based perspective).

It has been implicitly assumed that the ventilation rates prescribed by EN and ISO standards would create protection against other risks, including the risks arising from common indoor air pollutants, however this is not explicitly stated and nor is there clear evidence to support this assumption (Carrer, 2018). Indeed the fact that some of the earlier odour adaptation research, underpinning these standards, included testing occupant adaptation to cigarette odours (e.g. Gunnarsen, 1992) without consideration of the associated health risks, illustrates a fundamental limitation of this approach from a health-based perspective.

Moreover, the ventilation implications of addressing the health risks associated with seasonal and/or pandemic airborne diseases are not addressed by the current European norms and ISO standards. Therefore such standards are only applicable to indoor spaces where the criteria for indoor environments are defined solely by human occupancy (i.e. where the processes occurring in the room, and environmental contaminants in the surrounding air do not have a major impact on the indoor air quality). In everyday practice such environments are extremely rare. In this regard, Wargocki and Kostyrko (2022) concluded that olfactory methods should be considered supplementary to the use of chemical measurements as neither method can independently provide complete characterization of indoor air quality. It could be argued that from a holistic perspective such a formulation still ignores the critical dimension of biological contaminants, associated with both seasonal and epidemic airborne diseases as well as the building biology.

Table 2-13. Summary table of normative standards and guidelines for CO_2 concentration and ventilation

Country	Name	Year	CO_2 Values	Ventilation Rate Values	Value Type *	Notes
AUT	Arbeitsstätten-verordnung (AStV)	2024		35 m³/(h·person), for low physical loads (p.l.) 50 m³/(h·person), normal p. l. 70 m³/(h·person), high p. l.	Limit Value	For mechanical ventilation und different physical loads (p.l.)
AUT	ÖNORM H 6039:2023	2023	≤ 1000 ppm for classrooms (arithmetic mean over a school lesson)	For 1000 ppm: 28 m³/(h·person), < 10 yr. 33 m³/(h·person), 11-18 yr. 36 m³/(h·person), > 19 yr.	Guideline Value	≤ 1400 ppm for secondary rooms (arithmetic mean over a school lesson)
AUT	BMK - Richtlinie zur Bewertung der Innenraumluft – Kohlenstoffdioxid als Lüftungsparameter	2024	Room Cl. A+: ≤ 800 ppm Room Cl. A: ≤ 1000 ppm Room Cl. B: ≤ 1400 ppm Room Cl. C: ≤ 5000 ppm		Guideline Value	A: classrooms; B: secondary rooms (no intellect. activ.); C: low occupancy rooms (< 0.5 h/day)
EU INTL	EN 16798-1:2024 ISO 17772-1:2017	2024 2017	IEQ_I: ≤550 ppm ab. o.d. IEQ_{II}: ≤800 ppm ab. o.d. IEQ_{III}: ≤1350 ppm ab. o.d. IEQ_{IV}: ≤1350 ppm ab. o.d.	IEQ_I: 10 l/(s·person) IEQ_{II}: 7 l/(s·person) IEQ_{III}: 4 l/(s·person) IEQ_{IV}: 2,5 l/(s·person)	Guideline Value	IEQI: High level expectations (e.g. for children); IEQII: Medium level expectation.
INTL	ISO 16000-41:2023	2023	Qlt.Cl. A: ≤ 1000 ppm Qlt.Cl. B: 1001–1400 ppm Qlt.Cl. C: 1401–5000 ppm Not accept.: > 5000 ppm		Guideline Value	A: for continuous stay (with intellect. activity); B: general req. for continuous stay; C: for brief use
USA	ANSI/ASHRAE Standard 62.1-2022	2022		5 l/(s·person) for classrooms	Guideline Value	3.8 l/(s·person) for lecture halls. Additional Area Outdoor Air Rate of 0.3–0.6 l/(s·m²) req.
USA	ASHRAE Standard 241-2023	2023		20 l/(s·person) for classrooms	Guideline Value	25 l/(s·person) for lecture halls. Only applicable under pandemic conditions.

GER	ASR A3.6	2018	< 1000 ppm		Limit Value	For Workplaces: 1000–2000 ppm: optimization required; >2000 ppm: further action req.
INTL	WHO - Roadmap to improve and ensure good indoor ventilation in the context of COVID-19	2021		10 l/(s·person)	Guideline Value	Ventilation rate acc. to EN 16798-1

* Limit Value: A legally established assessment value that must be adhered to.
Guideline Value: A toxicologically justified value based on established toxic effects and dose-response relationships of the substance.

2.5.6 Health based ventilation standards

The first documented appearance of Sick Building Syndrome (SBS) in the mid-1970s has been widely attributed to the reduced ventilation flowrates in commercial buildings, which were implemented in response to strategies to increase energy efficiency, following the Arab oil embargo of 1973 (Boslaugh, 2023). A subsequent report by the WHO, in 1984, suggested that up to 30% of new and refurbished buildings worldwide may be the subject of excessive complaints related to indoor air quality (IAQ) (USEPA, 1991). The so called 'Sick Building Syndrome era', caught the attention of researchers and seeded a new field of study focused on indoor air quality (IAQ). In the 1980s and 1990s, this emerging research field generated evidence suggesting that ventilation rates, above the existing minimum standards, were associated with numerous health and cognitive benefits. Since this time, research efforts have continued to expand the knowledge base and value proposition of better indoor air quality (Allen, 2024). Amongst numerous related findings, studies have documented that higher ventilation rates are associated with better mathematic and reading scores in students (Petersen, 2016), reduced school absenteeism (Mendell, 2013), reduced workplace absenteeism (Myatt et al., 2002), lower risk of respiratory disease infection (Riley, 1980; Rudnick and Milton, 2003), higher cognitive function scores (Allen et al., 2016), and improved workplace performance (Seppänen, 2006). In addition to these benefits researchers at Lawrence Berkeley National Laboratory (LBNL) estimate a combined potential for more than $20 billion (USD) in economic benefits could be accrued by the US economy as a result of improvements to ventilation (Fisk et al., 2011) (Allen, 2024).

The concept of 'health-based' ventilation standards is a logical progression of this research and the short-comings of existing olfactory-based methodologies (Section 2.5.5). Following the COVID-19 pandemic, this concept was further developed as a means of providing additional prophylaxis to reduce the likelihood of long-range airborne disease transmission at periods when the risks are elevated. This approach is generally considered as an adjunct to existing standards and guidance, such that 'health-based' standards are used to respond intermittently to seasonal or epidemic waves in infection. In recent years professional ventilation organisations in Europe (e.g. CIBSE, REHVA) and North America (ASHRAE/ANSI) as well as medical consortia (e.g. The Lancet COVID-19 Commission) have been at the forefront of advancing new 'health-based' ventilation standards.

<u>REHVA</u> – COVID-19 Guidance (REHVA, 2021)

In response to the pandemic the Federation of European Heating, Ventilation and Air conditioning Associations (REHVA) produced detailed operational guidance for public buildings. As part of this guidance REHVA advocated the use of CO_2 sensors to regulate ventilation in public buildings, including classrooms; stating that "*During an epidemic it is recommended to temporarily change the default* *settings of the traffic light indicator so that the yellow/orange light (or warning) is set to 800 ppm and the red light (or alarm) up to 1000 ppm in order trigger prompt action to achieve sufficient ventilation even in situations with reduced occupancy*" (REHVA, 2021, p16). In relation to the operation of mechanical ventilation systems REHVA made the recommendation to "*to change the CO_2 setpoint to 550 ppm in demand-controlled ventilation systems, in order to maintain the operation at nominal speed*" (REHVA, 2021, p4). This advice is intended to cover both the occupied period and the unoccupied (or partially occupied) pre- and post-conditioning periods.

The guidance also emphasises the importance of 'short-range' transmission routes, wherein the commonly accepted distance of 1.5 m, for the trajectory of large respiratory droplets, applies only if there is no air movement in the room. Typical air distribution in rooms with human occupancy, from ventilation and convection air flows from heat gains, can cause air velocities between 0.05–0.2 m/s. Using these velocities as plausible lower and upper bounds, together with particle settling velocities, estimates of how far droplets can travel, before falling a height of 1.5 m to the ground (under the influence of gravity), can be made. Accordingly, these estimates illustrate that droplets, even as large as 30 µm, can travel in excess of 10 m before settling (REHVA, 2021), thus blurring the boundary between conventional assumptions regarding short-range vs. long-range transmission.

WHO – Roadmap to improve and ensure good indoor ventilation in the context of COVID-19 (WHO, 2021a)

In response to the COVID-19 pandemic the WHO presented guidance to ensure that all public buildings provided appropriate ventilation to minimise the spread of the disease. The WHO guidance recommends 10 l/(s·person) as a minimum ventilation rate for non-residential settings (WHO, 2021). Whilst the WHO endorsement of this minimum ventilation rate adds weight to its use, it should be noted that this value was not derived using a health-based risk analysis methodology but was simply based on adopting the highest category (IEQ_I) set out in EN 16798-1:2019 (CEN, 2019).

The Lancet – Designing infectious disease resilience into school buildings through improvements to ventilation and air cleaning (The Lancet COVID-19 Commission, 2021)

The Lancet COVID-19 Commission Task Force on Safe Work, Safe School, and Safe Travel set out to provide schools with strategic, evidence-based guidance for healthy building-level interventions to reduce the risks of airborne infectious disease transmission in schools. According to the report *"Buildings play a critical role in minimizing, or conversely exacerbating, the spread of airborne infectious diseases. COVID-19 outbreaks occur indoors, and within-room long-range transmission beyond two meters (six feet) has been well-documented in conditions with no masking and low ventilation rates"*. The report also notes that, "*Building-related interventions have been shown to reduce the spread of many other airborne infectious diseases, including severe acute respiratory syndrome (SARS), Middle East respiratory syndrome (MERS), tuberculosis, measles, and influenza*" (The Lancet COVID-19 Commission, 2021, p3).

To address this issue the The Lancet COVID-19 Commission (2021) report recommended prioritizing five control strategies (Tbl. 2-14).

Table 2-14. Five priority control strategies (The Lancet COVID-19 Commission, 2021)

	Recommended control strategies
1	Commission buildings and examine existing systems
2	Ventilate with clean outdoor air
3	Improve the building's air cleaning efficiency through evidence-based air cleaning treatment such as filtration
4	If the ability to upgrade ventilation and air cleaning is limited, use portable air cleaners with high efficiency particulate air (HEPA) filtration
5	Consider other evidence-based air cleaning approaches in the context of existing strategies

The Lancet guidance notes that building-level strategies to reduce the risk of airborne infectious disease transmission in schools (Tbl. 2-14) must be considered in the context of a layered approach to infection prophylaxis. In this regard they suggest that masks are a critical control strategy during an airborne disease pandemic since they serve two key roles: (i) reducing the concentration of infectious respiratory particles emitted by the wearer who is infected (i.e. 'source control'), and (ii) reducing the concentration of particles breathed in by the wearer who is susceptible (i.e. the 'receptor') (The Lancet COVID-19 Commission, 2021).

The Lancet – Proposed Non-infectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Infectious Diseases (The Lancet COVID-19 Commission, 2022)

The Lancet COVID-19 Commission Task Force on Safe Work, Safe School, and Safe Travel updated their guidance in November 2022, stating that "*There is urgency in setting new minimum standards that can help reduce respiratory disease risk indoors and promote better health overall*" (The Lancet COVID-19 Commission, 2022). The Lancet COVID-19 Commission Task Force on Safe Work, Safe School, and Safe Travel reviewed the scientific evidence around ventilation and disease transmission for SARS-CoV-2 and other airborne pathogens and found that despite differences (across studies, experts, and metrics) there was consensus agreement for ventilation targets above the current minimums. Based on that assessment, The Lancet Task Force proposed the following Non-infectious Air Delivery Rates (NADR) for reducing exposure to airborne respiratory infectious diseases (Tbl. 2-15).

Table 2-15. Proposed Non-Infectious Air Delivery Rates (NADR) for reducing exposure to airborne respiratory diseases (The Lancet COVID-19 Commission, 2022)

Category	Volumetric flow rate per volume [h^{-1}]	Volumetric flow rate per person [l/(s·person)]	Volumetric flow rate per floor area [$l/(s \cdot m^2)$]
Best	> 6	> 14	> 5.1 + ASHRAE min*
Better	6	14	5.1 + ASHRAE min*
Good	4	10	3.8 + ASHRAE min*

* ASHRAE minimum outdoor air ventilation rate refers to the values provided by ASHRAE 62.1

According to The Lancet COVID-19 Commission, (2022, p3) a volumetric flow rate greater than 14 l/(s·person) is recommended to achieve maximum protection from airborne respiratory infectious diseases. According to the Task Force such targets "*are feasible and achievable right now with existing and widely available approaches and technologies*" (The Lancet COVID-19 Commission, 2022).

REHVA – Health-based target ventilation rates and design method for reducing exposure to airborne respiratory infectious diseases (REHVA, 2022)

The purpose of this document was to establish comprehensive guidance on health-based target ventilation rates, including a design method for reducing exposure to airborne respiratory diseases in non-residential buildings (REHVA, 2022). This guidance builds on previous REHVA guidance (above) and addresses epidemic periods (such as those caused by seasonal influenza or COVID-19 waves) as well as normal operating conditions.

REHVA advise that the change from normal operation to the use of enhanced ventilation airflow rates must be managed manually, since respiratory pathogen sensors are not currently available for automated control. In relation to mechanical systems REHVA's most recent guidance reiterates the advice issued in the previous COVID-19 guidance. Wherein (during epidemic periods), "In ventilation systems controlled according to room CO_2 and temperature sensors, this can be done using the CO_2 setpoint change to 550 ppm. With a 550-ppm setpoint, ventilation will be operated during regular operating hours continuously at full speed in rooms with normal occupant density and at reduced speed in rooms with lower occupancy" (REHVA, 2022, p6).

REHVA recommends that infection-risk-based outdoor air target ventilation rates for occupied rooms should either be calculated using equations, specific to the room type and occupancy, or alternatively a maximum CO_2 threshold of 800 ppm should be maintained in classrooms and meeting rooms (and 650 ppm in offices, restaurants, and gyms). These airflow rates and CO_2 thresholds assume that portable air cleaners are not being used, and that there is a fully mixed air distribution (REHVA, 2022). Outside of epidemic or pandemic periods, REHVA recommend the use of normative ventilation rates (as described in EN 16798-1:2019 and ISO 17772-1:2017) appropriate to the room type and occupancy.

REHVA recommend that non-residential buildings are equipped with measuring and control devices for the regulation of indoor air quality (IAQ). Since the direct measurement of most indoor air pollutants is impracticable, and generally requires sampling, REHVA advocate that CO_2 concentrations are continuously monitored as a proxy for ventilation and IAQ. Low-cost sensors are also available for particulate matter $PM_{2.5}$ monitoring. REHVA state that the latter are particularly recommended in the context of natural ventilation and hybrid ventilation systems, where supplementary air filtration may be required, dependant on the operation mode (REHVA, 2022).

ASHRAE – Standard 241-2023 – Control of Infectious Aerosols (ASHRAE, 2023)

At the end of 2022, following discussions between ASHRAE and the White House, ASHRAE was encouraged to develop a new standard for the control of airborne pathogens. Standard 241 is intended to supplement the requirements set out in the existing ANSI/ASHRAE Standards 62.1 and 62.2 as well as ANSI/ASHE/ASHRAE Standard 170, in order to provide an infection risk management mode (IRMM) when higher levels of infection risk mitigation are desired (or required) by authorities in response to public health data (ASHRAE, 2023).

The requirements stated in Standard 241 are given in terms of an "*equivalent clean airflow rate in units of flow per occupant in a space (ECAi)*". As such the equivalent clean airflow rate can be met by a combination of fresh outdoor air and filtered recirculated air, as well as air disinfected by various other technologies. This approach allows buildings with existing ventilation systems, which cannot readily supply the additional ventilation required to fulfil the standard, to meet the requirements using room based air purifiers and similar devices.

Table 2-16. ASHRAE-241 minimum Equivalent Clean Airflow rate per person in Infectious Risk Management Mode (ASHRAE, 2023)

Occupancy Category	ECAi* [l/(s·person)]
Classroom	20
Lecture hall	25

* ECAi values refer to the equivalent clean airflow rate in the breathing zone

It can be seen (Tbl. 2-16) that the ECAi values proposed by ASHRAE Standard 241 for classrooms and lecture halls are significantly higher than the 'health-based' airflow rates recommended by REHVA (REHVA, 2022) and exceed the 'Best' category threshold specified by The Lancet COVID-19 Commission's proposed NADRs (The Lancet COVID-19 Commission, 2022).

An independent review of the ASHRAE 241 standard carried out by Dr Joseph Allen (Harvard TH Chan School of Public Health) (Allen, 2024) commented that the standard recommended a total "clean air" target (outdoor air + filtered/cleaned air) that was more in-line with historical, health-focused ventilation rates. However, Allen criticised the inclusion of an "on/off switch" in the standard (i.e. its applicability being only in "risk management mode"). Allen states that this mechanism implies that the adoption of enhanced ventilation protocols are discretionary and that baseline levels of influenza, COVID-19, and other respiratory diseases are somehow not worthy of being declared a full-time risk. In support of this argument Allen cites that for influenza alone, the US Centers for Disease Control and Prevention (US CDC) estimate that up to 41 million illnesses, 710,000 hospitalizations, and 51,000 deaths have occurred annually since 2010 (CDC, 2024) (Allen, 2024).

2.5.7 Summary of Health Based ventilation standards

Despite the accumulated research on the health and economic benefits of adopting higher 'health-based' ventilation rates, little has changed, and the use of olfactory-based 'acceptable' ventilation rates remains the basis for many normative standards and industry guidelines. Furthermore, there is little harmonization and consensus between the various global standards and guidelines, and even the interpretation of commonly used standards is often poorly understood in practice. This situation is exacerbated by weak legislation and a lack of enforcement, which can be witnessed in the well documented 'performance gap' existing between the design intent and the in-situ performance of ventilation systems (Haverinen-Shaughnessy et al., 2011; Persily, 2021). Countries such as Belgium and France have recently enacted new legislation that seeks to redress many of these issues by imposing higher standards in public buildings supported by evidence based inspections and continual monitoring of room CO_2 concentrations.

The year 2020 marked a major turning point in the evolution of ventilation standards globally. SARS-CoV-2 spread predominantly indoors with the most severe outbreaks being recorded in buildings designed to the minimum 'acceptable' ventilation standards (Allen, 2024). In February 2020, researchers raised concern over airborne transmission and highlighted that enhanced ventilation and filtration were key control strategies. In 2020, global building services organisations (including ASHRAE, CIBSE and REHVA) made recommendations for increased ventilation rates in response to the pandemic. It should be noted however that 'health-based' ventilation standards (such as ASHRAE 241) only address the risk of long-range transmission of infectious aerosols (i.e. from an infector who is not in close proximity to a susceptible person). It should be noted that such standards are unlikely to significantly reduce transmission risks in all situations due to the diversity of transmission modalities, as well as factors such as the duration of exposure and personal susceptibility to infection (Section 4.5).

Moving forward it is clear that there is an urgent need to incorporate 'health-based' requirements into existing European and Austrian ventilation standards to end the dichotomy between existing olfactory based standards and those aimed at supporting optimal human health and performance. Alongside this, compliance monitoring is required to ensure that 'health-based' standards are correctly implemented and maintained in public settings. The latter being essential to avoid the unfair imposition of health-inequalities upon the occupants of poorly managed buildings. These issues are particularly important in densely occupied school buildings, where students and staff spend the majority of their waking lives (outside of their own homes).

3 Study design and research methods

3.1 Overview of the research methodology

The ImpAQS study used a mixed-methods research methodology, combining quantitative and qualitative methods, in order to answer the research questions set out in Section 1.4. Mixed methods study designs are increasingly adopted in building research involving occupied buildings in order to account for the complex interactions between building physics, building services and the stochastic and contextually dependent behaviour of the occupants. Such an approach is strongly indicated for the ImpAQS study where the aim is to evaluate the ventilation characteristics and indoor air quality (IAQ) in Austrian classrooms, as experienced by a wide range of age groups, across multiple geographic regions, in varied building typologies and across different seasons of the year.

The overall research methodology is designed to account for the dominant factors influencing ventilation practices and indoor air quality in schools (Fig. 1-2). Apart from the physical monitoring of CO_2, and other indoor environmental variables, in classrooms (and their calibration requirements), this includes factors affecting the outdoor environment (such as the schools' location, the outside CO_2 and localised air pollution concentrations etc.), physical details of the classrooms (such as their location, openable window areas, the design occupancy of classrooms etc.). Objective parameters affecting students and teachers (such as the number of absent days recorded over the year or the airborne infection risk) are also evaluated, as well as the subjective attitudes of teachers towards the use of CO_2 sensors and ventilation.

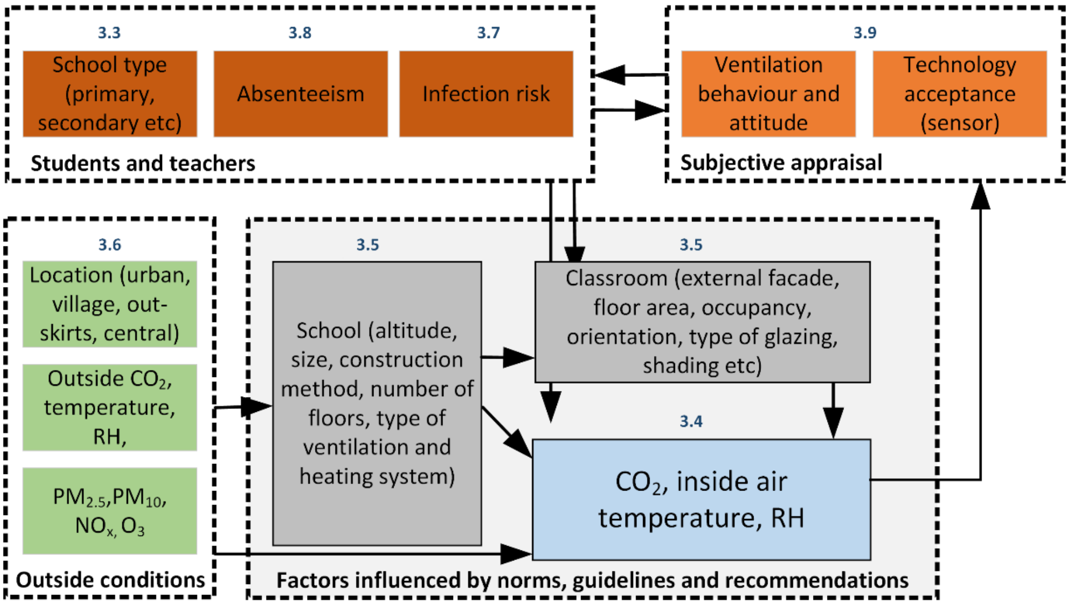


Figure 3-1 Conceptual overview of the research methodology linking each component of the study design to the corresponding methods section

The quantitative methods used to gather and analyse the primary data in this study (including the matched-pair[7] longitudinal research design, equipment used, calibration methods and installation

[7] This is an experimental design in which the participants are paired on the basis of certain characteristics (classrooms with the same or similar occupancy, ventilation type, etc.) and then paired into two different groups

process) are described in detail in Sections 3.2–3.5. Classroom survey data is described in Section 3.6, and the outdoor ambient CO_2 and air pollution data in Section 3.7. The analytical infection risk model, used to determine the relative risk of airborne disease transmission is described in Section 3.8. School absenteeism data is described in Section 3.9. The Austrian SARS-CoV-2 waste-water data and its use in the context of this study is described in Section 3.10. Whilst the qualitative methods (including the survey design, distribution, and implementation) are described in Section 3.11.

3.2 Project duration and monitoring period

The workflow and timeline of the ImpAQS project are illustrated in Fig. 3-2 and Appendix A.1. The installation of the monitoring equipment (Section 3.5) commenced at the end of June 2023 and, with a few exceptions, was completed during the summer holiday period before the school term commenced in early September. As a result, the monitoring phase commenced on time, at the beginning of the new academic year (4th September 2023) and was completed one year later (3rd September 2024). The data was subsequently cleaned (Section 3.4.2) to reflect the academic year 2023–24 by removing all of the regional holiday periods, including additional autonomous holidays [German: *Schulautonometage*] where known. In addition, where rooms were found to be unoccupied or partially occupied additional data cleaning procedures (Section 3.4.2) were applied, in order to selectively remove these periods for both the control and test data (in a pair-wise fashion). This was done to prevent biased comparisons being drawn between fully occupied and unoccupied (or partially occupied) classrooms (Section 3.4.2).

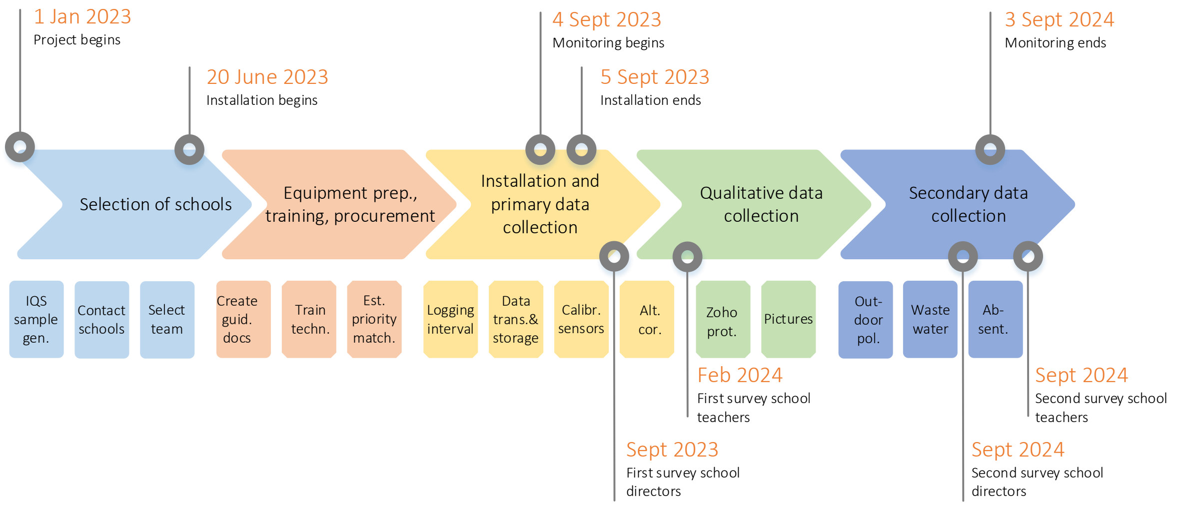


Figure 3-2 ImpAQS project workflow, including the timeline for installation, monitoring and surveys

The school directors' surveys took place at the beginning and the end of the project, in September 2023 and 2024. The main purpose of these surveys (Section 3.11) was to understand the school directors' perceptions with regard to ventilation and indoor air quality and the use of CO_2 sensors. The teachers' surveys (Section 3.11) were run during the winter (February) and summer (September) periods in order to capture information about the effect of seasonal factors on classroom ventilation behaviour. These surveys were designed to solicit information about the teachers' attitudes towards

(here: CO_2 sensors with a visible display and without a visible display). In the matched pairs design, the classrooms are then randomly assigned to either the control (C) or experimental test group (T).

the use of CO_2 sensors and to gain a deeper understanding of the barriers and drivers faced by teachers when attempting to ventilate their classrooms.

The following sections of this chapter describe the methods used to collect and validate the data required by the ImpAQS project.

3.3 Participating schools

The study aimed to include a broad cross-section of school types drawn from a sufficiently large sample to be representative of the schools in the 9 federal regions of Austria. At the same time the sample had to be sufficiently homogenous to allow valid 'like-for-like' comparisons to be drawn between different classes, school types, and regions. As a result of these objectives certain categories of schools were excluded from the study (e.g. because they were school types that are attended intermittently or operate outside the core hours in which most schools operate). Small schools (i.e. those with less than 10 classrooms) were also excluded because including such schools would have been more resource intensive (i.e. each school required its own LoRaWAN gateway) and this would have limited the total number of classes that could be included in the study for budgetary reasons. Moreover, due to the 'matched-pairs' study design it was important that each of the schools included in the study had sufficient rooms to allow two, almost identical, classrooms to form a matching Test (T) and Control (C) study pair (Section 3.5.4.1).

3.3.1 Sample size calculation

The size of the study sample and its representativeness (in relation to the population being studied) affects the confidence level in the results. Therefore it was important that the sample selected was adequately sized and sufficiently varied to avoid bias and sampling errors.

The total number of classrooms chosen for the study was selected on the basis of having sufficient confidence to make inferences about the use of CO_2 sensors and ventilation characteristics which would be generalisable to the larger population of all Austrian classrooms. There are many mathematical formulas which are used for calculating sample sizes and Yamane's method (Eq. 3-1) is often used for this purpose.

$$n = N / (1 + N(e)^2) \qquad [3\text{-}1]$$

Where:

n is the sample size,
N is the population size,
e is the margin of error accepted by the study (typically 0.05 or 0.01).

Based on Yamane's method and an estimated $N = 57{,}000$ public school classrooms in Austria (Statistik Austria, 2022) if 99% confidence on the statistical inference is sought the required sample size would be $n = 8507$; whilst for 95% confidence a sample size of 397 would suffice. However, in the ImpAQS study a matched-pair sample is created, meaning that two samples are required to derive one observation. Therefore, two equally sized groups are needed and a sample size of double the value predicted by Yamane's method is required to preserve the desired statistical confidence. This would imply that a minimum sample size of 794 would be required to draw first order inferences with 95% confidence. Given that further higher order inferences would eventually be made, based on an unknown subset of the sample (for example in relation to the sub-set of naturally or mechanically ventilated schools), the sample size would need to be further increased to maintain the desired confidence. For this reason, as well as the possibility of attrition losses (i.e. drop-out from the study) the size of the ImpAQS sample was increased to $n_{ImpAQS} = 1{,}200$ classrooms. Consequently, the size of the matched-pair sample is $n_{pairs} = 600$.

3.3.2 Sample selection and geographic distribution

Based on the above selection criteria the widest possible range of different school types and age groups were included in the sampling strategy, which was drawn from all nine federal regions of Austria. The study sample was then generated in collaboration with the Institut des Bundes für Qualitätssicherung im österreichischen Schulwesen (IQS) using Monte Carlo sampling methods. During the stratification process the sample was drawn with the aim of representing the specific population as accurately as possible. If the difference between the sample and the actual population is small and the sample size is sufficiently large (Section 3.3.1) it is possible to make very accurate statements about the results collected.

The use of strata in sampling is an important procedure for mapping subpopulations as accurately as possible and thus increasing the overall representativeness of a sample. 'Representativeness' describes how well the number of units in a particular sampling stratum (e.g. a specific school type) reflect how they occur in reality. In the sampling procedure strata were used to group the population as representatively as possible. In this case the strata included federal states, school types, urban/rural setting. Within these strata, further variables were used for sorting (e.g. school size). 'Concrete groups' are referred to as explicit strata and 'sorting variables' as implicit strata. Schools were then randomly selected from within these strata. Once the sample was created further checks were carried out to confirm whether the sample generated was sufficiently representative (i.e. in this case whether the ratio of school types, and geographic locations corresponded to existing survey data (Section 4.1.1).

An overlap control was then conducted. This means that schools that had already been selected to participate in other studies were excluded. For studies conducted by the IQS (e.g. iKM-PLUS pilot projects), care is taken to exclude schools that were already included in studies one or two years prior to the current study. For studies carried out by an external contractor, the IQS also takes care to exclude as many schools as possible that are already included in another sample.

In terms of fulfilling the specifications of the ImpAQS project, 120 schools were drawn that had at least 10 classrooms. For each school, 2 reserve schools were drawn. The stratification characteristics were federal state (explicit), urban/rural (in 2 categories), primary school type, school size (implicit), in this order). Following the overlap control, some schools were excluded that had already been drawn for other studies in the same school year. The geographic distribution of the ImpAQS schools is shown in Fig. 3-3 and a more detailed analysis of the sample selection process is provided in Section 4.1.

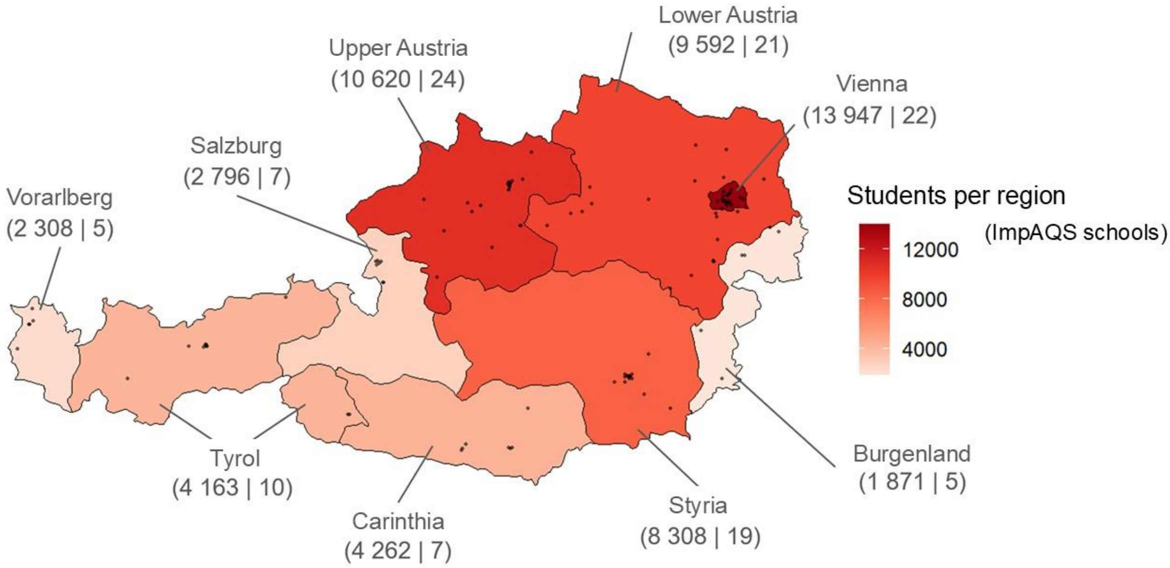


Figure 3-3. Geographic location of the ImpAQS school sample, the total number of students in the ImpAQS schools and the number of ImpAQS schools in each region

3.3.3 Participant recruitment

Once the study sample was generated (Section 3.3.2), initial contact with the selected schools was made via email in May 2023[8]. Whilst schools located in Graz responded relatively swiftly to this invitation (likely due to previous contacts with some of the schools), in schools outside of Styria responses were less forthcoming. As a result of the initial poor response the contact strategy was changed to telephone calling. June 2023 was a challenging month for most schools due to end-of-school exams (Matura) and related end-of-year deadlines, and contact was difficult at this time. In the months of July and August the remaining schools were successfully contacted and (despite the holiday season) sufficient schools were recruited to be able to finalise most installations by the end of August.

3.4 Theoretical principles – calculation procedures and data processing

3.4.1 Ventilation rate calculations

The empirical measurement of ventilation rates in naturally ventilated buildings is a complicated and time consuming process (Persily, 2015) and carrying out such procedures at the scale of the ImpAQS project would be very resource intensive. The conversion of measured CO_2 concentrations into ventilation flow rates is possible however, using either transient or steady state based methods. Transient methods can offer more precise solutions in situations where the CO_2 fluxes into and out of

[8] An example of the original approach letter can be found in Appendix B.1.

the domain air are not stable, however the use of such procedures requires precise knowledge of any state changes in the system (such as changes in occupancy, metabolic rate etc). In the absence of such information steady state methods can produce reliable results provided the room achieves a steady state CO_2 concentration within the period of assessment. This condition is typically affected by the air change rate (or time constant) of the particular room, and in most cases this unlikely to occur in a one-hour (or shorter lesson) period (Persily, 2022). Over a longer duration, of several hours or a school day, it is usually possible to achieve steady state conditions to carry out a mass-balance conversion calculation with sufficient reliability.

In order to assess the ventilation rates in each classroom the underlying model for the calculation of ventilation rates in this report is based on a fully mixed mass balance equation. This equation is expressed as follows (Persily, 2022).

$$V \cdot \frac{dC}{dt} = G(t) + Q(t) \cdot C_{out}(t) - Q(t) \cdot C(t) \quad [3\text{-}2]$$

Where,

V is the volume of the space [m³],
t is the time [h],
C is the CO_2 concentration in the space [ppm],
C_{out} is the mean outdoor CO_2 concentration, circa 420 to 430 ppm (Sonnblick Observatorium, 2023),
Q is the air flow rate between room and outside air [l/(s·person)],
G is the human CO_2 generation rate in the space [l/(s·person)]

Assuming that G, Q and C_{out} are constant, a system will eventually reach a steady-state concentration (C_{ss}). At this point, the CO_2 being generated inside the space by occupants is balanced by the dilution through ventilation. In this steady-state condition, the CO_2 concentration indoors becomes constant and the rate of change (dC/dt) equals zero, indicating no further change in concentration over time. By neglecting both the indoor removal of CO_2 as well as transport between different zones within the same building, the solution to Eq. 3-2 can be simplified as follows (Persily, 2022):

$$0 = G + Q \cdot C_{out} - Q \cdot C_{ss} \quad [3\text{-}3]$$

$$C_{ss} = C_{out} + G/Q \quad [3\text{-}4]$$

Where,

C_{ss} is the steady-state indoor CO_2 concentration,
Note: If G and Q use the units l/(s·person), G/Q needs to be multiplied by 10^6 to arrive at the unit ppm.

Rearranging Eq. 3-4, to solve for Q, corresponds to the mass balance formula described in EN 16798-1 method 2 for the determination of design parameters for IAQ (CEN, 2019), neglecting ventilation effectiveness and fitting the units (see Section 2.5.2 for more information on EN 16798-1).

$$Q = \frac{G}{C_{ss} - C_{out}} \quad [3\text{-}5]$$

Equation 3-5 is commonly used to determine ventilation rates based on peak or steady-state CO_2 concentrations (Andamon, 2023), assuming that under a constant ventilation rate the space eventually reaches a steady-state condition (Persily, 2016; Batterman, 2017). However, naturally ventilated classrooms often exhibit variable ventilation and occupancy patterns, making it rare for a steady-state concentration to be achieved. Additionally, the time required to reach an equilibrium between CO_2 generation and its dilution through ventilation depends on the inverse of the air exchange rate. Typically, a steady state is only reached after approximately three times the inverse of the air exchange rate (Q / V). For example, at an air exchange rate of 1 h^{-1}, a steady state will be reached after approximately 3 hours. Thus, the lower the air exchange rate, the longer it takes to reach a stationary room CO_2 concentration.

Given these constraints, this study utilised the daily average CO_2 concentration (i.e. integral of the room CO_2 concentration divided by occupancy time) to provide a more accurate representation of the varying ventilation conditions throughout the day. This approach for the calculation of the daily mean per-person ventilation rate is similar to that used in a study of UK schools (Wood et al., 2024) shown in Eq. 3-6.

$$\left|\overline{Q_{pp}}\right|_{est} = M \cdot \frac{T_{occ} \cdot \langle\overline{G_N}\rangle_{est}}{\int_{t_0}^{t_{end}} C \, dt} \qquad [3\text{-}6]$$

Where,

$\left|\overline{\mathrm{Q_{pp}}}\right|_{\mathrm{est}}$ is the probability density function of daily average per-person ventilation rate [l/(s·person)],
$\mathrm{T_{occ}}$ is the typical classroom occupancy time [h],
$\langle\overline{\mathrm{G_N}}\rangle_{\mathrm{est}}$ is the average per-person CO_2 generation rate [l/(s·person)],
C is the excess CO_2 concentration (i.e. the difference between the indoor and outdoor concentration),
M is the mean value bias factor for the study (Wood et al., 2024)

The exhaled CO_2 rates depend on a number of factors including: the metabolic rate, age, and gender of the occupant. Choosing an appropriate average CO_2 generation rate per person (which accounts for age, metabolic rate, and gender) is crucial because the emission rate (G) has a linear relationship with the ventilation rate (Q), as shown in the equation. Wherein, an overestimation of the CO_2 generation rate by a factor of 2 would result in a calculated ventilation rate (Q) that is twice as high.

EN 16798-1:2024 defines a standard CO_2 emission rate of 20 l/(h·person) for calculating the design outdoor airflow rate using the mass balance equation. Persily and de Jonge estimated CO_2 generation rates for different body masses and physical activities, highlighting the variability in emissions. Table 3-1 presents a range of emission rates for various space types, based on their study (Persily and de Jonge, 2017).

Table 3-1. Average CO_2 generation rate for different spaces (Persily and de Jonge, 2017).

Space Type	Avg. CO_2 generation rate		Note
	l/(s·person)	l/(h·person)	
Office	0.0048	17.3	adults (50% male and 50% female) at 1.4 met.
Conference room	0.0048	17.3	adults (50% male and 50% female) at 1.4 met.
Educational (5 to 8 yrs)	0.0030	10.8	24 students at 1.4 met (50% male and 50% female, 5 to 8 yrs), one adult female at 1.6 met.
Lecture classroom	0.0043	15.5	64 students at 1.2 met (50% male and 50% female, 16 to 20 yrs), one adult at 1.4 met.
Lecture hall	0.0041	14.8	148 students at 1.2 met (50% male and 50% female, 16 to 20 yrs), one adult at 1.4 met.
Residence	0.0040	14.4	Children and adults (50% male and 50% female) at 1.4 met

In the analysis carried out in this study reference values were taken from Wood et al. (2024), following Persily (2016) and the occupants were divided into two distinct age groups (primary schools and secondary schools). For primary schools, a CO_2 emission rate of 3.1 ml/(s·person) was applied, equivalent to 11.16 l/(h·person), while for secondary schools, a rate of 4.32 ml/(s·person) was used, equivalent to 15.55 l/(h·person), as outlined by Wood et al. (2024).

3.4.2 Measurement data – cleaning, aggregation and analysis periods

Since the study aimed to evaluate the CO_2 and ventilation rates in occupied classrooms, additional data cleaning procedures were applied to remove periods where the rooms were likely to be unoccupied. In the first step the duration of the school day was standardised to the core six-hour period from 8:00–14:00 Monday to Friday, with the exception of two vocational (ABHS) schools (school numbers 21 and 59) which were defined as operating from 10:00–16:00.

To ensure that the analysis focused only on effective school days, periods such as weekends (i.e. Saturdays and Sundays), national and regional holidays, and individual school holidays or closures were removed from the dataset. This step aimed to capture data as closely as possible to the actual occupied hours and exclude any periods where the classrooms were expected to be unoccupied. Since it is possible that empty periods existed even within these “core-hours” further methods were applied to remove unoccupied and partially occupied periods that might otherwise distort the results.

To achieve this aim a lower threshold limit was set on the hourly mean CO_2 concentration and hours within the core-period with hourly mean CO_2 concentrations below 460 ppm being excluded on the basis that such rooms are likely to be unoccupied, or only partially or intermittently occupied. This assumption was verified by visual inspection of a random sample of the discarded hours to ensure that the majority of these periods were correctly categorised as unoccupied rooms.

Additionally, occasional readings above 7500 ppm were also removed from the dataset. These unusually high values were sometimes recorded over relatively short durations and likely resulted from students intentionally manipulating the CO_2 sensors (e.g. by blowing directly into the sensor), causing sharp spikes in the CO_2 levels that do not reflect typical classroom occupancy patterns. Such outliers were excluded to ensure the integrity and accuracy of the analysis.

The data was initially recorded at a 2-minute resolution, but due to the large volume of data and to streamline the analysis, the data was aggregated. First, it was aggregated to a 15-minute resolution using the central method, i.e. aggregating data within a ± 7-minute window of the observed times. However, since CO_2 threshold limits in indoor air quality standards (e.g. 1000 ppm according to ISO 16000-41, EN 16798-1, and Raumklasse A of the Austrian BMK guidelines) are typically based on hourly averages, there is a need to aggregate data to the hourly level. Moreover, the removal of unoccupied periods, where the mean CO_2 concentration is below 460 ppm, is most meaningful when applied at an hourly resolution. Therefore, the data was aggregated into hourly means and also into daily means, and these time periods form the basis for most of the analyses presented in this report.

The hourly data was aggregated using the floor method[9] approach (i.e. grouping data into hourly intervals by rounding down to the nearest hour), this method was applied to the filtered periods (8:00–14:00 and 10:00–16:00) which forms the 'core' daily data. For example, the 8:00 hour represents the average of the observations taken at 8:00, 8:15, 8:30, and 8:45, since the data was originally processed at 15-minute intervals. This effectively means that the 8:00 hourly reading covers an averaging window from 7:53 to 8:52, which aligns well with the classroom occupancy period for a typical lessons of 50 duration (RIS, 2024). For the last period of the 'core' school day at 14:00, the data includes additional observations from 13:53 to 14:07. This short extension is included to capture the final part of the lesson before the room empties. This adjustment is necessary because the last hour cannot be fully represented by a typical 60-minute window (i.e. up to 13:52), as this would truncate the final period before the students have packed up and left for the day.

Having defined the hourly data on this basis the daily data was aggregated from the hourly data to represent the daily CO_2 concentrations during the 'core' occupied period (from 8:00–14:00 and 10:00–16:00, according to the school type). Where additional analysis is carried out, outside of these 'core' occupied periods, this is clearly noted in the text.

For the matched-pair analysis of control and test sensors (Section 4.4), mechanically ventilated schools were excluded to avoid bias. Indeed, according to expectations, control and test classrooms in mechanically ventilated schools showed very similar CO_2 levels. Additionally, multiple control classrooms recorded daily mean CO_2 concentrations below 600 ppm, a value that corresponds to a ventilation rate of approximately 30 l/s per person (at a standard adult CO_2 emission rate of 20 l/(h·person)). Such high ventilation rates are implausible as a daily mean value in fully occupied naturally ventilated classroom. Upon further investigation, it was found that the low indoor CO_2 concentrations were found to indicate unoccupied or partially unoccupied classrooms, highlighting the need for further filtering of the data to ensure an accurate control-test comparison. Moreover, since indoor CO_2 concentrations were higher during colder months and lower during warmer months, a fixed cut-off value of 600 ppm was considered unsuitable as a means of consistently excluding partially occupied rooms across the entire school year. Applying a fixed threshold in this way would have risked excluding some well-ventilated occupied classrooms during the warmer months. Thus, a dynamic cut-off threshold (i.e. fuzzy-boundary) was derived from the 25th percentile of the daily mean CO_2 concentrations of the control sensors (Appendix B.2). Hourly mean observations from control sensors that fell below this fuzzy threshold were excluded (along with their matching test pair) from the analysis. This process resulted in a refined set of control and test sensors, with fewer empty and partially empty rooms which would otherwise have biased the control–test comparisons.

[9] The floor method rounds a number down to the nearest integer multiple of specified significance.

3.5 Measurement equipment and data management

3.5.1 Equipment – sensor measurements, uncertainty and logging interval

Battery powered nondispersive infrared sensors (NDIRs) (AM 103, Milesight) were used to monitor the indoor environmental conditions in the 1200 classrooms. These devices measured the CO_2 concentrations, air temperature, and relative humidity at 2-minute intervals. The sensor measurement resolution is 1 ppm, and the measurement accuracy is specified by the manufacturer as ± (30 ppm + 3% of the reading) for CO_2 measurements, resulting in an inaccuracy of ± 43 ppm at outdoor CO_2 concentrations of approximately 420 to 430 ppm and ± 60 ppm at the standard indoor threshold concentration for CO_2 of 1000 ppm. The accuracy of air temperature measurements is defined as ± 0.3°C for temperatures between 0°C and +70°C. For relative humidity the accuracy is specified as ± 3% within a 10–90% RH range, and ± 5% for readings below 10% or above 90% RH.

In addition to the indoor sensors, an outdoor sensor (EM 500, Milesight) was positioned outside the main school building at each school. The purpose of this device was to record the localised ambient CO_2 concentration and environmental conditions occurring at the school site. The EM 500 contains four sensors (CO_2, air temperature, relative humidity and barometric pressure) and is designed for the outdoor environment (IP65 rating). It uses an NDIR sensor for CO_2 with a measurement range from 400–5,000 ppm and a manufacturer specified sensor accuracy of ± (30 ppm + 3% of the reading). Temperature is measured with a micro-electromechanical systems (MEMS) sensor with a stated accuracy of ± 0.3°C for temperatures between 0°C and 70°C, ± 0.6°C for temperatures between -30°C and 0°C. The relative humidity is measured with a MEMS sensor with a stated accuracy in the range from 10–90% RH of +/- 3%, whilst below 10% and above 90% RH it is +/- 5%. The barometric pressure is measured with a MEMS sensor with a range of 300–1100 hPa (-40°C–85°C) with an accuracy of ± 1 hPa.

The indoor and outdoor sensors measure and transmit data in 2-minute intervals. Whilst a shorter (1-minute) data-logging interval was initially desired, due to the higher data resolution it would provide, this proved to be technically infeasible due to the Milesight devices' configuration and the implications this would have had for the sensor battery life.

3.5.2 Equipment – sensor data transfer and storage

During the installation phase of the project, 11 CO_2 sensors (10 indoor and 1 outdoor) and one gateway (Fig. 3-4) were installed in each of the 120 schools, resulting in a total of 1320 sensor and 120 gateway installations.

To transmit the data from the sensors to the project server a LoRaWAN (Long Range Wide Area Network) system was established in each school. LoRaWAN is a wireless telecommunication technology commonly employed to connect IoT (Internet of Things) devices due to its energy efficient and wide coverage capabilities. This system comprises of four integral components: the CO_2 sensors, a gateway (radio base station), a network server and a cloud platform (Fig. 3-4). The sensor equipment, gateways, network server and cloud services (including data hosting and technical support) were provided by the company LineMetrics GmbH (based in Haag, Lower Austria).

The gateways receive the measurement data from all sensors in their coverage area and then transfer it via a Long Term Evolution (LTE) or Fourth Generation (4G) mobile telephone network to the server.

A mobile network was used in order to ensure data security and to obviate the need to use school Wi-Fi networks. Subsequently the data was accessed, visualized and exported through a secure General Data Protection Regulation (GDPR) compliant cloud platform. The integration of the cloud platform and data server enables real-time access, with remote control capabilities (e.g. password protection of the devices' near-field communication (NFC) functionality, to prevent 3rd party tampering) and the ability to establish alerts and notifications in response to connection losses or other anomalies. Without such an automated monitoring system a far greater rate of data loss would be anticipated.

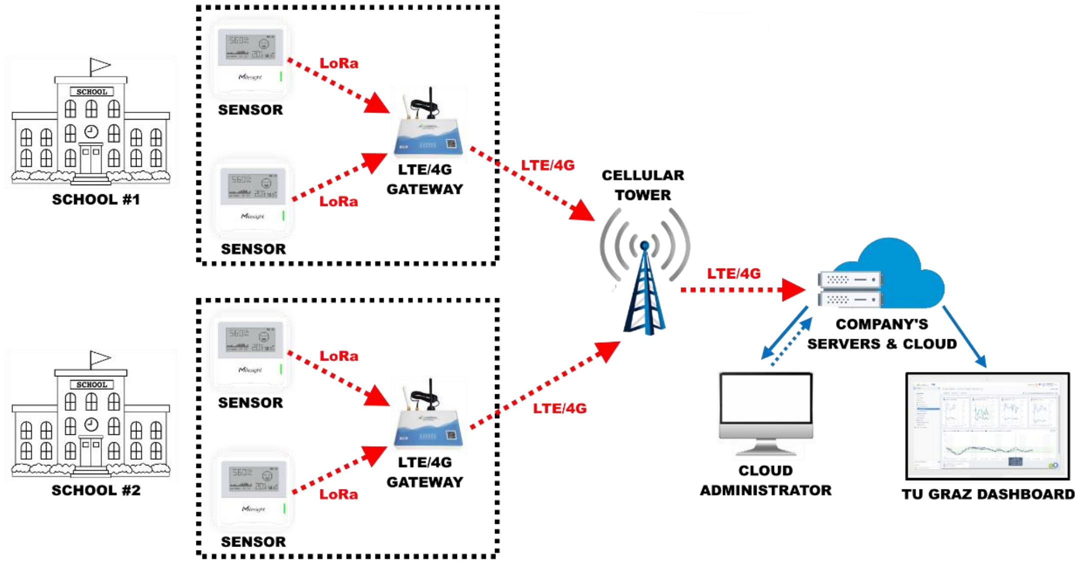


Figure 3-4. Overview of sensor and gateway data communication to the cloud and server

3.5.3 Carbon dioxide sensors – calibration and altitude compensation

3.5.3.1 Initial calibration process

Although the sensors dispatched by the manufacturer (Milesight) were pre-calibrated in the factory, further tests carried out at TU Graz revealed that the manufacturer's calibration process was not always sufficiently reliable for the purposes of this study. As a quality assurance procedure every sensor was therefore checked and recalibrated to ensure an accurate and reliable measurement of CO_2. Calibration is the process of adjusting and validating the sensor's reading to align with a known and accurate reference point. Sensors require calibration for various important reasons, including quality control, measurement accuracy and to counteract potential variations introduced by disparities in the manufacturing process as well as fluctuating environmental conditions. Moreover, calibration forms an integral part of the periodic maintenance regimen for these devices, ensuring consistent performance and rectifying any potential drift in measurement accuracy that may occur over time. Typically a simple and rapid calibration process can be accomplished by exposing the sensor to the ambient atmosphere, which maintains a relatively consistent CO_2 concentration, which is currently between 415 and 425 ppm (varying slightly according to the time of day, seasonal and local influences) (Ludewig and Senoner, 2024). During this procedure, the sensor is placed in the outside air for a period of 10 minutes and its readings are then adjusted to match those of the external atmosphere.

By carrying out this process in large batches (several hundred sensors at a time) it is possible to obtain the mean and standard deviation of the entire batch and thereby assess whether the mean value is sufficiently close to the reference value and the measurement variation (between individual sensors) lies within an acceptable range. Calibrating the paired sensors together in batches provides the assurance that each pair of sensors was calibrated under identical conditions, thereby reducing the possibility of measurement bias occurring between 'test' and 'control' pairs.

Figure 3-5. Two-stage sensor calibration process, showing the initial ambient outdoor calibration (left) followed by laboratory calibration using reference gas mixtures (centre) in a sealed chamber (right) to derive individual calibration curves.

3.5.3.2 Second stage calibration process

An additional laboratory calibration process was carried out on a sub-set (n=150) of the sensors following the stage-1 calibration process (Section 3.5.3.1). The purpose of this step was to further improve the calibration of a smaller number of sensors, such that they could be used as reference sensors for further calibration tests involving large batches of sensors being calibrated simultaneously. This step was important due to the rapid roll-out time needed to install all of the sensors prior to the commencement of the new school year.

The outcome of the stage-2 calibration process was the creation of a unique calibration curve for each CO_2 sensor (Fig. 3-6, bottom) based on four-point laboratory calibration process using reference gases. This procedure consisted of the following three steps. (i) In the first step 10 CO_2 sensors at a time were exposed to a series of reference gas concentrations (inside a sealed chamber) ranging from 0.04% to 0.20% CO_2 (Fig. 3-5). (ii) During this calibration the sensors were connected to a LoRaWAN network, and the readings were logged at the respective CO_2 concentration levels over a continuous interval of approximately 10-minutes (to generate a normally distributed sample at each reference point). (iii) An ordinary least squares regression (OLS) was then carried out using the measured values (Fig. 3-6) to obtain the line of best fit. Since the true value of y is equal to the reference gas concentration, the regression equation can be rearranged to solve for x. This process results in the creation of a unique calibration curve for each sensor. The resultant calibration curve provides a unique adjustment function needed to correct the influence of the two types of systematic error (offset and span) which effect each individual sensor measurement.

Since repeating the second stage calibration process for all 1320 sensors was impractical in the time available, an additional mass calibration procedure was created to expedite the process. During this step, the remaining 1170 sensors underwent a systematic two-point calibration process in a university seminar room. The procedure involved initially placing the sensors in a room equipped with decentralized ventilation ($n > 6\,h^{-1}$) and purge ventilated windows. The behaviour of these new sensors was compared with the mean of 20 reference sensors that already possessed calibration curves (as described above). This mass calibration process took place over approximately 30 minutes, with the room's doors sealed, and the CO_2 concentration maintained at outdoor ambient levels (to obtain the lower calibration reference point). Subsequently, the CO_2 concentration in the room was artificially increased to approximately 2800 ppm (to obtain the upper calibration point) using commercially available CO_2 canisters containing approximately 100% CO_2. The upper reference room CO_2 concentration was defined by a mass balance calculation and verified by measurement (based on the mean of the reference sensors). With the windows closed, and doors sealed, the sensors were then remotely observed for an additional 30 minute period. In this way, sufficient data was gathered at the lower and upper reference points that were used for the subsequent regression analyses, facilitating the generation of further unique calibration curves for each device. Throughout this process, the 20 reference sensors were evenly distributed across the room at different heights to measure the average CO_2 concentration in the room domain. Moreover, three fans were positioned in the room to facilitate thorough mixing of the air and to avoid localised peaks in CO_2 concentrations.

In the third stage of this process, the quality of the measurement data generated by the sensors was checked by further statistical analysis. Sensors that exceeded the measurement accuracy specified by the manufacturer (+/-30 ppm and +/-3% of the reading) either side of the calibrated mean value were set aside. These sensors were then subjected to recalibration and further testing to ensure their reliability. Any sensors that failed to meet the manufacturers stated accuracy level following subsequent testing were returned to the supplier.

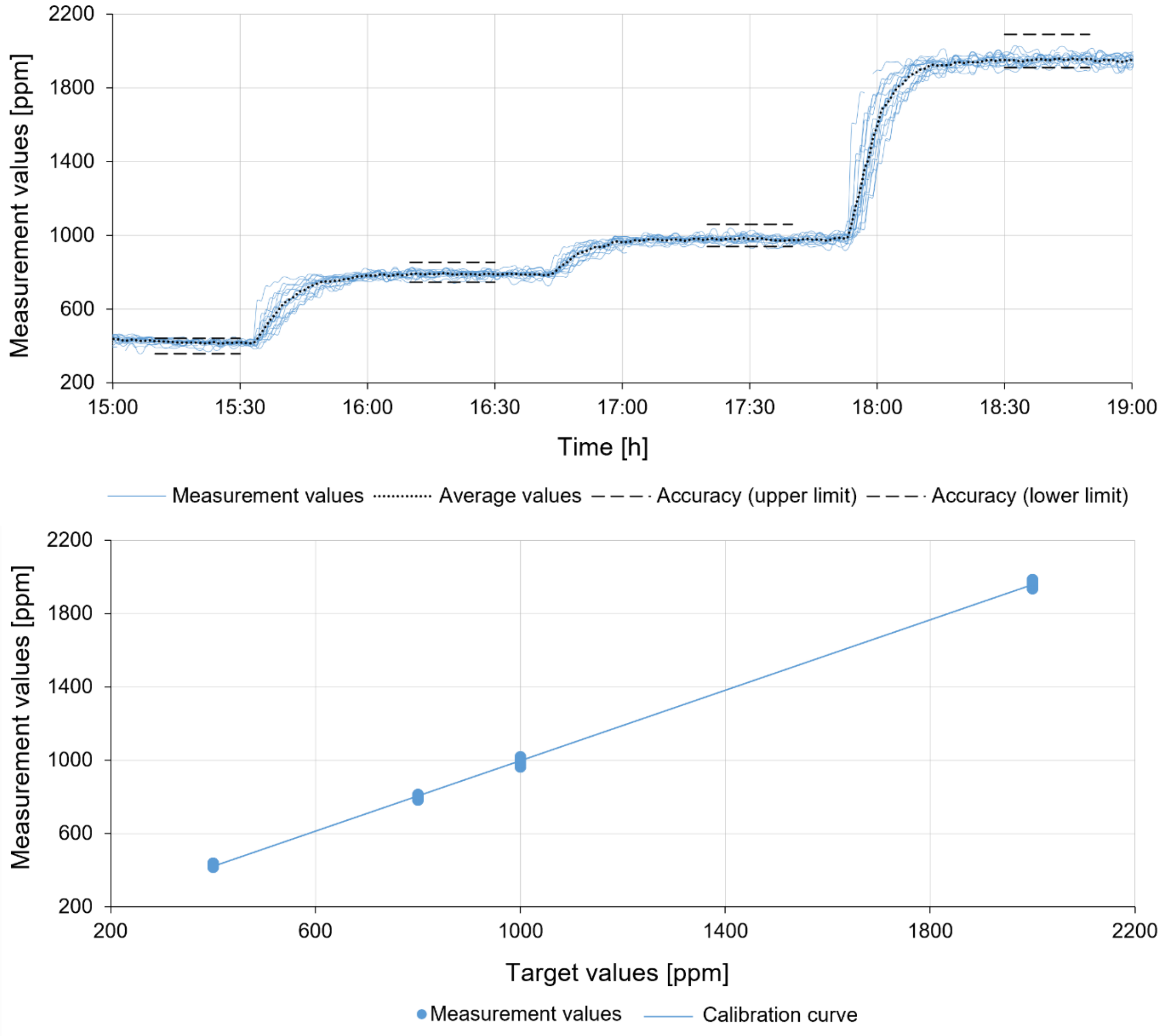


Figure 3-6. Second stage calibration procedure under laboratory conditions. Upper figure shows sensor measurements of all tested sensors over time. Lower figure displays measured CO_2 concentrations of an example sensor (y-axis) regressed against four reference gas concentrations (400, 800, 1000 and 2000 ppm).

3.5.3.3 Altitude compensation

An altitude compensation algorithm (Appendix B.3) was implemented in each sensor in order to rectify the pressure dependent sensor measurements to account for the final altitude at which the sensor was installed. This process takes place independently of the initial calibration process, which means that the sensor can be calibrated at a known altitude and then have its altitude reset to match the altitude at which it is installed without affecting the original calibration process. Standard atmospheric pressure at sea level is approximately 101.3 kPa and this decreases exponentially with altitude. This calibration adjustment is therefore necessary because relatively small changes in the altitude can have a significant impact on air density (i.e. the number of gas molecules in a given volume of air). Altitude compensation corrects these pressure dependent density variations, ensuring more precise CO_2 concentration measurements. By implementing this compensation across all 120 schools, which ranged in altitude from 150 to 1020 meters above sea level, more consistent and accurate measurements were achieved, thereby allowing direct comparison from one school to another. Since both temperature and pressure affect the density of gases the Combined Gas Law can be used to derive an altitude compensation equation to determine the corrected CO_2 ($CO_{2,korr}$)

reading (Eq. 3-7). Since indoor temperatures are often in a narrow range (i.e. between 20–23 °C) the final term in Eq. 3-7 is often close to unity and can therefore be ignored (provided that the initial calibration took place at a similar temperature).

$$CO_{2,cor} = CO_{2,uncor} \cdot \frac{p_{ref}}{p_{inst}} \cdot \frac{T_{inst}}{T_{ref}} \qquad [3\text{-}7]$$

Where,

$CO_{2,cor}$ is the corrected CO_2 concentration [ppm]
$CO_{2,uncor}$ is the uncorrected CO_2 concentration [ppm]
p_{ref} is the reference air pressure at the altitude the device was calibrated [hPa]
p_{inst} is the reference air pressure at the altitude the device is installed [hPa]
T_{ref} is the reference air temperature at the location the device was calibrated [°C]
T_{inst} is the reference air temperature at the location the device was installed [°C]

By applying Eq. 3-7 to the height dependent atmospheric pressure difference an altitude compensation factor [-] can be derived (Tbl. 3-2) which enables the uncompensated CO_2 sensor reading to be adjusted to provide a corrected reading which is independent of altitude. From Tbl. 3-2 it can be seen that in the range of altitudes at which the ImpAQS schools are located (150–1020 meters above sea level) a maximum compensation factor of 1.13 is needed to rectify the uncorrected CO_2 measurements at the highest school (relative to the altitude of Graz). Without this correction a pressure induced difference of approximately 52 ppm would exist.

Table 3-2. Altitude compensation of CO_2 under standard atmospheric pressure

Altitude [m]	Air pressure [hPa]	Factor for altitude compensation [-]	Compensated CO_2 concentration [ppm]
0	1013	1.00	400
50	1006	1.01	403
100	1000	1.01	405
150	993	1.02	408
200	986	1.03	411
250	980	1.03	414
300	973	1.04	417
350	966	1.05	419
400	960	1.06	422
450	953	1.06	425
500	947	1.07	428
550	941	1.08	431
600	934	1.08	434
650	928	1.09	437
700	921	1.10	440
750	915	1.11	443
800	909	1.11	446
850	903	1.12	449
900	897	1.13	452
950	890	1.14	455
1000	884	1.15	458

1050	878	1.15	462
1100	872	1.16	465
1150	866	1.17	468
1200	860	1.18	471

3.5.4 Equipment installation process

Once the sensors had been checked and calibrated (Section 3.5.3), the installation process began. In total 18 technicians were involved in the installation roll-out. The technicians underwent practical training at TU Graz and were then accompanied by an experienced staff member on their first few projects, before working autonomously (see Appendix B.4. for the installation manual, describing the installation process). Due to the large number of schools and the logistics involved, the sensor installation phase took place over a period of several months (June-Sept 2023). The process began locally in Graz, Styria and was then widened out to all other schools in Styria. This approach provided the opportunity to trial and test the installations, train project technicians locally, and sort out potential equipment problems, prior to the nationwide roll-out.

3.5.4.1 Matched-pairs research design and room selection process

As part of the matched-pairs research design, the objective was to select 10 classrooms per school from which to form five, nearly identical, matching room-pairs. Each of these five pairs consisted of one test (T) and one control (C) classroom. In the T classrooms, CO_2 sensors with an active (i.e. visible) display, LED traffic light and accompanying ventilation instructions were installed (Appendix B.6). Conversely, in the C classrooms, identical sensors but with deactivated displays, and deactivated LED traffic lights, were installed without ventilation instructions. The randomised matched-pairs design was designed to allow comparisons to be drawn between the effects of visible interventions, such as the use of CO_2 sensors and ventilation guidance, against a paired control sample (with similar room and occupancy characteristics, but no visible influencing factors) in the same school.

The process of pairing classrooms required a methodical approach, following a predefined hierarchy in the selection process (Appendix B.5). The main priority was to pair rooms of a similar size and function with similar ventilation options and characteristics, ensuring, for example, that a room with mechanical ventilation was not paired with a room that was ventilated solely by windows. In addition, it was important that the comparator classrooms met several additional criteria to allow 'like-for-like' comparisons to be drawn and to avoid biasing the study. These included being situated on the same floor, having the same window orientation, similar glazed area, floor area, and ceiling height, although it was not possible to comply with all of these criteria in all cases. Moreover, efforts were made to match classrooms based on the grade or age range of students and class size. Where possible, rooms without fixed class groups and with changing student populations, such as subject-specific rooms for physics, chemistry or woodworking, were excluded. This exclusion aimed to minimise the potential influence of changing student populations on the results of the matched-pairs research design, thereby ensuring that the measurements would be more accurate and reflective of the intended interventions. The assignment of T and C rooms, within a pair, was then carried out randomly, prior to visiting the schools, to avoid unintended bias in the final room selection (Appendix B.5). An Excel tool was created, incorporating a random number generator, to facilitate the randomised (T or C) room assignment process.

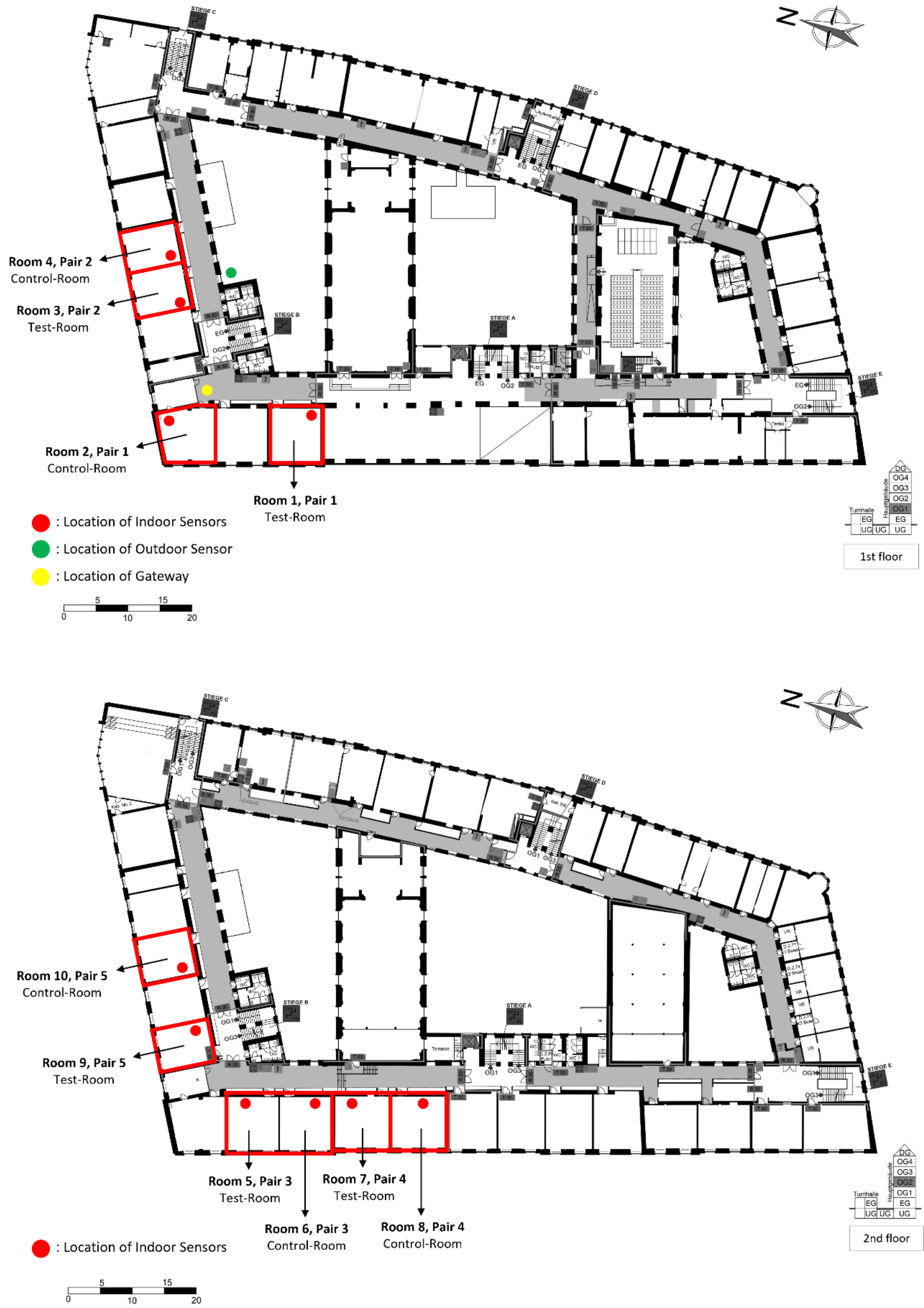
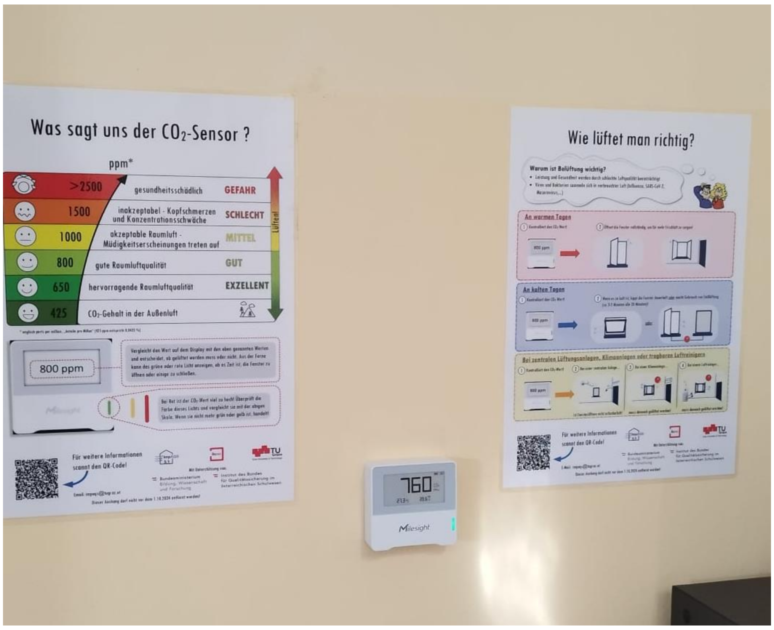


Figure 3-7. Example school, first storey (top) and second storey (bottom), demonstrating the concept of paired-room selection. Rooms with sensors are indicated with a red dot, and test and control rooms face the same orientation, have the same ventilation (window openings), are on the same floor and have a similar room size

3.5.4.2 Indoor CO_2 sensor positions

In each school, ten sensors (AM 103, Milesight) were placed at a height of 1.2 meters (above floor level) on the inside walls of the classrooms. Particular attention was paid to placing the indoor sensors at a considerable distance (more than 1 metre) from fresh air sources such as doors and windows, and from potential CO_2 sources such as students and teachers (Hopfe et al., 2022). In accordance with the matched-paired study design (Section 3.1) CO_2 sensors with active displays (Fig. 3-8) were installed in the five test classrooms, while sensors with deactivated displays (Fig. 3-9) were placed in the five control classrooms (Section 3.5.5). Additionally, the test classrooms were equipped with two wall mounted display posters. The first poster contained guidance on appropriate CO_2 thresholds, whilst the second provided practical instructions on how to ventilate the room correctly, as shown in Fig. 3-8 and Appendix B.6. These posters contained QR codes that linked to additional information on the ImpAQS project website. The posters were mounted next to each other on an internal wall in close proximity to the sensor (Fig. 3-8).

In coordination with the school's facilities staff, the indoor sensors were either securely fastened using screws and wall-plug fixings or attached with double-sided adhesive tape, provided by the sensor manufacturer.



3-8. Example showing installed Test (T) sensor and room-display posters

Figure 3-9. Example showing a Control (C) sensor (with deactivated display)

3.5.4.3 Outdoor CO_2 sensor positions

One battery operated outdoor sensor (EM 500, Milesight) was placed in the grounds outside each school. These sensors were non-invasively fixed to secure building elements (e.g. railings, lantern posts etc.) using standard galvanised hose clamp fixings. Care was taken to ensure that the sensor was not placed near windows and ventilation systems that might otherwise influence the CO_2 temperature and humidity measurements. Locations were chosen were the sensor was positioned in the free air but also partially protected from environmental factors (such as direct sunlight, rain, snow) and potential theft. These sensors were generally positioned at heights between 1.5 and 2 m above ground level (Fig. 3-10).

Figure 3-10. Example showing the installation of an outdoor (EM 500) sensor

3.5.5 Test and Control classrooms – CO_2 displays, thresholds and ventilation guidance

In the test classrooms the CO_2 sensors were configured with visible displays, whilst in the control classrooms the displays were deactivated (for the duration of the research study). Bespoke firmware updates were provided for the test sensors, by the manufacturer (Milesight) to enlarge and simplify the display according to the ImpAQS team's specifications. The reconfigured displays were designed to make the CO_2 concentration values more visible in the classroom. In addition a coloured LED warning light (RAG alert) was set on the test sensors to display 3 different colour signals (green, amber, and red) according to the room CO_2 concentration. For this purpose the green light was set to go on when CO_2 concentrations were below 800 ppm, the light turned amber at concentrations from 800 to 1000 ppm, and red at concentrations above 1000 ppm. These values were chosen in line with recommendations from the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and CO_2 threshold guidance in ISO 16000-41:2023 (ISO, 2023) and ÖNORM EN 16798-1 (CEN, 2024).

In order to minimise the impact of the project on school staff it was agreed with the BMBWF that no formal training would be provided to classroom teachers in relation to the use of the CO_2 sensor or appropriate ventilation methods. Instead, two wall mounted display posters were created and installed in each test classroom. The purpose of these posters was to provide staff with simple guidance which they could refer to on how to interpret the information displayed on the CO_2 sensor and how to regulate the ventilation rate using openable windows. The ventilation guidance addressed ventilation during warm and cold periods of the year and also the appropriate use of ventilation in conjunction with air filtration and air conditioning systems (Appendix B.6).

3.5.6 Measurement data – quality assurance procedures

Once the equipment was installed an ongoing quality assurance (QA) process continued throughout the entire monitoring phase of the project. There were two main aspects to the QA process:

(i) *Remote surveillance of the equipment status via the cloud* (Fig. 3-4). This involved setting automated alarms that indicated, for example, when batteries were losing power and needed replacing or when unusual (extremely high or low) CO_2 values were recorded.

(ii) *Audit inspections and recalibration checks on sensors in the field*. Both planned (i.e. in response to implausibly low or high values) and random QA audits were carried out. Verification of the accuracy of the installed sensors was carried out using a high quality pre-calibrated CO_2 sensor (LiCOR 850, LI-COR Environmental USA) as a means of cross validation. Devices which were identified as having significant measurement discrepancies were then recalibrated in the field, whilst devices with minor discrepancies underwent a mean bias error correction process at the final data processing stage. This process was based on statistical inference using the collective mean bias of all the sensors in a given calibration batch (Appendix B.7).

In addition to these planned QA processes, school staff occasionally reported issues with equipment (e.g. missing or damaged sensors) and these were logged, by the ImpAQS Project Manager, and followed up with telephone calls and site visits.

3.6 Classroom survey data protocols

During the installation phase detailed room surveys were carried out by the ImpAQS technicians in each classroom. A system to record the main physical characteristics of each school and room surveyed was created using the Zoho Forms tool (Zoho Corporation Pvt. Ltd., 2024) which was linked directly to the project cloud database. The purpose of collecting school and classroom survey data was to allow further analysis to be carried out to better understand the nature of relationships between the ventilation rate and IAQ and the specific characteristics of an individual school room or classroom pair. The school data recorded in the surveys is summarised in Tbl. 3-3 and the main room survey inputs are summarized in Tbl. 3-4. An example of the Zoho Form used is included in Appendix B.8.

Table 3-3. School data collected as part of the survey during the installation process

School data
region name
school ID number (an internally assigned number)
type of school (e.g. primary school, middle school etc.)
size of school (the total number of students)
altitude
number of total floors
overall size of school
ventilation system type(s)
construction method

Table 3-4. Classroom data collected as part of the survey during the installation process

Classroom data	
general	time of survey, date of survey
	control or test room
	network strength (needed for sensor signal transmission to gateway)
classroom	classroom floor level
	room type (classroom, subject room, other)
	room geometry (width, length, height)
	orientation room faces
	CO_2 sensor already present (none, yes with display and RAG alert, RAG alert only)
	background noise (audible human, outside, ventilation noise)
	table layout (rows, sloped, U-layout, circular, grouped, other)
	actual occupancy (if known)
	maximum occupancy (based on seats and desks)
	plants in room
building services	ventilation type (none, natural, mechanical, hybrid, other)
	mechanical/hybrid ventilation (none, central, in room, extract, hybrid-supply, hybrid-extract, hybrid-extract distributed)
	portable filters (single room , multiple room HEPA, UV-C, other)

	heating system (none, radiators, hydronic, radiators electric, underfloor heating, room convector, portable heater, unknown
	cooling system (split system, chilled beam, cooling coil, unknown)
windows and shading	window aspects (single sided, 2-sided, 3-sided, 4-sided, none, other
	orientation glazing (north, north-east, east, south-east, south, south-west, west, north-west, horizontal roof light
	roof light window (yes, no, other)
	external facade total area
	maximum openable window area
	openable windows (tilt and turn, turn only, bottom hung, top hung, sliding horizontal, sliding vertical, pivot horizontal and vertical, none, openable, other)
	window restrictors type (if yes, degree of opening 5, 10, 15, 20, 25-45%)
	window opener (manual, mechanical, button, mechanical automated, other)
	window position (central, full height opens, low & high level, high level only, low level only, non-openable, other)
	number of glazing panes (single, double, triple, quadruple)
	frame type (vinyl, aluminium, solid-wood, wood clad)
	external shading (horizontal moveable or fixed, roller shutter, overhang, recessed window, vegetation, other)
	internal shading (curtains, venetian blinds, roller blinds)

3.7 Outdoor CO_2 reference values and UBA air pollution data

Knowledge of the outdoor air quality in the proximity of a school is an important factor in assessing the overall quality of the indoor air. According to the North American standard ASHRAE 62.1 compliance with national ambient air quality standards should be determined as part of the outdoor air quality assessment process before installing any new ventilation system. This regional level assessment should be supported by an observational survey, carried out at the building site and/or its immediate surroundings, in order to identify any potential sources of hazardous local contaminants (ASHRAE, 2022). Approximately 90% of Austrian schools are naturally ventilated using openable windows (Section 4.2.1.5), which means that it is not possible to filter the incoming air. In contrast most mechanical ventilation systems are able to filter particulate matter from the supply air, using the appropriate class of filter (Eurovent, 2018). Conversely, most of the existing mechanical ventilation systems in schools are not equipped with activated carbon filtration or other methods of removing gaseous pollutants (such as NO_2 and O_3). This is an important consideration since the air inside a classroom is unlikely to be better than the air outside the classroom, unless the supply air is filtered, or the fresh air supply is cut-off (e.g. windows are closed) at times when external pollution levels are high (Greenpeace, 2018).

Ideally, detailed on-site monitoring (in the school grounds and inside the school building) of a broad range of air pollutants[10] would provide the most accurate insight into the outdoor pollution (and corresponding indoor pollution) risks at the location of an individual school. In the absence of on-site

[10] A detailed list of such design compounds (i.e. pollutants) and their design limits can be found in ASHRAE Standard 62.1-2019 (ASHRAE, 2019) and its Addendum aa (ASHRAE, 2021)

measurements data from the nearest Austrian Environment Agency (UBA) monitoring station was used as a proxy for the background air quality at the site of the schools. The UBA measurement stations were located on average approximately 10km (Appendix B.9., Tbl. A-3) from the schools and can therefore only provide a broad indication of the air quality outside the schools. None-the-less, analysis of this information helps to provide an indication of the ambient air quality in proximity to the schools, as well as highlighting potential risk areas that should be investigated with further research.

Harmful airborne contaminants are widespread in the background air mass across Europe, with 96% of the EU's urban population being exposed to unsafe concentrations of fine particulate matter ($PM_{2.5}$) (EEA, 2024). Whilst significant improvements in ambient air quality have been made in recent decades, the European Environment Agency (EEA) estimates that in excess of 300,000 premature deaths occur annually as a result of fine particulate, NO_2 and O_3 pollution (EEA, 2024a). Whilst most conventional air pollution assessments consider exceedances for each pollutant separately, when multiple pollutants exceed safe guidelines concurrently, they can have a synergistic impact on overall health risks (Inness et al., 2019; De Marco et al., 2022). In Europe it is estimated that over 86% of the population experiences one or more *compound pollution events*[11] per year (Chen et al., 2024).

Depending on the type of pollutant, local sources of contamination can greatly influence the pollution load at a specific site. Road traffic is one of the main factors affecting the localised concentration of outdoor air pollution (Greenpeace, 2018). The most recent annual report of the EEA showed that in 2022-23, road transport was the main source of nitrogen dioxide (NO_2) and soot (black carbon) emissions. For fine particles PM_{10} and $PM_{2.5}$, 16% and 2% of the population respectively live in a region where the concentration is above the current EU limit value. It should be noted however, that the EU limit values for all major air pollutants are set at significantly higher levels than the WHO 'health-based' guideline values. For example the WHO annual mean guideline level for PM2.5 is 5 µg/m³ and 95% of Europe's population are estimated to be exposed to levels at or above this threshold (EEA, 2024b).

Although local pollution sources can significantly amplify background pollutant concentrations, at a distance of approximately 100 to 150 m from a road, localised air concentrations are no longer directly influenced by traffic. However, in some cases, the distance between schools and a main road may be significantly less than 100 m (Greenpeace, 2018).

3.7.1 Ambient carbon dioxide (CO_2) – health effects and baseline reference values

Carbon dioxide concentrations measured near to ground level are mainly governed by the global carbon cycle. However emissions from local CO_2 sources (chiefly from the combustion of fossil fuels) and sinks (such as trees and plants which sequester CO_2 from the atmosphere during photosynthesis) can influence the local CO_2 concentration, particularly in dense urban areas (Bergeron and Strachan, 2011). The CO_2 content measured in air is usually reported in the unit parts per million (where 1 ppm as a volume fraction is 1 µmol/mol) (ISO, 2012), wherein the current global CO_2 average concentration of approximately 420 ppm would be equivalent to an air volume fraction of 0.042%. Largely as a result of the combustion of fossil fuels, the CO_2 concentration in the outside air is rising by approximately 2.5 ppm per year. CO_2 is colourless, odourless and tasteless, it is also readily water

[11] A compound air pollution episode, is defined as one in which the WHO daily guidelines are simultaneously exceeded for two or more air pollutants (Chen, 2024).

soluble and chemically stable under standard conditions and is not considered hazardous to human health at ambient concentrations.

One of the most well-known global CO_2 monitoring sites is the Mauna Loa observatory, on the Big Island of Hawaii. Although the Mauna Loa observatory, located at an altitude of 3400 m, is considered to be well situated to measuring air masses that are representative of very large areas (Tans and Thoning, 2020) there are variations in the ambient CO_2 levels on different continents. For example the background CO_2 concentration in Cologne, Germany is on average about 10% higher than at the Moana Loa observatory in Hawaii (ISO, 2012, p2). Background CO_2 measurements in Austria are recorded at the Central Institute for Meteorology and Geodynamics (ZAMG) Sonnblick observatory, located at an altitude of 3100 m on Hoher Sonnblick (Ludewig, 2024). Other than in densely forested areas it is unlikely that the local ambient CO_2 concentrations in Austria will fall below the values measured at the Sonnblick observatory. For this reason the Sonnblick CO_2 timeseries values (dark blue line, Fig. 3-11) are a useful source of background comparator values for the ImpAQS study.

Vienna is the largest urban area in Austria, and CO_2 reference values in densely populated parts of the city are likely to reflect some of the highest concentrations in Austria. There is however a paucity of ground level ambient CO_2 monitoring with which to establish typical urban reference values. For this reason measurements from the Vienna Urban Carbon Laboratory research station on the Arsenal tower in Vienna have been used as an estimate of plausible CO_2 values in urban locations (Matthews et al., 2024). Due to the upward flux of CO_2 above urban areas CO_2 values measured at the Arsenal radio tower (144 m above ground level) are likely to be somewhat higher than ground level measurements in the same location. As such these values (dark red line, Fig. 3-11) can be seen as an approximate upper-limit of the typical daily mean CO_2 concentrations likely to occur in an urban area in Austria. From this desktop analysis it is evident that daily mean CO_2 values 10 – 80 ppm above the ambient background level are plausible in urban areas, with larger differences more likely during the winter heating season.

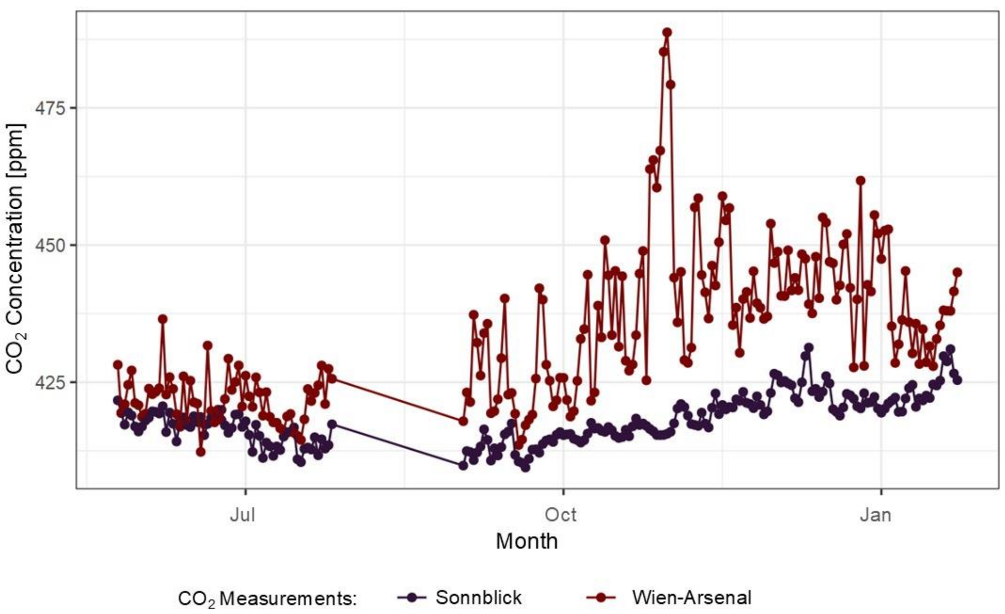


Figure 3-11. Outdoor CO_2 measurements – Sonnblick observatory (rural background concentration) vs. Arsenal Tower Vienna (urban setting) (2023-24) (Matthews, 2024)[12].

[12] This image is third party material, exempted from the terms of the CC BY-NC-ND 4.0 license agreement.

3.7.2 Particulate matter ($PM_{2.5}$) – health effects and normative reference values

Particulate matter with a diameter of 2.5 µm or less ($PM_{2.5}$) is more likely to travel into and deposit on the surface of the deeper parts of the lung in contrast to PM_{10}, which deposits in the upper region of the lungs. As such fine particles (i.e. $PM_{2.5}$ and smaller) are typically considered to be more dangerous to human health. Similarly to PM_{10}, the main sources of $PM_{2.5}$ originate from the combustion of solid fuels for domestic heating, industrial activities and road transport. As with PM_{10}, they can also come from natural sources and can form in the atmosphere (EEA, 2024). Long-term exposure to $PM_{2.5}$ has been linked to premature deaths, cardiopulmonary illnesses (such as heart disease, respiratory infections, chronic lung disease, cancers, preterm births) and other illnesses as well as reduced lung function growth in children (Thangavel et al., 2022). The EU annual mean $PM_{2.5}$ limit is 25 µg/m³ whilst the WHO annual mean guideline level is 5 µg/m³ and the daily guideline level (at the 99th percentile[13]) is 15 µg/m³.

3.7.3 Particulate matter (PM_{10}) – health effects and normative reference values

Particulate matter with a diameter of 10 µm or less (PM_{10}) is emitted mainly by the combustion of solid fuels for domestic heating, although agriculture, road transport and industrial activities, are also considered to be important sources (EEA, 2024). Exposure to high concentrations of PM_{10} can result in a number of health impacts ranging from coughing and wheezing to asthma attacks and bronchitis to high blood pressure, heart attack, strokes and premature death. Studies indicates that both symptomatic and asymptomatic children may suffer acute health effects of respirable particulate pollution, with symptomatic children suffering the most (Pope and Dockery, 2012). The EU daily limit value for PM_{10} is 50 µg/m³ whilst the corresponding WHO daily guideline level is 45 µg/m³ (at the 99th percentile). The EU annual mean limit is 40 µg/m³ whilst the WHO annual mean guideline level is 15 µg/m³.

3.7.4 Nitrogen dioxide (NO_2) – health effects and normative reference values

Nitrogen dioxide (NO_2) is considered to be an important indicator of road traffic-related air pollution. In 2015 it was estimated that 9% of the European population lived in a region where the annual concentration of nitrogen dioxide (NO_2) exceeded the EU limit value (40 µg/m³) (Greenpeace, 2018). However, as a result of tighter emission controls that figure has now fallen to 1% (EEA, 2024). It should be noted however, that the European annual limit value for NO_2 is four times higher than the health-based value recommended by the WHO (10 µg/m³) (WHO, 2021b). In contrast, the WHO's daily threshold level is 25 µg/m³ (at the 99th percentile). The WHO's guidance refers to studies indicating that the negative effects of exposure to NO_2 (and other contaminants associated with it) on children's health have been conclusively demonstrated, even at relatively low concentrations. The strongest evidence pertains to the risk of asthma (WHO, 2021b), which increases by 15% for every 10 µg/m³ increase in the average annual NO_2 levels. These findings highlight the notable health risks which are present at concentrations well below the current European threshold limit (Greenpeace, 2018).

[13] Note, a daily guideline assessed at the 99th percentile implies that the limiting value cannot be exceeded for more than 1% of the days in a year (i.e. 3.65 days) hence a maximum daily exceedance of 3–4 days is permitted.

3.7.5 Ozone (O_3) – health effects and normative reference values

Ozone (O_3) like other photochemical oxidants is not directly emitted by a primary source. Rather, it is formed through a series of complex reactions in the atmosphere driven by the energy transferred to nitrogen dioxide (NO_2) and volatile organic compounds (VOCs) (including methane) when they absorb heat and light from solar radiation. According to the US EPA (2024) O_3 can trigger a number of respiratory health issues including: inflammation of the airways, as well as aggravating lung diseases such as asthma, emphysema, and chronic bronchitis. The WHO long-term air quality guideline (AQG) level for O_3 is linked to the so-called 'peak-season exposure' level. Peak season is defined as the six consecutive months of the year with the highest six-month running-average O_3 concentration. In the northern hemisphere this period typically occurs in the warm summer period. The EU target value for O_3 is 120 µg/m³ whilst the WHO peak season guideline level is 60 µg/m³ and the short-term guideline level is 100 µg/m³. In Austria, the Ozon Act (Ozongesetz) (RIS, 2024d) aligns with the EU guidelines, setting a target value of 120 µg/m³. These values are not simply daily averages but are based on the daily maximum 8-hour moving average. This means that an 8-hour moving average is computed every hour throughout the day, considering the current hour and the previous 7 hours, resulting in 17 unique 8-hour averages. The highest of these hourly moving averages is then selected as the daily maximum moving average.

3.7.6 Summary of EU and WHO outdoor pollutant threshold limiting values

In order to assess the status of the ambient outdoor air quality in proximity to the schools the UBA data for each outdoor air pollutant ($PM_{2.5}$, PM_{10}, NO_2, and O_3) was assessed relative to both the EU limit values and the WHO (daily, annual and peak season) air quality guideline (AQG) levels. The guideline values for outdoor air pollutant concentrations published by the WHO (2021b) are periodically updated based on emerging science regarding their impacts on human health. The relevant EU standards were originally set out in the 2008 Ambient Air Quality Directive (EU Directive 2008/50/EC12). In October 2022, as part of the European Green Deal, the Commission proposed to revise the Ambient Air Quality Directives (European Commission, 2024). This revision aligns the EU air quality standards more closely with the recommendations of the World Health Organization. The threshold limiting values used for these assessments are defined as time-weighted averages (Tbl. 3-6).

The European Parliament's Fitness Check of the Ambient Air Quality Directives (Directives 2004/107/EC) (European Union, 2004) and 2008/50/EC (European Union, 2008) showed that, "*limit values are more effective in bringing down pollutant concentrations than other types of air quality standards, such* as *target values*" (European Parliament, 2023). However there is concern that current EU limit values may not fully reflect the severity of the health risks in the manner which the WHO guideline values do, especially in relation to fine particulate matter (PM2.5) (European Commission, 2019; European Parliament, 2023), for this reason both values are reported here.

Outdoor Air Quality (ODA) classification is a concept analogous to the IEQ classification system used for indoor air in EN 16798-1 (CEN, 2019) and other normative documents. ODA classification was primarily intended as an aid for ventilation designers in assessing the effects of outdoor pollutants on the indoor environmental conditions for the occupants of a given space (Eurovent, 2018). The ODA is divided into three pollutant concentration categories (Acceptable, Moderate, High) based on the ambient air pollutant concentration. The procedure for applying this process is based upon location dependent exceedances of hourly threshold values, as described in EN 16798-3; wherein, the ratio of the hourly exceedance to the maximum permissible value determines the ODA class (Tbl. 3-5). It is recommended that the ODA classes should be assessed separately for particulate matter ODA (P) and for gaseous components ODA (G), wherein the worst parameter in each class determines the overall ODA category (CEN, 2022).

Table 3-5. Outdoor Air Quality (ODA) classification based on WHO limit values

ODA category	Pollutant concentration	Description
ODA 1	< 1.0 x WHO limit	Acceptable
ODA 2	1.0 x WHO limit ≤ pollutant concentration < 1.5 x WHO limit	Moderate
ODA 3	≥ 1.5 x WHO limit	High

The relevant WHO, EU, and Austrian air quality guideline (AQG) threshold limits for the assessment of the four major outdoor air pollutants ($PM_{2.5}$, PM_{10}, NO_2, and O_3) assessed in this study are shown in Tbl. 3-6. The WHO limits were most recently revised in 2021 (WHO, 2021b) and are, in most cases, significantly lower than either the EU or Austrian limits.

Table 3-6. Summary of outdoor air pollutants and the respective WHO, EU and Austrian thresholds

Pollutant	Averaging period	WHO guideline	Current EU limit	Austrian law	Exceedances
$PM_{2.5}$	Yearly average	5 µg/m³	25 µg/m³	25 µg/m³	
	Daily average	15 µg/m³	N/A	N/A	WHO: 3-4 exc. days per year (99th %ile)
PM_{10}	Yearly average	15 µg/m³	40 µg/m³	40 µg/m³	
	Daily average	45 µg/m³	50 µg/m³	50 µg/m³	WHO: 3-4 exc. days per year (99th %ile) EU: 35 exc. days per year AUT: 25 exc. days per year
NO_2	Yearly average	10 µg/m³	40 µg/m³	30 µg/m³	
	Daily average	25 µg/m³	N/A	80 µg/m³ (target value)	WHO: 3-4 exc. days per year (99th %ile)
	Hourly average	200 µg/m³	200 µg/m³	200 µg/m³	EU: 18 exc. per year
O_3	Peak season avg. *	60 µg/m³	N/A	N/A	
	Maximum daily 8-hour avg.	100 µg/m³	120 µg/m³ (target value)	120 µg/m³ (target value)	WHO: 3-4 exc. days per year (99th %ile) EU: 25 exc. days averaged over 3 years AUT: 25 exc. days averaged over 3 years
	Yearly average	N/A	N/A	N/A	

* Average of daily max. 8-hour mean conc. in the six consecutive months with the highest six-month running average O_3 conc.

3.7.7 Mapping UBA air quality monitoring stations to school locations

In the absence of atmospheric pollutant measurement equipment at the site of each school, outdoor air quality data from the nearest Austrian Environment Agency (UBA) measuring station was used to estimate the background air quality in proximity to the schools (Fig. 3-12). Two particulate ($PM_{2.5}$, PM_{10}) and two gaseous (NO_2, and O_3) pollutants were selected for this assessment, based on the spatial coverage and quality of the available data. Expert input from UBA Austria (Spangl, 2023) was provided to help determine the most appropriate measuring station for each variable in relation to each of the ImpAQS schools.

In most cases, suitable measuring stations were identified for each of the four parameters ($PM_{2.5}$, PM_{10}, NO_2, and O_3) for each school, with approximately 73% of stations being located less than 10 km from the schools. In 16% of cases, stations were located between 10 and 30 km away from schools. A further 11% of the stations were located more than 30 kilometres away from the schools (Appendix B.9., Tbl. A-3). It is acknowledged that more distal measurements are unlikely to closely reflect the air quality profile at an individual school site, however the measurements are considered to be indicative of the background air pollution concentrations in the general vicinity of the schools.

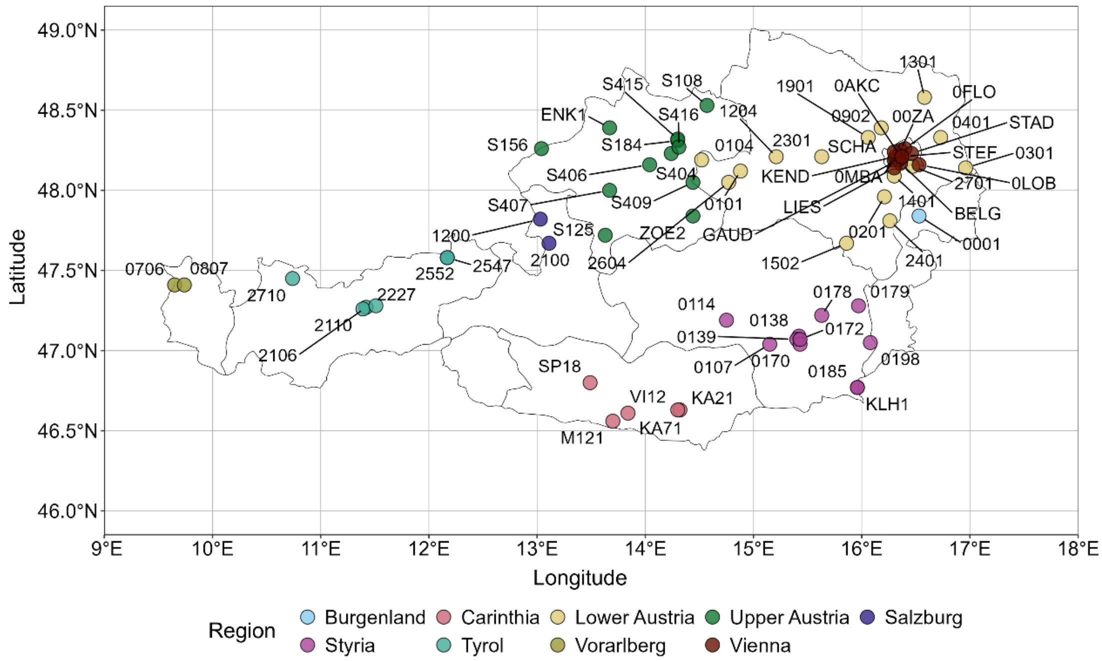


Figure 3-12. Map showing the location of the UBA outdoor monitoring stations and proximity to schools

3.8 Analytical infection risk models

The risk of infection through aerosol transmission of the SARS-CoV-2 virus was estimated with an analytical method developed by researchers from the Max Planck Institute for Chemistry (MPIC), Germany, and the Cyprus Institute, Cyprus (Lelieveld et al., 2020). The purpose of this infection risk calculation is not to precisely predict the probability of an individual infection occurring at a given point in time, but rather to provide a comparison of the relative prophylaxis benefits of different ventilation rates, when applied to the same context.

This method calculates the time-dependent concentration of airborne virus particles, and the accumulated number of inhaled virus particles. These calculations are based on human aerosol emission rates and viral removal rates, which result from the air exchange rate and the virus's lifetime when suspended in an aerosol medium. The probability of infection is determined from the inhaled dose of virus particles and the infective dose (D_{50}) (of n=154) for the Omicron variant of the SARS-CoV-2 virus. Wherein, the D_{50} value represents the mean dose that causes infection in 50% of susceptible people. Group risk refers to the probability that at least one person within a group will be infected, assuming the presence of one infectious person in the room. The method along with the associated formulas and parameters, as well as the reference scenario used for comparison can be found in Appendices B.9 and B.10.

Section 4-5 presents illustrative examples of the risk of infection based on occupancy, ventilation rate, and exposure duration. Additionally, the theoretical average daily infection risk for all 1200 classrooms over the measurement period from October 2023 to July 2024 was calculated using daily mean ventilation rates derived from the CO_2 measurements.

3.9 Absenteeism data

Anonymous absenteeism data was collected from the participating schools in order to assess whether relationships existed between school attendance and IAQ, ventilation and other environmental parameters. This data proved to be difficult to obtain, in part due to the lack of a standardised reporting system in Austria. Whilst the majority of schools used the WebUntis reporting system (Untis GmbH, 2024) an additional system needed to be developed for those schools which recorded their absenteeism data using another method. A bespoke data collection method was developed for this purpose using a unique QR code for each classroom linked to a web-based Zoho Form (Zoho Corporation Pvt. Ltd., 2024). Of the 120 schools participating in the ImpAQS project just over half reported anonymised attendance data for the winter (n=61) and summer semester (n=62).

For the schools that reported absenteeism data, two anonymised spreadsheets were provided for each classroom: one for the first semester and one for the second semester. Each spreadsheet contained a weekly table where each row represented an anonymised student, and for each day of the week, the number of absent hours was recorded.

Given the large volume of data, manually counting absenteeism was considered impractical. To address this, a custom script was developed to automate the process. The script iteratively loaded each spreadsheet, automatically identifying the number of students from the table structures and their absences for each school day based on the recorded daily absent hours per student. Since there was no information provided regarding the cause of absence, any student who was absent for 4 hours or more (in any given) day was categorised as being absent for the entire day, while those with absences lasting less than 4 hours were considered present. The script processed the absenteeism data for each classroom and semester, computing the total number of students, absent students, and present students, both in absolute and relative terms, across the entire school year.

Although the process was largely successful, some irregularities and variations in the structure of the spreadsheets resulted in a small amount of data being lost during the automated extraction process. Despite the limited number of schools (~50%) that provided absenteeism data, the automated process successfully retrieved absenteeism figures for approximately 42% of the daily dataset from the total of 120 participating schools. This allowed for a reasonably comprehensive assessment of absenteeism trends, even with the challenges posed by variations in data reporting across different schools

3.10 Austrian national SARS-CoV-2 RNA waste-water data

The Austrian Abwassermonitoring (wastewater monitoring) program tracks the concentration of SARS-CoV-2 viral RNA in wastewater across Austria. Currently the system covers 48 strategically selected sewage treatment plants in Austria, which include more than 58% of the Austrian population within its catchment area (BSGPK, 2024). This surveillance provides valuable insights into the spread of the virus, providing an early warning system and a way to monitor infection trends. Wastewater surveillance captures data from both symptomatic and asymptomatic individuals, making it a valuable adjunct to clinical testing. It also helps monitor emerging variants and gives a real-time snapshot of the viral load in the population, which can support public health decision-making.

In this report, the dataset from the national Abwassermonitoring dashboard (BSGPK, 2024), corresponding to the 2023 –24 school year, was used to analyse the relationship between the prevalence of SARS-CoV-2 (measured in units of RNA genome copies per inhabitant/day) and absenteeism rates in schools. The objective was to determine whether there is an association between the levels of SARS-CoV-2 viral RNA in wastewater and school absenteeism rates, potentially revealing a leading or lagging relationship between community viral loads and school attendance.

The correlation analysis was conducted using daily mean absenteeism percentages, aggregated across all schools, and the daily mean national genome copy data for Austria, alongside other environmental variables such as indoor CO_2 concentrations, outdoor $PM_{2.5}$ levels, outdoor temperatures, and indoor ventilation rates. The aim was to investigate whether any meaningful associations could be identified between these factors and school absenteeism rates. Although the inclusion of wastewater data in this analysis was exploratory, it provided valuable insights into the potential influence of environmental and community-level factors on school absenteeism.

3.11 Qualitative surveys (of directors and teachers) and their statistical analysis

Conducting qualitative research via surveys or interviews with the occupants of buildings is a well-established approach, that can provide valuable insights into end-user opinions, behaviours, and attitudes as well as their acceptance of new technologies. Socio-technical methods are increasingly used in research in the built environment based on the premise that the operation of buildings and their associated engineering systems should be a process that considers both social *and* technical factors (Bordass et al., 2001; Lowe et al., 2018). In this respect occupant surveys facilitate the systematic gathering of qualitative data, allowing researchers to measure specific variables within a chosen sample. This structured approach also enables the extrapolation of findings to larger populations, enhancing the generalisability of the results. The evolution of modern survey methodologies, including the use of online platforms and mixed-mode approaches, has expanded the reach and efficiency of data collection. Online surveys, in particular, have become increasingly popular due to their cost-effectiveness and ability to reach larger and more diverse populations (Evans and Mathur, 2005).

The ImpAQS surveys aim to gather and evaluate end-user perspectives regarding IAQ and ventilation in Austrian classrooms, as experienced by school directors and teachers working in varied building typologies across a wide range of school types, spanning multiple student age groups, and geographic regions.

It is postulated that conducting a survey with school directors and schoolteachers can provide valuable insights that will inform the following research objectives: (i) Understanding the challenges faced by schools (including the directors' personal perspectives and responses to these issues). It is hoped that the survey findings will highlight common issues as well as helping to identify the specific challenges faced by individual schools. (ii) Documenting and evaluating schoolteachers' attitudes towards ventilation and sensors will provide valuable insights into the problems faced ventilating classrooms in a 'real-world' context. These surveys may also highlight barriers to technology adoption and possibly also technology aversion. By conducting the schoolteachers' survey twice, during the winter and summer periods, further information can be gathered in relation to seasonal differences in ventilation practices.

The survey questions to the school directors are shown in Tbl. 3-7; the survey to the classroom teachers is summarized in Tbl. 3-8 for winter, and Tbl. 3-9 for summer, respectively.

The open-source tool LimeSurvey (version 5.6.17) (Limesurvey GmbH., Germany) was used to create all four surveys. In terms of the school director surveys: these were closed access surveys, which means that the survey could only be accessed through a unique link generated by LimeSurvey. For analysis purposes, the links were assigned to the school's project ID number, but did not include the respondent's personal details, in order to maintain anonymity. The links were sent to the school director's email address in a form of an email invitation. As a further quality assurance measure, at the beginning of the survey, there is a question regarding the respondent's position; '*Which option best describes your role at the school?*' (Tbl. 3-7, Q01) which acted as a second filter to ensure that the respondent was indeed the school director. If the person answered anything other than '*School Director*', they were redirected to the end of the survey and their responses were discarded.

In terms of the seasonal surveys for the classroom teachers: these surveys were created as an open access survey and the link for the surveys was sent to the school directors via the schools' email addresses and was then internally redistributed to the teachers involved in the project. To guarantee the surveys were sent to the correct teachers, a redistribution table listing the 10 participating classrooms (which included the floor level and respective room numbers) was included in the invitation email in order to inform the school to forward the link only to those selected teachers. A similar quality assurance question was inserted at the beginning of the teachers' survey to ensure that only the selected teachers responded to the survey. The question '*Which option best describes your role at the school?*'' led to answers 'Class/Subject teacher (Sensor Display **ON**)' or 'Class/Subject teacher (Sensor Display **OFF**)' and there was a note below that, stating that, '*The survey is only to be completed by the class teachers in the 10 selected classrooms in which Milesight CO_2 sensors were installed by TU Graz.'* (Tbls. 3-8 and 3-9, Q01). If the respondents selected anything other than one of these two options, they were redirected to the end of the survey and their responses were discarded. By handling the surveys this way, using anonymised and pseudonymised personal data, and with encrypted storage of the survey results the process remained fully compliant with the General Data Protection Regulations (GDPR) (European Commission, 2016).

The following survey questions were directed at the school directors in two surveys, the first of which took place in September 2023 (project start) and the second in September 2024 (project end):

Table 3-7. Question school directors' survey

	Question
Q01	Which option best describes your role at the school? (mandatory question with 3 options, if "other" is selected, the survey ends as it is only meant to be answered by school directors)
Q02	Please answer the following questions about ventilation, indoor air quality, health and transmission of airborne diseases:
Q02A	How important do you consider ventilation in the classroom? (Likert scale: not at all, somewhat, quite, very, extremely, I don't know)
Q02B	To what extent do you believe that indoor air quality affects pupils' academic performance? (Likert scale: not at all, somewhat, quite, very, extremely, I don't know)
Q02C	How important do you consider indoor air quality in terms of health and the transmission of airborne diseases (e.g. influenza, measles, SARS-CoV-2 etc.) (Likert scale: not at all, somewhat, quite, very, extremely, I don't know)
Q03	Why do you think ventilation is important? (11 options with 'yes' or 'not selected')
Q04	Thinking about your own classrooms, which of the following statements best describes your approach to ventilation? (4 options from 'occasionally', 'every hour', 'continuously', 'other method (e.g. portable filter or hybrid method)'
Q05	Which of the following sentences can you identify with? (15 options listed with 'yes' or 'no' options)
Q06	CO_2 is often used as an indicator of good air quality. What do you think the maximum CO_2 level should be if you want to ensure a healthy working environment in a classroom? (Slider ranging from 0-10,000)
Q07	Do you know which factors influence the air quality in a classroom? (14 options with 'yes' or 'not selected')
Q08	Do you think students should be informed about the impact of ventilation practices and air quality in the classroom? (4 options: all should be informed, it depends on their age, it is not their responsibility, if it does not distract from class). If option 'it depends on their age' is selected, 6 options are available to select (5 years or older, 8 years or older, 10 years or older, 12 years or older, 15 years or older, others)
Q09	Do you think students should play an active role in maintaining ventilation quality in the classroom? (3 options 'yes', 'maybe', 'no'). If 'yes' is selected , 2 options ('make students responsible to monitor CO_2 and ventilate' or 'other'). If 'no' is selected, 2 options ('it is responsibility of school' or 'it is responsibility of teachers'). If 'maybe' is selected, 2 options ('it depends on their age' or 'if it does not distract from class'). If 'it depends on their age' is selected, 6 options (5 years or older, 8 years or older, 10 years or older, 12 years or older, 15 years or older, others)
Q10	Do you think a CO_2 sensor (with a coloured traffic light indicator) and instructions on how to use it would help improve indoor air quality in your classrooms? (Please select one or more answers that apply) (8 options with 'yes' or 'not selected')
Q11	To what extent do you feel that you have received sufficient guidance and support on how to properly ventilate your school during the COVID-19 pandemic? ('yes' or 'no')

The following survey questions were directed at the schoolteachers in the first teachers' survey, which took place in February 2024 (winter survey):

Table 3-8. Questions used in the schoolteachers' survey during the winter period

	Question
Q01	Which option best describes your role at the school? (mandatory question with 3 options, if "other" is selected, the survey ends as it is only meant to be answered by teachers with sensors in the classroom)
Q02	Please answer the following questions about ventilation practices and room temperature: A, How many times did you experience the average room temperature as too warm or too cold when ventilating? (Likert scale: never, seldom, sometimes, often, always). B, How often would you have preferred the temperature to be cooler or warmer (Likert scale: never, seldom, sometimes, often, always)
Q03	How do you experience the air movement (draughtiness) with ventilation (Likert scale: very pleasant, pleasant, not noticed, unpleasant, very unpleasant)
Q04	How would you prefer the air movement to be? (Likert scale: less, somewhat less, no changes, somewhat more, more)
Q05	How do you experience the (outside) noise when using ventilation? (Likert scale: not disturbing, neutral, disturbing, very disturbing)
Q06	Do you feel that the students can concentrate better or worse during ventilation? (Likert scale: worse, somewhat worse, neutral, somewhat better, better)
Q07	Have you experienced one or more of the following ventilation-related issues during the winter season? (13 issues with a 'yes' or 'no' answer)
Q08	If you have encountered one or more of the above problems and have found a way to work around the problem, please describe the problem in more detail and how you solved it. (Open-ended question that relates to the issues in Q07, not mandatory to answer)
Q09	What has helped you to ventilate better? (9 options with 'yes' or 'not applicable' and comment box)
Q10	What would help you to provide better ventilation? (6 options with 'yes' or 'not applicable' and comment box)
	General Attitude to Technology
Q11	How often do you manage to stay within the recommended CO_2 range? (Likert scale: always, sometimes, seldom, never, and others)
Q12	How difficult is it to ventilate properly using a CO_2 sensor? (Likert scale: very easy, easy, difficult, very difficult, and others)
Q13	What difficulties do you have when using the CO_2 sensor? (7 options with 'yes' or 'not selected')
Q14-Q18	Please tick a box if you agree with the following statement on the use of a CO_2 sensor (9 options with 'yes' and 'not selected')

The following survey questions were directed at the schoolteachers, in the second teachers' survey which took place in September 2024:

Table 3-9. Questions used in the schoolteachers' survey during the summer period

	Question
Q01	Which option best describes your role at the school? (mandatory question with 3 options, if "other" is selected, the survey ends as it is only meant to be answered by teachers with sensors in the classroom)
Q02	Please answer the following questions about ventilation practices and room temperature: A, How many times did you experience the average room temperature as too warm or too cold when ventilating? (Likert scale: never, seldom, sometimes, often, always). B, How often would you have preferred the temperature to be cooler or warmer (Likert scale: never, seldom, sometimes, often, always)

Q03	How do you experience the air movement (draughtiness) with ventilation (Likert scale: very pleasant, pleasant, not noticed, unpleasant, very unpleasant)
Q04	How would you prefer the air movement to be? (Likert scale: less, somewhat less, no changes, somewhat more, more)
Q05	How do you experience the (outside) noise when using ventilation? (Likert scale: not disturbing, neutral, disturbing, very disturbing)
Q06	Do you feel that the students can concentrate better or worse during ventilation? (Likert scale: worse, somewhat worse, neutral, somewhat better, better)
Q07	Have you experienced one or more of the following ventilation-related issues during the winter season? (13 issues with a ‘yes’ or ‘no’ answer)
Q08	If you have encountered one or more of the above problems and have found a way to work around the problem, please describe the problem in more detail and how you solved it. (Open-ended question that relates to the issues in Q07, not mandatory to answer)
Q09	What has helped you to ventilate better? (9 options with ‘yes’ or ‘not applicable’ and comment box)
Q10	What would help you to provide better ventilation? (6 options with ‘yes’ or ‘not applicable’ and comment box)
Q11	CO_2 is often used as an indicator of good air quality. What do you think the maximum CO_2 level should be if you want to ensure a healthy working environment in a classroom? (Slider ranging from 0-10,000)
Q12	Do you think students should be informed about the impact of ventilation practices and air quality in the classroom? (4 options: all should be informed, it depends on their age, it is not their responsibility, if it does not distract from class). If option ‘it depends on their age’ is selected, 6 options are available to select (5 years or older, 8 years or older, 10 years or older, 12 years or older, 15 years or older, others)
Q13	Do you think students should play an active role in maintaining ventilation quality in the classroom? (3 options ‘yes’, ‘maybe’, ‘no’). If ‘yes’ is selected , 2 options (‘make students responsible to monitor CO_2 and ventilate’ or ‘other’). If ‘no’ is selected, 2 options (‘it is responsibility of school’ or ‘it is responsibility of teachers’). If ‘maybe’ is selected, 2 options (‘it depends on their age’ or ‘if it does not distract from class’). If ‘it depends on their age’ is selected, 6 options (5 years or older, 8 years or older, 10 years or older, 12 years or older, 15 years or older, others)
Q14	Do you currently have a CO_2 champion (who keeps an eye on the CO_2 level and is responsible to ventilate)? (2 options with ‘yes’ or ‘no’)
	General Attitude to Technology
Q15	How often do you manage to stay within the recommended CO_2 range? (Likert scale: always, sometimes, seldom, never, and others)
Q16	How difficult is it to ventilate properly using a CO_2 sensor? (Likert scale: very easy, easy, difficult, very difficult, and others)
Q17	What difficulties do you have when using the CO_2 sensor? (7 options with ‘yes’ or ‘not selected’)
Q18-Q22	Please tick a box if you agree with the following statement on the use of a CO_2 sensor (9 options with ‘yes’ and ‘not selected’)

4 Quantitative results and analytical investigations

This section of the report provides the results of the quantitative investigations needed to answer research questions 1–4 (Section 1.4). The analysis involves the evaluation of five principle datasets, both separately and in combination:

1. **ImpAQS school and classroom survey data** – this dataset was compiled by the ImpAQS project technicians during the equipment installation phase and provides detailed information on the physical characteristics of each school and each classroom involved in the study (Section 3.6).
2. **ImpAQS CO_2 and environmental quality monitoring data** – this dataset contains monitored data, recorded at a 2-minute interval, from 1200 indoor (CO_2, temperature and relative humidity) sensors and 120 outdoor (CO_2, temperature and relative humidity) sensors for the school year 2023–24 (Sections 3.5).
3. **Air pollution monitoring data** – this dataset contains monitored data recorded by the Austrian Federal Environment Agency (UBA) at an hourly interval, for the outdoor air pollutants ($PM_{2.5}$, PM_{10}, NO_2 and O_3) measured in proximity to the schools (Section 3.7).
4. **Absenteeism data** – this dataset contains anonymised information regarding the hourly absenteeism in the participating classes and was provided by the schools using anonymised data from the WebUntis attendance system (Section 3.9).
5. **Waste-water data** – this dataset contains information on the epidemiological surveillance of SARS-CoV-2 RNA in municipal waste-water during the school year 2023–24. The data was provided by the Federal Ministry for Social Affairs, Health, Care and Consumer Protection (BMSGPK) national wastewater monitoring programme (Section 3.10).

The first two datasets, listed above, are primary data which were gathered during the course of the ImpAQS research study. The last three datasets are comprised of secondary data, wherein Datasets 3 and 5 were provided by the respective federal agencies of the Austrian government, whilst Dataset 4 was compiled from individual datasets provided by the participating schools. Datasets 1,2, and 3 are initially analysed separately in relation to the applicable normative standards and are subsequently analysed in combination to evaluate associations between factors such as thermal comfort and ventilation. Datasets 1 and 2 are further explored to identify statistically significant differences between control and test classrooms. Finally, datasets 1–5 are incorporated in further statistical analysis investigating associations between ventilation rates, CO_2 concentrations, absenteeism, external pollutants and other environmental parameters.

A summary of the analyses carried out in this section is presented in Section 4.6, where a consolidated answer to each of the four quantitative research questions, posed in Section 1.4, is provided.

4.1 Participating schools

4.1.1 Sample selection and geographic distribution

Based on the school selection criteria (Section 3.3) the widest possible range of different school types and age groups were included in the sampling strategy, which was drawn from the nine federal regions of Austria. The study sample was then generated in collaboration with the Federal Institute for Quality Assurance in Austrian Education (IQS) using Monte Carlo sampling methods. During this process the number of schools selected per region was weighted according to the student numbers in the respective regions (Fig. 3-3).

Figure 4-1 illustrates the breakdown (in per cent) of schools per region within the ImpAQS sample along with the actual percentages of students per region. The plot illustrates that the distribution of ImpAQS schools across the nine regions closely reflects the distribution of students in the country, thus indicating that the ImpAQS sample is representative of the student population's geographic distribution.

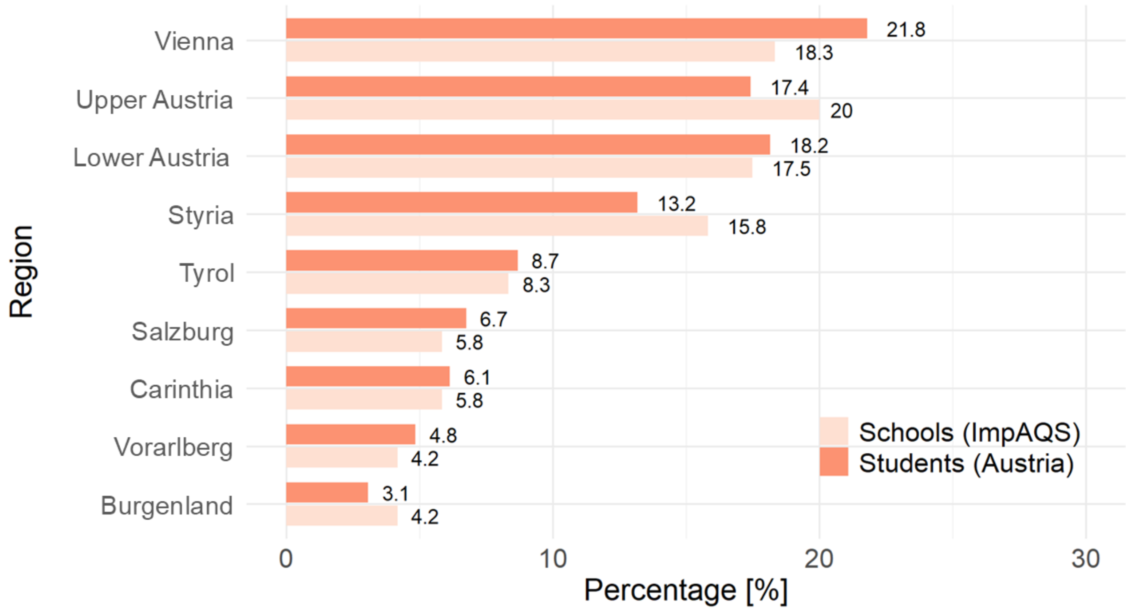


Figure 4-1. Percentage of selected schools per region in the ImpAQS study (pale-orange) in relation to the percentage of students per region (dark-orange)

Based on the aim of equipping 5 paired classrooms (i.e. 10 classrooms) per school a total of 120 schools were selected for the study. Figure 4-1 shows the regional distribution of the selected schools as a percentage of the total, ranked in descending order. With a total of 24 schools, the largest number of schools was selected in Upper Austria (Oberösterreich) region. Although Upper Austria is the region with the third most students after Vienna and Lower Austria (Fig. 4-2), this final selection is a consequence of the lower response rates observed in Vienna and Lower Austria during the project's participant recruitment phase.

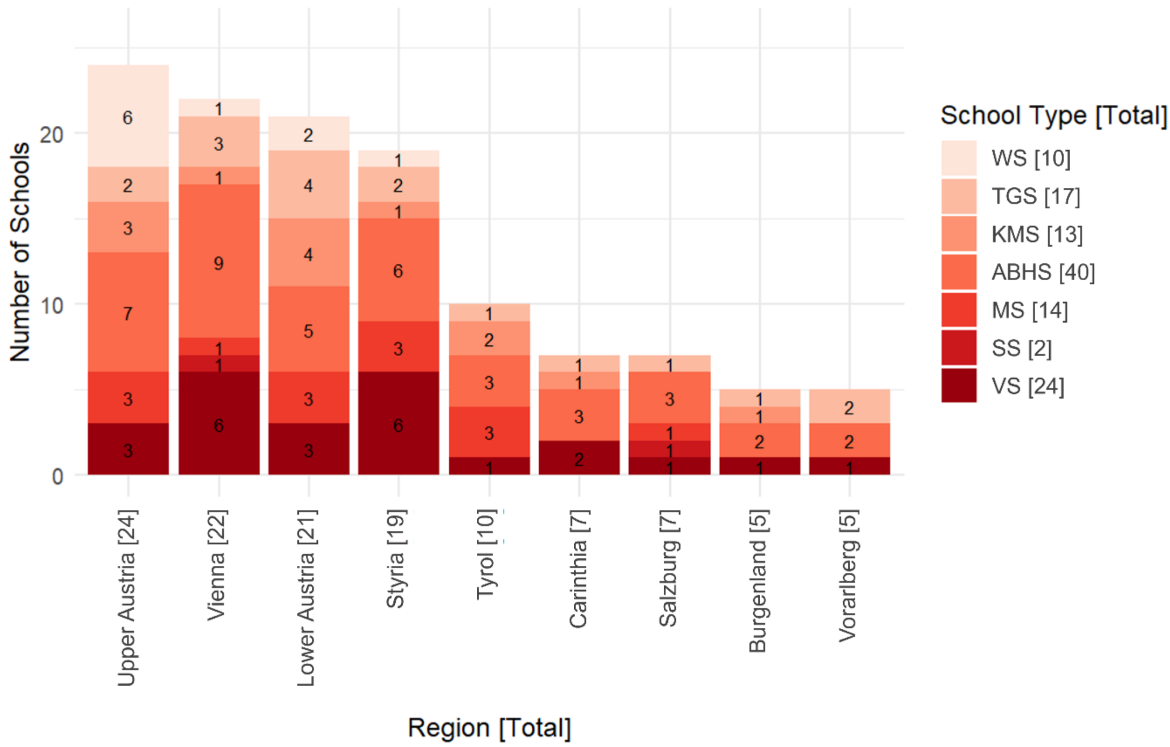


Figure 4-2. Distribution of the selected schools by region and school type

The selected school types included in the study and their respective percentages are: elementary school (Volksschule, **VS**) (20.0%), special school (Sonderschule, **SS**) (1.7%), middle school (Mittelschule, **MS**) (11.7%), general secondary school (Allgemein bildende höhere Schule, **ABHS**) (33.3%), commercial middle or higher school (Kaufmännische mittlere oder höhere Schule, **KMS**) (3.3%), technical and commercial middle or higher school (Technische und gewerbliche mittlere oder höhere Schule, **TGS**) (14.2%), and business vocational middle or higher school (Wirtschaftsberufliche mittlere oder höhere Schule, **WS**) (8.3%).

In the legend of Fig. 4-2 the school abbreviations are followed by the total number of schools in each category (e.g. VS [24] indicates that the ImpAQS sample contains a total of 24 elementary schools). Similarly, on the horizontal axis, each region name is followed by the total number of schools per region (e.g. Upper Austria [24] indicates that a total of 24 schools were included in the Upper Austria region).

Note: vocational schools (Berufsschule) and pre-vocational schools (Polytechnische Schulen), comprising 4.4% and 2.5% of Austrian educational institutions respectively, were deliberately excluded from the sample. This decision was influenced by their strong focus on practical subjects and the dynamic nature of on-site student attendance throughout the school year, which could potentially disrupt the study's 'like-for-like' matched-pairs research design (Section 3.1 and 3.5.4.1).

4.2 Overview of the adequacy of ventilation practices in Austrian schools'

This section aims to answer **research question 1** *"What percentage of Austrian classrooms are adequately/inadequately ventilated according to existing norms and emerging 'health-based' ventilation guidance?"*

In order to answer this question and contextualise the differences in outcomes between individual schools and classrooms it is important to understand the dominant physical and social factors (Section 5) which may be influencing the results. This section begins with a summary of the principle physical characteristics of the classrooms, which are derived from room survey data, obtained during the installation phase of the project (Section 3.5.4 and 4.2.1). This is followed by an analysis of the indoor CO_2 concentration findings in relation to existing standards and emerging 'health-based' thresholds (Section 4.2.2). The measured daily mean CO_2 concentrations are then transformed into ventilation rates, using mass balance models, and the resultant values are compared to existing ventilation standards and emerging 'health-based' ventilation thresholds (Section 4.2.3).

4.2.1 Physical characteristics of Austrian schools and classrooms

The following section summarises the main physical characteristics of the ImpAQS school sample in relation to factors which may exert an influence on the resultant IAQ and ventilation rates. These parameters include physical factors, such as room sizes and ventilation systems as well as the types of schools included in the study and their geographical distribution. A detailed overview of the results of this section can be found in Appendix C.1.1.

4.2.1.1 School type

Austria's educational system is characterized by a diverse array of school types that cater to various educational needs and pathways. In 2022, Austria had a total of 5,921 schools (Statistik Austria, 2024). The main school types include primary schools (Volksschulen), middle schools (Mittelschulen), general secondary schools (Allgemein bildende höhere Schulen) and vocational middle or higher schools (Berufsbildende mittlere und höhere Schulen), each serving distinct purposes within the educational framework. The different school types selected in the ImpAQS study can be seen in Fig 4-3 and are listed as follows: general secondary schools (ABHS) (33.3%) (Allgemein bildende höhere Schule), commercial middle or higher schools (KMS) (10.8%) (Kaufmännische mittlere oder höhere Schule), secondary middle schools (MS) (1.7%) (Mittelschule), Special schools (SS) (1.7%) (Sonderschule), technical and commercial middle or higher schools (TGS) (14.2%) (Technische und gewerbliche mittlere oder höhere Schule), primary elementary schools (VS) (20%) (Volksschule), and business vocational middle or higher schools (WS) (8.3%) (Wirtschaftsberufliche mittlere oder höhere Schule).

Austria is a country of vocational education and training and it has a large percentage of vocational schools and an equal percentage of academic secondary schools (Statistik Austria, 2024). Seven out of ten students in upper secondary education are in vocational education and training which is the second highest rate in the OECD, tied with Finland, after the Czech Republic (73%) (Der Standard, 2016); this explains the equal representation of vocational schools (33.3%) in comparison to general secondary schools (33.3%) found in the ImpAQS study (see Fig.4-3).

The school sample for the ImpAQS project demonstrates a typical subset of the above. Polytechnic schools however were dismissed from the sample as they support 14- to 15-year-old students who want to learn a trade immediately after their compulsory education at the ninth level of schooling, and hence such students are not present in the classroom for the entire academic year.

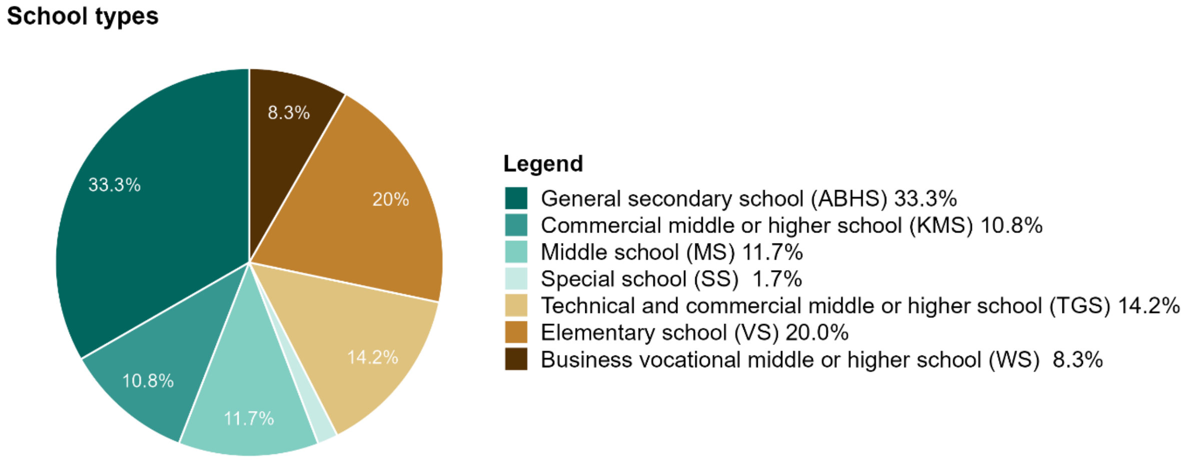


Figure 4-3. ImpAQS school types [%]

Table 4-1. ImpAQS school types in absolute numbers

School types	Number
General secondary school	40
Commercial middle or higher school	13
Middle school	14
Special school	2
Technical and commercial middle or higher school	17
Elementary school	24
Business vocational middle or higher school	10

4.2.1.2 School regions

Austria is divided into nine federal states. These states are: 1. Burgenland 2. Carinthia (Kärnten) 3. Lower Austria (Niederösterreich) 4. Upper Austria (Oberösterreich) 5. Salzburg 6. Styria (Steiermark) 7. Tyrol (Tirol) 8. Vorarlberg 9. Vienna (Wien). Each of these states has its own government and administrative structure, contributing to the federal system of governance in Austria. The federal states have significant autonomy, particularly in areas such as education, health, and infrastructure. The majority of schools in the ImpAQS project are located in Upper Austria (20 %), Vienna (18.3 %), Lower Austria (17.5 %), and Styria (15.8 %) which reflects the number of schools in these federal states (Fig 4-4).

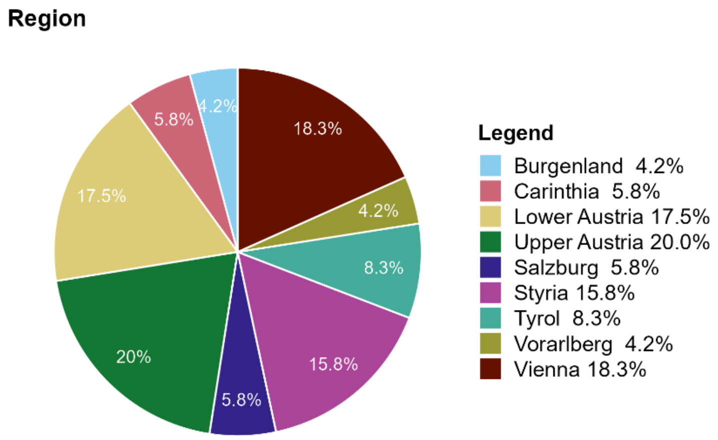


Figure 4-4. ImpAQS schools per region [%]

Table 4-2. Summary of ImpAQS schools per regions in absolute numbers

Region	Number
Burgenland	5
Carinthia	7
Lower Austria	21
Upper Austria	24
Salzburg	7
Styria	19
Tyrol	10
Vorarlberg	5
Vienna	22

4.2.1.3 School urban-rural zoning

The distribution of schools in **rural versus urban and semi-urban settings** is a significant topic in educational research, as it often reflects broader social and economic disparities. In Austria, a differentiation is commonly made between villages (less than 10,000 inhabitants), towns (10,000–39,999 inhabitants), small cities (40,000–100,000 inhabitants) as well as medium and large cities (greater than 100,000 inhabitants) (Baukulturpolitik, 2024). Generally, schools tend to be more concentrated in urban areas compared to rural regions. This trend is influenced by several factors, including population density, resource allocation, and educational policies. Urban areas in Austria (such as Vienna with 1.89 million inhabitants, Graz with 443,000 inhabitants, Innsbruck with 311,400 inhabitants or Linz with 203,000 inhabitants) have the highest urban population densities, which leads to a greater demand for educational facilities. As a result, cities often have a larger number of schools to accommodate the needs of their populations. In contrast, rural areas, with lower population densities, often face challenges associated with having fewer schools including limited access to a complete range of educational resources. This distribution of schools is reflected in the final school sample, which contains a large percentage of schools located in Austria's major cities (Fig. 4-5). Over half (51.6%) of all schools in the ImpAQS sample are located in medium and large cities (either centrally or on the outskirts). This is followed by small cities (10.8%), towns (18.3%), and villages (19.2%).

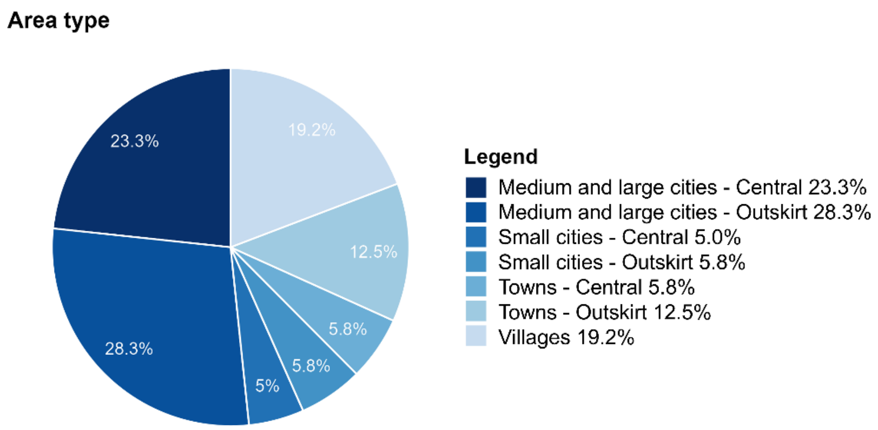


Figure 4-5. School urban-rural zoning classification

Table 4-3. Summary of ImpAQS urban-rural zoning in numbers

Zone		Number
Medium and large cities	Central	28
	Outskirt	34
Small cities	Central	6
	Outskirt	7
Towns	Central	7
	Outskirt	15
Villages		23

4.2.1.4 Construction type

In terms of construction type, the overall school sample set contains 122 unique entries (rather than 120) as two schools were built using a heavyweight construction in the main building but with either a newer extension or an additional new complex built in lightweight materials. As rooms in both building types were part of the sample, it changes the overall school building type sample size to 122. Nevertheless, the majority of the ImpAQS school buildings are of a thermally heavyweight construction type (~97%) (e.g. masonry or concrete) whilst only 3% are either lightweight (e.g. timber or glass and steel) or a hybrid construction (e.g. combined masonry and timber) (Fig.4-6).

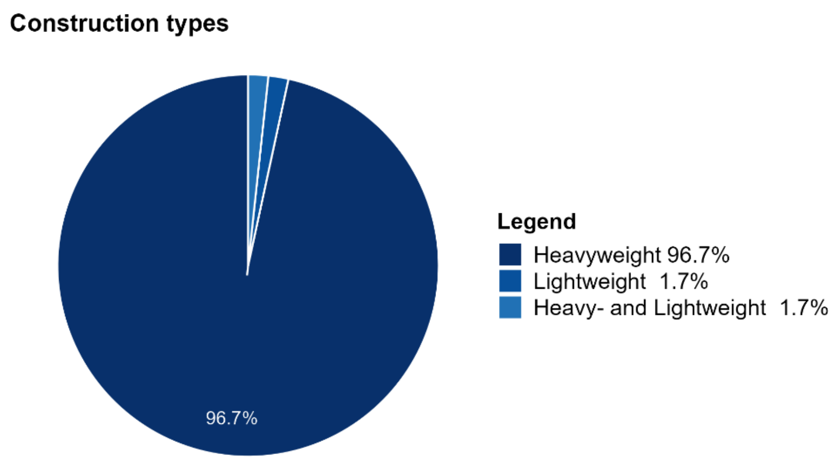


Figure 4-6. School construction type

Table 4-4. Summary of ImpAQS construction type entries in numbers

Construction types	Number
Heavyweight	116
Lightweight	2
Heavy- and Lightweight (hybrid)	2

4.2.1.5 Ventilation system type

The prevalence of naturally ventilated schools varies across different regions and educational systems. A significant body of research indicates that a substantial proportion of schools worldwide, particularly in Europe, rely on natural ventilation systems. For instance, the pan-European SINPHONIE project (2010-2012) estimated that approximately 86% of European school buildings utilise natural ventilation methods (Csobod, 2014). This reliance on natural ventilation is often due to the simplicity and cost-effectiveness of such systems, especially in regions where mechanical ventilation was traditionally considered unnecessary. To the authors' knowledge there is no up-to-date information available, in the literature, regarding the percentage of naturally ventilated schools in Austria in comparison to the number of mechanically ventilated schools. After the school survey data was analysed (Fig. 4-7), it showed that, in the ImpAQS sample, 104 schools are naturally ventilated (86.7%) and 11 have mechanical ventilation (9.2%) (Fig. 4-7), whilst 5 schools (4.2%) have a combination of naturally and mechanically ventilated classrooms[14]. Appendix C.1.1.11 presents examples of different ventilation types.

[14] It should be noted that, despite due diligence being applied in gathering the ventilation system data (Fig. 4-7 and Tbl. 4-5), there may be some uncertainty regarding the precise breakdown of the ventilation system type(s) in use. This is because in a few cases technicians may have been unable to ascertain whether a mechanical system was currently operational or not. In some cases, despite follow-up telephone calls, school staff were unable to confirm the type of system used in a particular classroom and/or whether the system was operational throughout the duration of the study. In other cases air handling units may have been changed, repaired or turned off during the time of the study without notifying the ImpAQS project team.

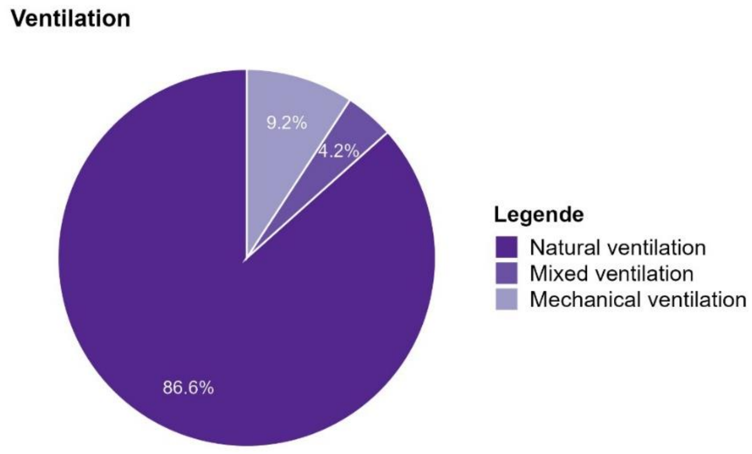


Figure 4-7. School ventilation types [%]

Table 4-5. Summary of ImpAQS school ventilation types in numbers

Ventilation Type	Number
Natural Ventilation	104
Mixed Ventilation	5
Mechanical Ventilation	11

4.2.1.6 School altitude

The altitude of schools in Europe and specifically Austria varies significantly depending on their geographical location, particularly in relation to the mountainous regions of the country. In general, schools located in urban areas, are typically found at lower altitudes of around 100 to 300 meters above sea level. In contrast, villages in alpine regions are found at much higher elevations, often ranging from 600 to 2,600 meters above sea level. This variation is particularly relevant in the context of environmental health studies, where altitude can indirectly influence factors such as air quality (Xing et al., 2023) and allergen concentrations (Gao et al., 2024) which may impact on the health and well-being of students. The highest located school participating in the ImpAQS project is located at an altitude of 1020 meters, with the majority of schools located below 500 meters of elevation (Fig.4-8).

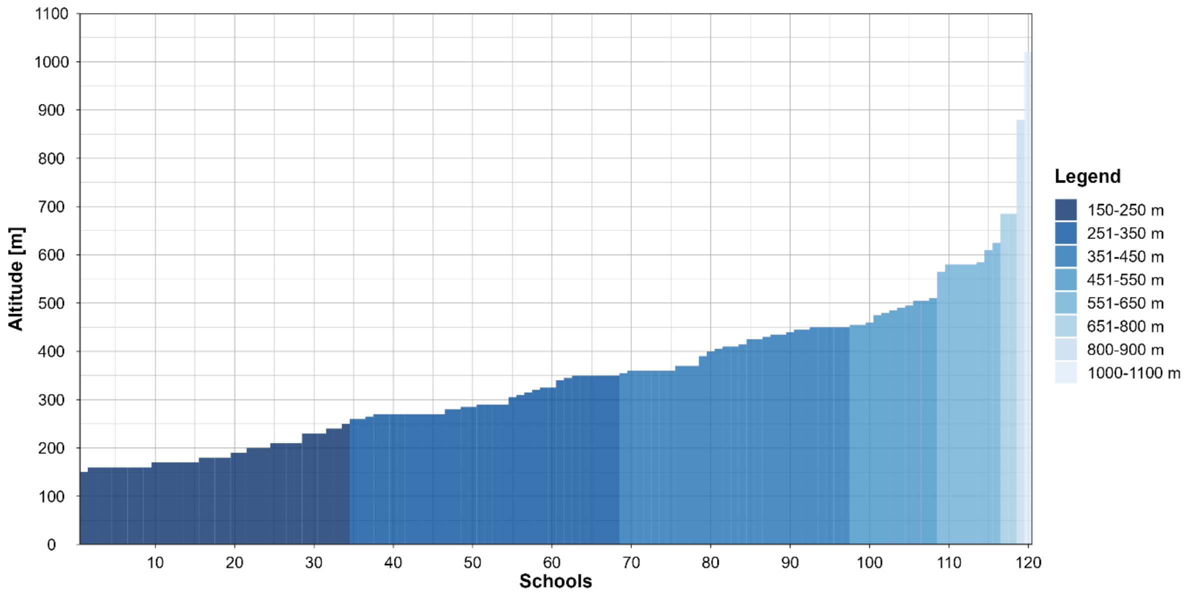


Figure 4-8. School altitudes [m]

4.2.1.7 Physical characteristics of classrooms

The internal floor area of classrooms, in square meters [m^2] (Fig.4-9) can vary significantly based on several factors, including the type of school (Appendix C.1.1.3), the number of students enrolled, and the specific design and architectural guidelines followed during the planning phase. Equally, the spatial density, or floor area per occupant [m^2/ person] (Fig.4-9) can vary considerably in schools based on several factors, including the design of the school, the age of the children, the specific activities taking place, the class size, and the overall demand for space in a particular school. The design of educational facilities often adheres to specific guidelines that dictate the minimum space required per student to provide a comfortable and effective learning environment. The Österreichisches Institut für Schul- und Sportstättenbau (ÖISS) guidelines intentionally avoid specifying a spatial density ratio (i.e. square meters per student). The reason for this is that only state schools (Bundesschulen, i.e. all school types except primary schools, middle schools, and special schools) are required to adhere to the ÖISS guideline. Compulsory schools (VS, MS, SS) are managed by the federal states (Bundesländer), which may have their own specific regulations (Raab, 2024).

Data from the Organisation for Economic Co-operation and Development (OECD) illustrates, that over the past two decades, the mean class size in the EU has comprised of approximately 19 students, but this figure is falling gradually over time (OECD, 2024). In Austria the average number of students per primary level class was estimated at 18.28 in 2019 (Statista, 2019). Specific figures for the spatial density of Austrian classrooms are scarce and can vary by region, however EU data suggests that typical primary classroom densities range from 2–3.1 ± 0.3 m^2/person (Daniels, 2016).

A number of studies have shown that the class size (in terms of absolute student numbers) has a considerable impact on both the educational experience students have and the academic results they attain (Konstantopoulos and Shen, 2023; Antoniou et al., 2024), however there is a paucity of research on the impact of classroom occupant density on student health, wellbeing and attainment.

Figure 4-9 provides a summary of the main classroom survey data, including (in the top row): the total glazed area [m^2], maximum openable window area [m^2], internal floor area [m^2], glazed area of the external façade [m^2], area per person based on actual occupancy[15] [m^2/person], area per person based on maximum design occupancy [m^2/person], openable window area per unit floor area [%]. In the bottom row: the actual occupancy [persons], maximum design occupancy [persons], total room volume [m^3], volume per person based on actual occupancy [m^3/person] and volume per person based on maximum design occupancy [m^3/person]. These numbers vary significantly dependent on state, school type, and other factors (Appendix C.1.1).

In the ImpAQS sample, the individual classroom floor area varies between 27 m^2 and 110 m^2 (arithmetic mean 64 m^2). The classroom ceiling heights vary between 2.10 m and 4.50 m (arithmetic mean 3.24 m). The internal room volume varies between 86 m^3 and 369 m^3 (arithmetic mean 207 m^3). The design occupancy (based on room surveys and plans) varies between 8 and 49 people, with an arithmetic mean of 23. The spatial density (floor area per occupant) [m^2/person] varies between 1.12 m^2/student and 8.33 m^2/student (arithmetic mean 2.93 m^2/student) and including the teacher 1.08 m^2/person and 7.4 m^2/person (arithmetic mean 2.79 m^2/person).

Accordingly, the room volume density varies between 3.58 m^3/student and 27.54 m^3/student (arithmetic mean 9.48 m^3/student) and including the teacher 3.44 m^3/person and 24.48 m^3/person (arithmetic mean 9.04 m^3/person).

There is little comparable data with which to contextualise these findings, apart from the SINPHONIE project (Csobod, 2014). Two Austrian schools participated in the SINPHONIE project, together with schools in Finland, France, Greece, Serbia, and the UK. In total, 337 classrooms were surveyed, the arithmetic mean floor area was 55 m^2 (varying between 24–135 m^2), with an arithmetic mean ceiling height of 3.3 m (varying between 2.5–5.3 m).

In comparison to the SINPHONIE project classrooms, the arithmetic mean floor area in the ImpAQS project is 9 m^2 bigger, despite the maximum floor area being 25 m^2 smaller than the largest room in the SINPHONIE project (135 m^2). The arithmetic mean ceiling height in both projects (SINPHONIE and ImpAQS) is very similar at around 3.2–3.3 m.

The mean spatial density [m^2/student] in the SINPHONIE project for the entire range of classrooms was 2.44 (with a maximum of 6.15 for an Italian school and a minimum of 0.83 for an Albanian school) (Csobod et al., 2014). In the ImpAQS sample, the arithmetic mean is 2.93 m^2/student, which is well above the European average and the maximum spatial density of 8.33 m^2/student is above the highest value reported in the SINPHONIE project.

In three classrooms (0.25% of the ImpAQS sample), the spatial density was lower than 1.5 m^2/per student (Figure 4.9), this compares to 8% of the SINPHONIE project sample. When compared against the minimum spatial criteria used by the American Society of Heating, Refrigerating and Air-Conditioning Engineers ASHRAE (2022) of 2.0 m^2/student, the proportion of ImpAQS classrooms below the recommended ASHRAE value rises to 5.75% compared with 23% reported by the SINPHONIE project (Csobod, 2014).

A summary of the schools' physical characteristics (including altitude, school type, ventilation system etc.) can be found in (Appendix C.1.1.1)

[15] Note: actual occupancy and design occupancy numbers include both the students and the teacher

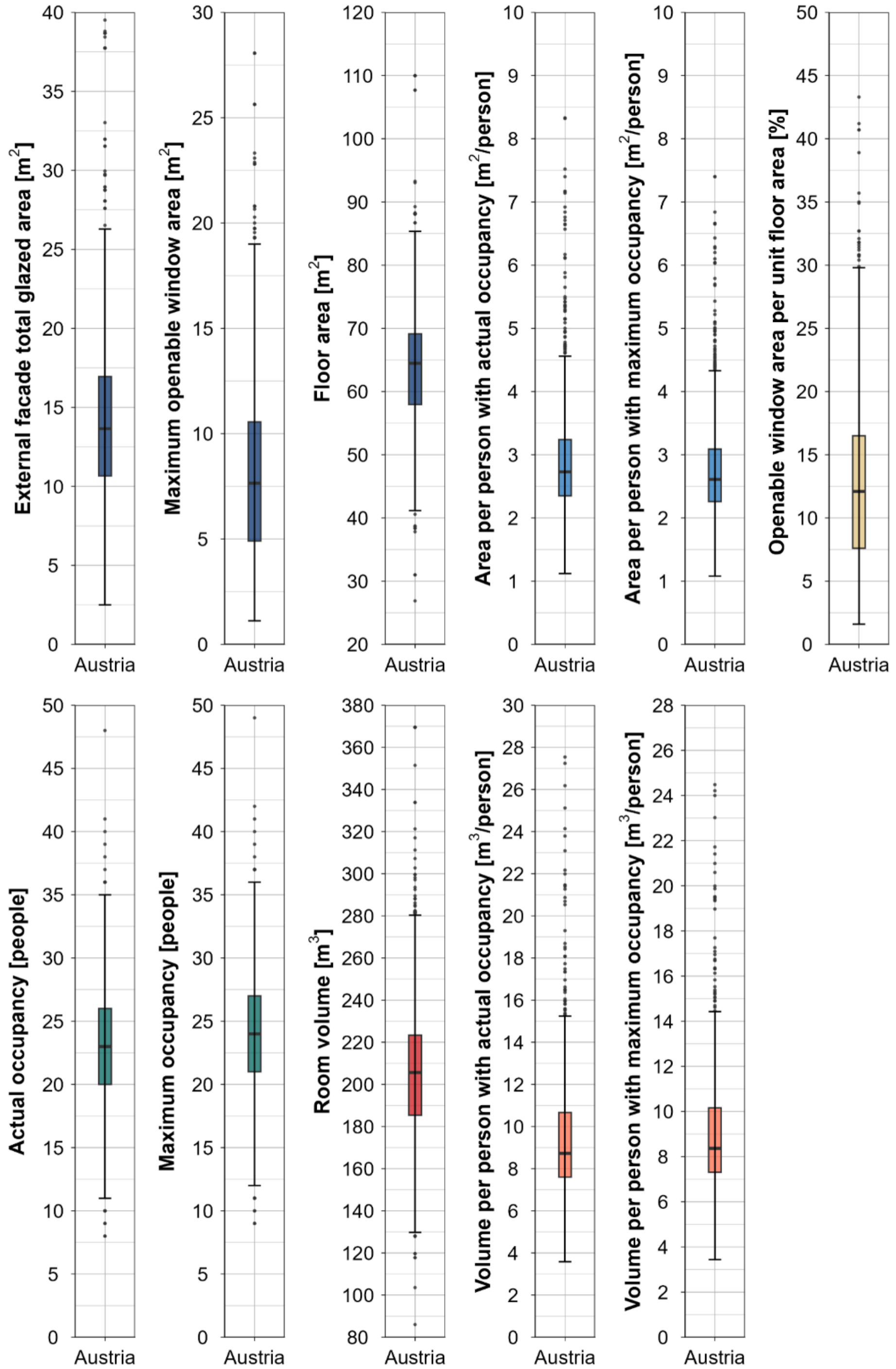


Figure 4-9. General physical characteristics of all ImpAQS classrooms, summarized for the whole of Austria. Some of this information is presented by region and school type in the Appendix C.1.1.

Figure 4-9 summarises the key physical characteristics of Austrian classrooms, with respect to factors which may have a bearing on indoor air quality and ventilation rates. Plots with blue boxes represent parameters based on areas (i.e. glazed area, window area, floor area and floor area per person), red boxes indicate volumetric parameters (i.e. room volume and room volume per person), green boxes show occupancy data (i.e. actual and maximum numbers of occupants), and yellow boxes illustrate surface ratios (i.e. openable window area per unit floor area).

The external glazed area typically ranges between 10.5−17.0 m², with an openable area of 5.0−10.5 m². Classrooms generally have a floor area of 58−69 m² and room volumes of 185−225 m³. With a typical occupancy of 22−27 people, this leads to a floor area per person of 2.25−3.25 m² and a room volume per person of 7.75−10.75 m³. The maximum openable window areas typically represent 7.5%−16.5% of the floor area. While these figures represent the interquartile range (i.e. 50% of the data, spanning the 25th to 75th percentiles), significant variability exists between classrooms and schools across Austria, as indicated by the long whiskers and outliers in the box plots (Fig. 4-9).

4.2.1.8 Window characteristics in classrooms

Windows play a central role in the provision of natural ventilation and this section evaluates the key parameters governing window ventilation, in relation to the classroom survey data. The maximum openable window area [m^2] as a function of the treated floor area [m^2] is an important parameter in assessing the adequacy of window opening areas, and this is shown as a per cent [%] by region in Fig. 4-10 (and in Appendix C.1.1.8 by school type). The survey data shows that the majority (83.6 %) of classrooms have single sided window openings, with only 11.8% having double sided window aspects. The principle orientation of the glazed façade is almost evenly spread in all directions (Fig. 4-12). By glazing type the majority of windows are double glazed (80.3%), whilst openable windows are mainly controlled using a tilt and turn opening mechanism (82.8%).

More than half of all classrooms have two or more different types of windows, with 643 classrooms having secondary windows (54% of all classrooms). Only 94 (8%) of all main windows have opening restrictors, whilst 216 secondary windows have restrictors (this represents almost 40% of all secondary windows and 18% of all windows). That means more than a quarter of all classrooms have at least one window that is restricted in its opening (Fig. 4-12). These window restrictors typically limit the maximum window opening angle to around 10–15 degrees (41%) but also up to 45 degrees in some cases. Almost all (97.8%) windows must be opened manually. More than 50% of all classrooms have a secondary window type, which is in some cases non openable (15.2%). Secondary windows are also often restricted by window stays which permit an opening from 10–45 degrees. The majority of windows have aluminium frames (40.3%), followed by wooden frames (30.8%). Almost half (46.3%) have no internal shading, whilst 38.7% have curtains.

More than a quarter (26%) of all school buildings do not have any external shading, whilst 39.5% have external roller shutters and 16.9% have horizontal or other types of moveable shades, with a smaller percentage (1.8%) having fixed shading (Fig. 4-11). Appendix C.1.1.10 presents various examples of commonly found window openings.

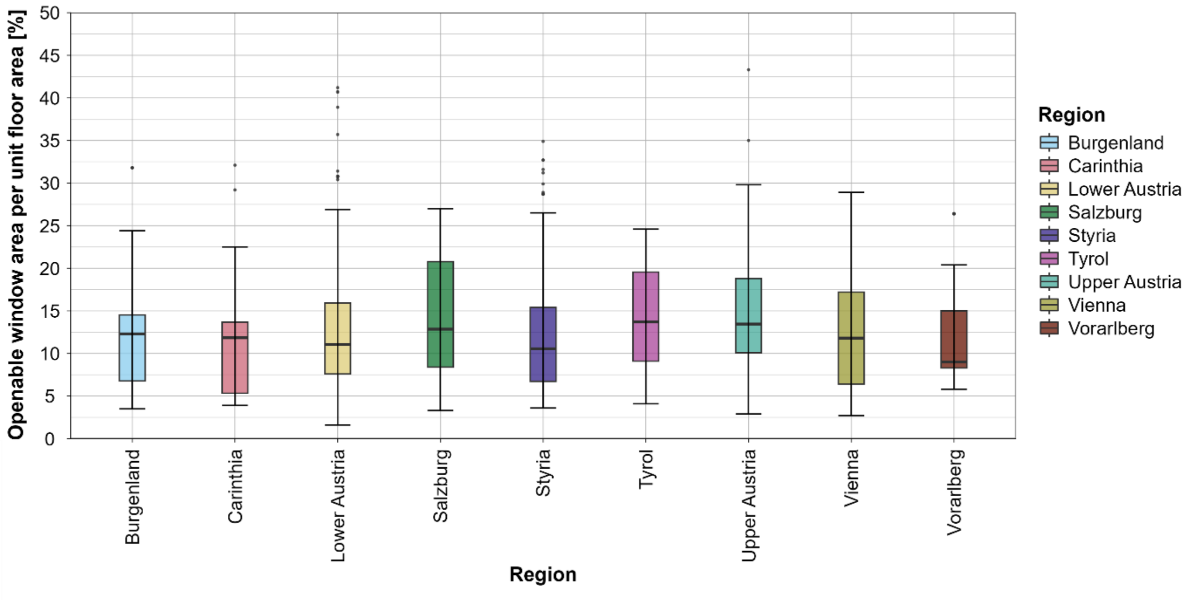


Figure 4-10 Overview of the percentage of maximum openable window area as a function of classroom floor area [%] by region.

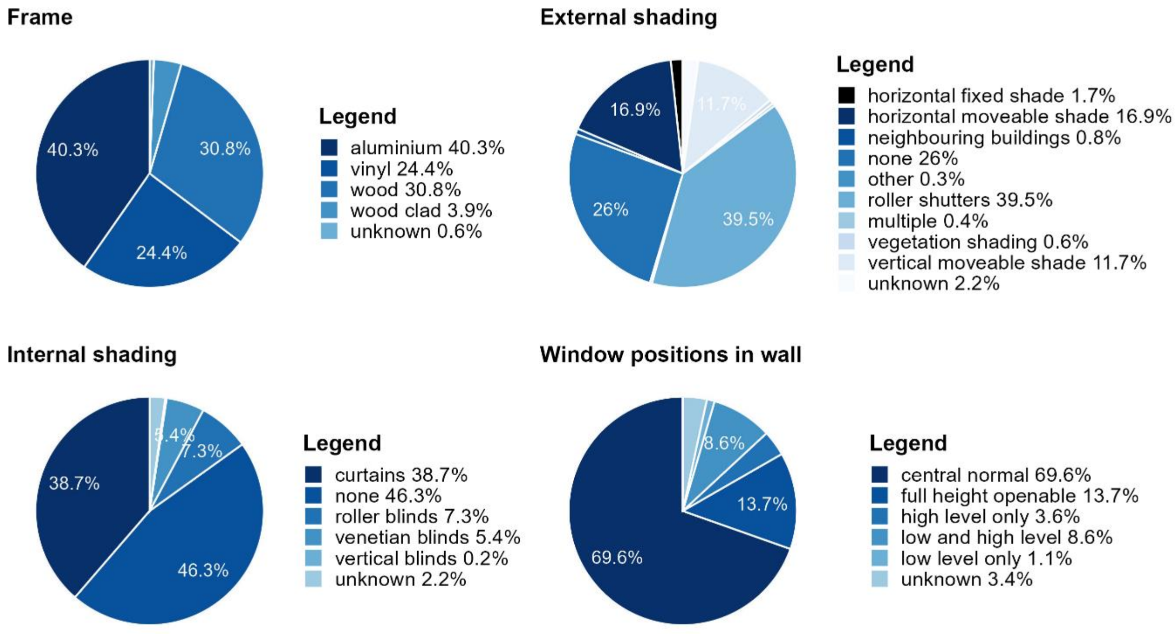


Figure 4-11. Pie charts summarizing window frame type, external and internal shading, and window positioning for all classrooms

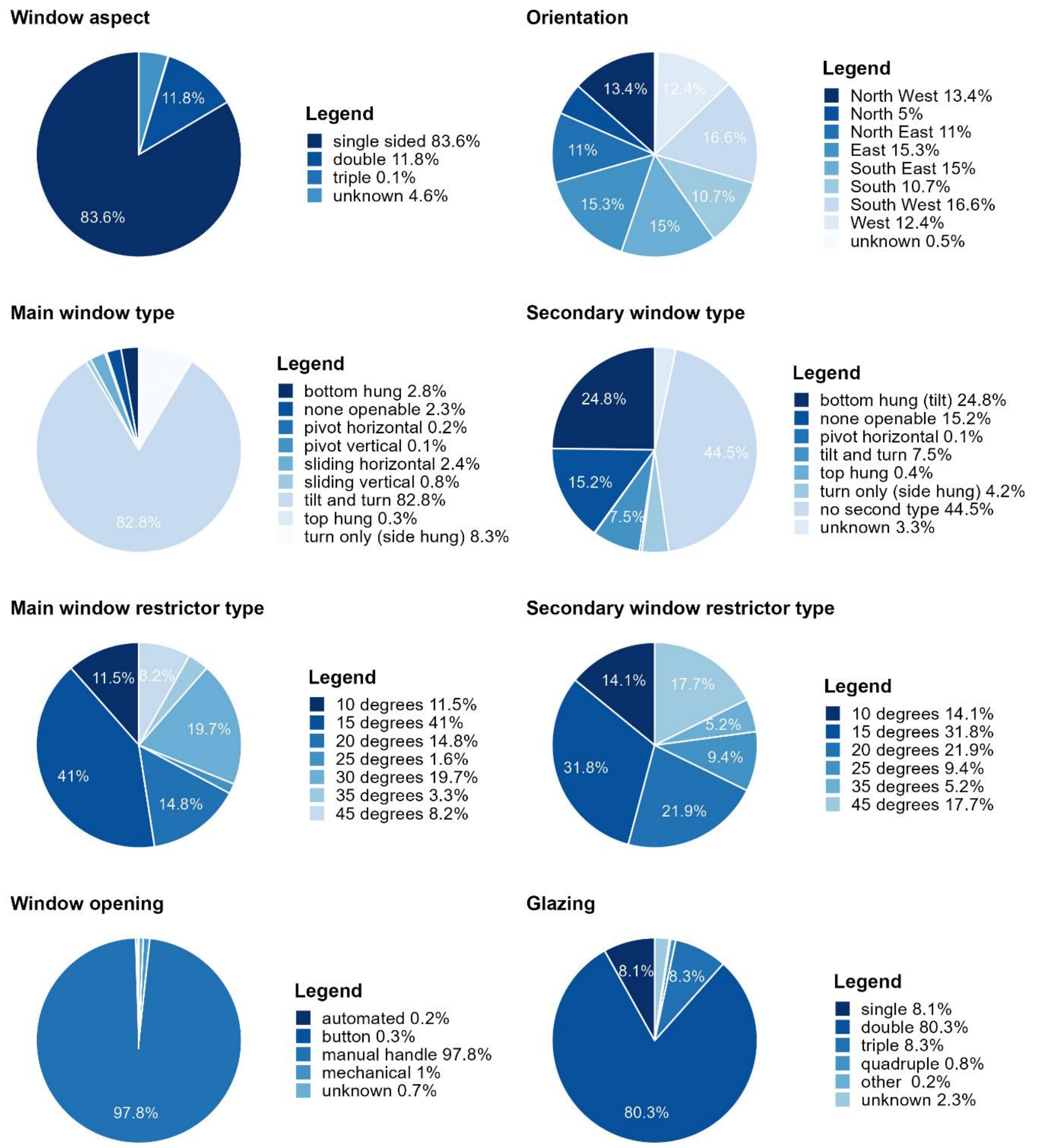


Figure 4-12. Pie charts summarizing the principle window characteristics of all classrooms, including window aspect, window orientation, restrictor type, main and secondary window types, and glazing type.

4.2.2 Carbon dioxide (CO_2) concentrations in Austrian schools

The main purpose of this analysis is to assess whether Austrian classrooms comply with existing international, European and Austrian standards and guidelines. The indoor CO_2 threshold values reported in EN16798-1 (CEN, 2019) (Tbl. 2-6), ISO 16000-41 (ISO, 2023) (Tbl. 2-12) and by the Austrian BMK position paper (BMK, 2024d) (Tbl. 2-13) are considered the most relevant in the context of assessing the ventilation performance of Austrian classrooms.

Carbon dioxide (CO_2) concentrations were recorded in 1200 Austrian classrooms at 2-minute intervals for the duration of the study period, namely the 2023–24 school year (Section 3.2). Data analysis focused on the occupied school hours from 8:00 to 14:00, as this is considered to be the core period when Austrian students are typically present in the classroom (RIS, 2024a) (Section 3.4.2). To account for unoccupied/partially occupied classrooms (due to unreported factors such as field trips, autonomous school holidays (German: 'Schulautonometagen') and other unknown reasons) classrooms with an hourly average CO_2 concentration of 460 ppm or lower were excluded from the analysis (following the approach used by Wood et al. (2024). Since the 'school day' (i.e. 6–8 h) is used as the assessment period, the 2-minute interval data were aggregated into hourly values and then into daily values for the core period (i.e. 8:00–14:00) following the procedure described in Section 3.4.2. The arithmetic means of the CO_2 values corresponding to this period are referred to as the 'daily mean' CO_2 concentrations.

The following plots depict seasonal trends in the daily mean CO_2 concentrations in Austrian classrooms, along with two threshold limiting values. The upper threshold denotes indoor CO_2 indoor concentrations at or below 1000 ppm (in accordance with ISO 16000-41, EN16798-1 and Raumklasse A of the Austrian BMK guidelines) and is shown as a dashed red line. Whilst the lower threshold denotes indoor CO_2 indoor concentrations at or below 800 ppm (in accordance with the Austrian BMK Raumklasse A+ target value, and the 'health-based' threshold value advocated by REHVA) and is shown as a dashed pink line. The plots are accompanied by tables that provide summary statistics, percentages of threshold exceedances, and the interquartile range (IQR). The IQR, a common measure of data spread (or variance), is calculated as the difference between the 75th (Q3) and 25th (Q1) percentiles. Appendix C.1.2 provides supplementary seasonal and monthly analyses of the results presented in this section.

4.2.2.1 CO_2 concentrations in classrooms

Fig. 4-13 illustrates the daily mean CO_2 concentrations in Austrian classrooms throughout the 2023-24 school year. The plot highlights several key trends such as the mean, median, and values at various percentiles (i.e 5th, 25th, 75th, and 95th) of the distribution, along with the minimum and the maximum trend lines. The grey-shaded area between the 25th and 75th percentile lines represents the range in which 50% of the daily mean CO_2 values fall, while the light grey area between the 5th and the 95th percentile lines covers 90% of the data. The trend lines and grey ribbons are interrupted during the long period holiday periods including the autumn, summer, and Easter breaks. The plot aggregates data from both the control and test sensors. A preliminary comparison of classrooms containing control and test sensors can be found in Section 4.2.2.3, while a more detailed analysis involving the matched control-test pairs (after more rigorous data cleaning and analysis procedures are applied) is provided in Section 4.4. Box plots of the annual CO_2 concentrations in each of the 120 schools can be found in Appendix C.1.2.1.

Throughout the 2023–2024 school year, daily mean CO_2 concentrations in Austrian classrooms generally exceeded the BMK Class A+ target threshold of 800 ppm, except briefly during the warm summer months (Fig. 4-13). Early in the school year (until mid-October 2023) and again during the last few months of the academic year (from May to July 2024) Austrian classrooms remained within the Class A compliance threshold of 1000 ppm, as shown by the mean trend (solid red line). During these warmer months, it can be seen (Fig 4-13) that the majority (75%) of the daily mean CO_2 concentrations are below the compliance threshold. However, during the colder months (November 2023 to April 2024), only 25% or less of the daily mean CO_2 concentrations remained within the 1000 ppm compliance threshold (Fig. 4-13).

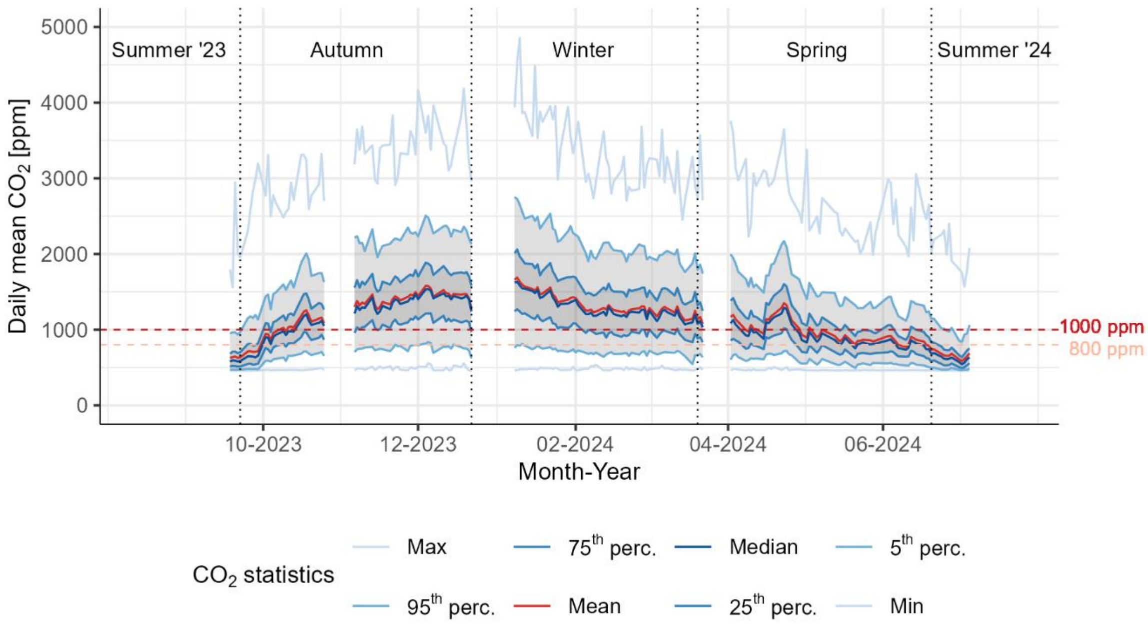


Figure 4-13. Overview of daily mean CO_2 concentrations in Austrian classrooms, highlighting key trends, as well as the CO_2 indoor compliance threshold (1000 ppm, dashed red line) and the target threshold (800 ppm, dashed pink line).

4.2.2.2 CO_2 concentration by month

The daily mean CO_2 concentration in classrooms varied significantly by month[16] (Fig. 4-14, Tbl. 4-6). This is to be expected in naturally ventilated rooms where the use of windows for ventilation is primarily influenced by thermal comfort considerations (Hawila et al., 2023). To a lesser extent mechanically ventilated classrooms also show a seasonal and monthly trend (Fig. 4-17), this reflects the fact that natural ventilation is often used to augment mechanical ventilation, particularly in the warmer summer months.

Monthly indoor CO_2 concentrations in classrooms tend to peak during the coldest months, of December and January, wherein 83% of the daily mean CO_2 values exceed the 1000 ppm threshold (93% above 800 ppm). The maximum daily mean CO_2 concentration recorded in January was

[16] Note: caution should be taken in interpreting the data for the months of September and July, since they represent only two weeks and one week of data, respectively.

4856 ppm, which is almost five times higher than the recommend compliance threshold and over six times higher than the target threshold.

Conversely during the warmer summer months of September, June and July (i.e. at the beginning of the school year and prior to schools closing for the summer) the CO_2 values are much lower. During the second half of September only 7% of the daily mean values exceed the compliance threshold of 1000 ppm (19% above 800 ppm). In June only 17% of the daily mean values exceed 1000 ppm (40% above 800 ppm), whilst during the first week of July only 4% of the daily values exceed 1000 ppm (12% above 800 ppm).

The mean of the daily CO_2 concentrations across the year is broadly similar to the monthly values for October and April (Fig. 4-14), with the majority (55%) of the annual daily values exceeding the 1000 ppm threshold (74% above 800 ppm). Additional analysis of the seasonal distribution of the daily mean CO_2 concentrations can be found in Appendix C.1.2.2.

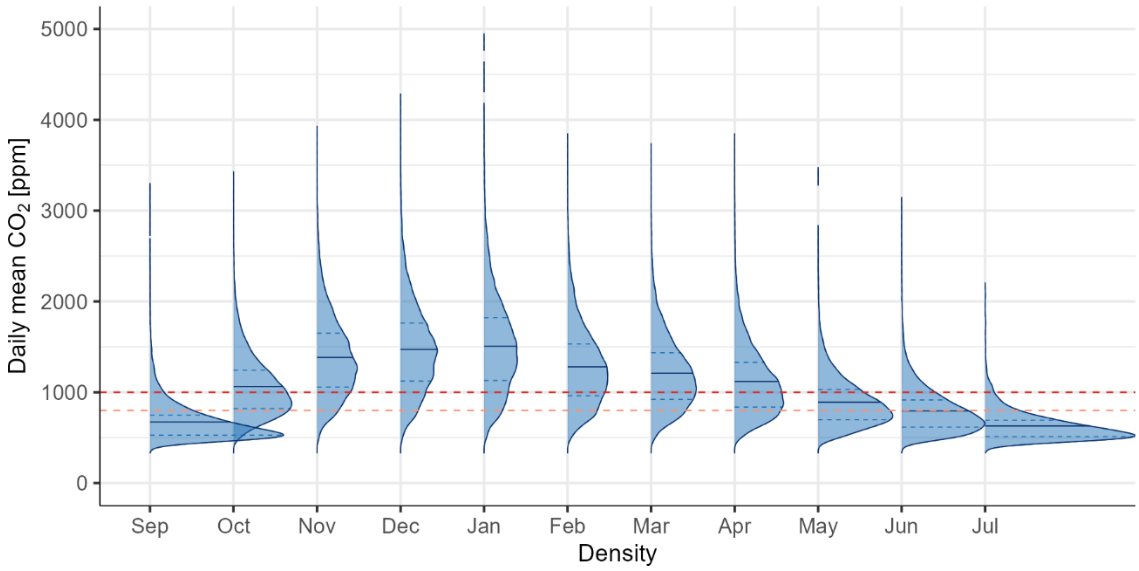


Figure 4-14. Monthly distribution of daily mean CO_2 concentration in classrooms (NV and MV), including the CO_2 indoor compliance threshold (1000 ppm, dashed red line) and target threshold (800 ppm, dashed pink line). The solid line within each distribution indicates the mean, whereas the dashed lines mark the 25th and 75th percentiles.

Table 4-6. Monthly statistical summary of daily mean CO_2 concentrations in classrooms (NV and MV), including frequency of CO_2 indoor threshold exceedances relative to 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances. For example, in January the maximum daily mean CO_2 concentration observed is 4856 ppm and 83% of the daily mean CO_2 values are above 1000 ppm.

Month	Min [ppm]	Max [ppm]	Percentile [ppm] 25th	50th	75th	IQR [ppm]	Mean [ppm]	Limit exceedance >1000 ppm [%]	>800 ppm [%]
Sep	460	3197	527	613	749	221	673	7	19
Oct	462	3326	820	1005	1242	422	1063	51	78
Nov	462	3833	1057	1329	1650	593	1384	80	93
Dec	460	4184	1124	1436	1761	638	1472	83	93
Jan	463	4856	1129	1461	1821	692	1508	83	93
Feb	461	3748	962	1231	1532	569	1280	72	88
Mar	461	3641	921	1157	1436	514	1209	67	86

Apr	461	3759	837	1056	1330	493	1119	56	79
May	460	3379	698	840	1031	332	891	28	57
Jun	460	3055	616	743	915	299	794	17	40
Jul	460	2084	512	587	692	180	629	4	12
Year	460	4856	785	1058	1417	633	1145	55	74

Percentages of threshold exceedance derived from hourly data (Tbl. 4-7) are generally lower than those calculated from daily data (Tbl. 4-6), particularly in the months from November to April. This is explained by the fact that hourly data are more right-skewed than the daily data. This results in hourly mean maxima values that are significantly higher than the daily mean maxima, but conversely the arithmetic monthly means (calculated with hourly data) are lower than those determined using daily values (Tbl. 4-6). For example, in January the maximum hourly mean CO_2 concentration observed is 6905 ppm (c.f. the maximum daily mean value of 4856 ppm) which is almost seven times higher than the recommend compliance threshold and over eight times higher than the target threshold.

Table 4-7. Monthly statistical summary of hourly mean CO_2 concentrations in classrooms, including frequency of CO_2 indoor threshold exceedances relative to the 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to hourly mean exceedances. For example, in January the maximum hourly mean CO_2 concentration observed is 6905 ppm and 75% of the hourly mean CO_2 values are above 1000 ppm.

Month	Min [ppm]	Max [ppm]	Percentile [ppm]			IQR [ppm]	Mean [ppm]	Limit exceedance	
			25th	50th	75th			>1000 ppm [%]	>800 ppm [%]
Sep	460	5422	525	615	765	240	686	9	21
Oct	460	5769	728	958	1287	559	1067	46	67
Nov	460	6767	936	1271	1720	784	1386	70	85
Dec	460	6176	996	1364	1840	844	1474	75	87
Jan	460	6905	1003	1396	1888	885	1510	75	87
Feb	460	5251	856	1172	1595	739	1284	63	80
Mar	460	4986	819	1103	1497	678	1213	59	77
Apr	460	5830	748	1005	1377	629	1124	50	70
May	460	5296	629	801	1064	435	898	30	50
Jun	460	5216	569	710	939	370	805	21	38
Jul	460	3031	501	571	706	204	643	6	16
Year	460	6905	720	1013	1448	729	1158	51	67

4.2.2.3 CO_2 concentration according to room classification (Test and Control)

The daily mean CO_2 concentrations recorded in the classrooms with control sensors (which have blanked-out displays) tend to be higher than those measured by the classrooms with test sensors (which have visible displays), particularly during the colder months (Fig. 4-15). The seasonal distributions[17] (Fig. 4-16 and Tbl. 4-8) show moderate differences between the control and test sensors data, with threshold exceedance frequencies differing by only a few percentage points (Tbl. 4-8). These differences become more apparent at the monthly level, where the variation in the daily mean CO_2 values between control and test sensors is more evident during the colder months (Appendix C.1.2.3 Tbl. A-7).

[17] Note: caution should be taken in interpreting the summer data, as both summer 2023 and summer 2024 represent only one week and two weeks of data, respectively.

This high-level comparison focuses exclusively on the overall differences between the control and test classrooms, without considering other potentially influential variables such as the ventilation type or the matched-pairing between control and test sensors. A more rigorous matched-pair analysis was undertaken to account for these compounding factors, and this is presented in Section 4.4.

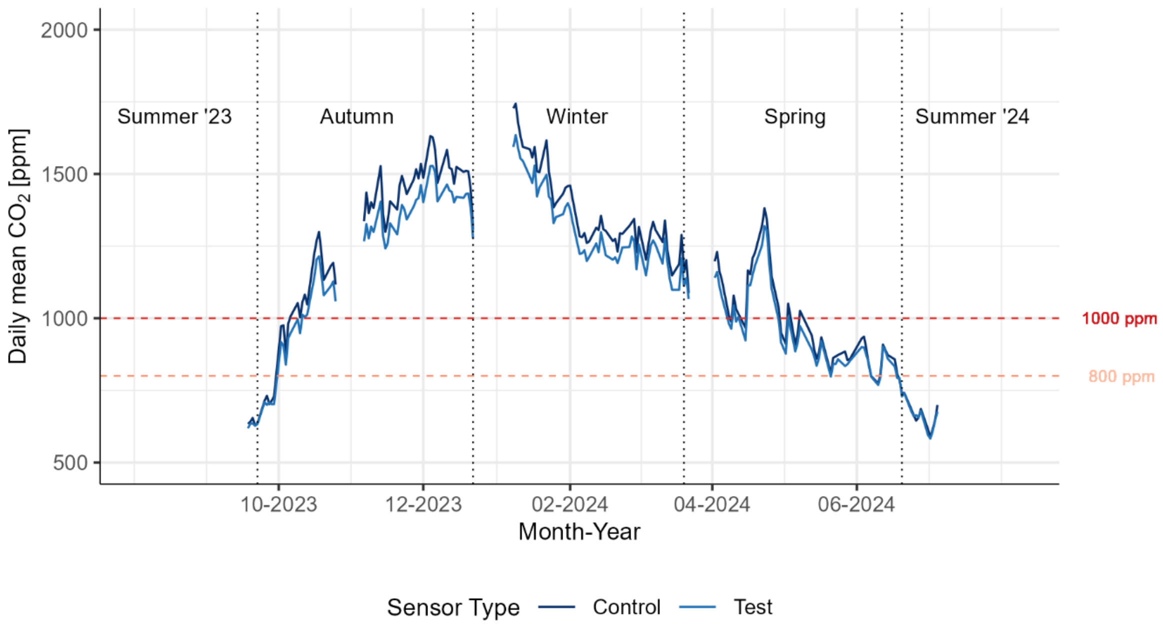


Figure 4-15. Overview of daily mean CO_2 concentrations in Austrian classrooms categorized by sensor type, highlighting key trends in relation to the CO_2 indoor compliance threshold (1000 ppm, dashed red line) and target (threshold 800 ppm, dashed pink line).

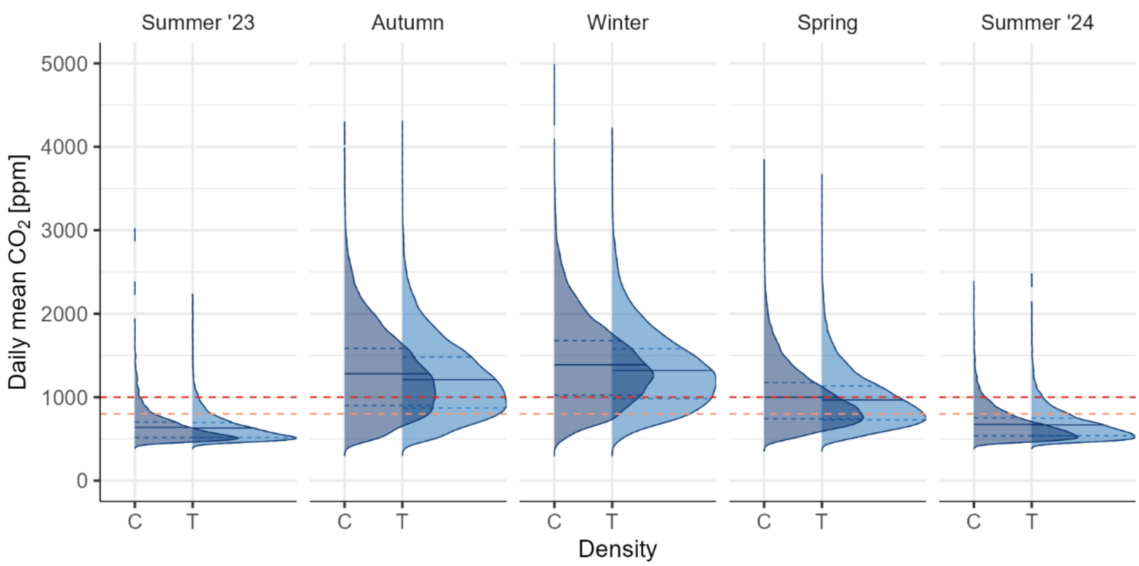


Figure 4-16. Seasonal distribution of daily mean CO_2 concentration in classrooms categorized by room type (C = Control, T = Test), including the CO_2 indoor compliance threshold (1000 ppm, dotted red line) and target threshold (800 ppm, dotted pink line). The solid line indicates the mean, whereas the dashed lines mark the 25th and 75th percentiles.

A summary of seasonal and annual daily mean exceedances of the 1000 ppm compliance threshold and the 800 ppm target limit is provided in Table 4-8. During the year, 57% of the classrooms with a control sensor exceed 1000 ppm compared to 53% of the classrooms with a visual test sensor. At the lower target level of 800 ppm, the difference between the two groups is negligible (1%). However, as noted earlier, these comparisons do not consider potential confounding factors, which are explored in Section 4.4.

Table 4-8. Seasonal statistical summary of the daily mean CO_2 concentrations in classrooms categorized by room type (C = Control, T = Test), including frequency of CO_2 indoor threshold exceedances relative to 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances.

Season	Room type	Min [ppm]	Max [ppm]	Percentile [ppm]			IQR [ppm]	Mean [ppm]	Limit exceedance	
				25th	50th	75th			>1000 ppm [%]	> 800 ppm [%]
Summer ´23	C	460	2947	516	586	702	186	638	5	13
	T	461	2158	516	585	694	178	630	3	12
Autumn	C	460	4165	901	1215	1586	685	1281	67	83
	T	460	4184	871	1144	1480	609	1210	63	81
Winter	C	461	4856	1024	1327	1676	652	1388	77	90
	T	463	4084	981	1261	1582	600	1320	73	89
Spring	C	460	3759	740	920	1174	434	999	41	66
	T	460	3589	729	901	1133	405	967	38	64
Summer ´24	C	460	2313	536	625	753	217	673	6	19
	T	460	2401	537	622	747	210	668	6	18
Year	C	460	4856	792	1082	1461	669	1172	57	74
	T	460	4184	779	1036	1377	598	1119	53	73

4.2.2.4 CO_2 concentration according to ventilation system type

Analysis of the classroom CO_2 concentration as a function of the type of ventilation system (natural or mechanical) helps to provide a better understanding of the relative merits of using mechanical or natural ventilation in a 'real-world' context. This is an important consideration since numerous studies have reported on the 'performance gap' existing between the design intent and the actual in-situ performance of mechanical ventilation systems (Dorer and Breer, 1998; Wouters et al., 2000; McLeod and Swainson, 2017). Moreover, natural ventilation systems often show pronounced evidence of seasonal variations in their performance; however to a lesser extent this is also true of mechanical systems.

The comparative analysis of ventilation types (Fig. 4-17) reveals that schools with natural ventilation (NV) have higher daily mean CO_2 concentrations than those with mechanical ventilation (MV) throughout the school year; except during the very final school week in July, where the CO_2 concentrations are generally very low. Mechanically ventilated classrooms exceed the daily mean compliance threshold of 1000 ppm for 21% of the time, compared to 59% of the time for NV classrooms (Tbl. 4-9). The largest differences between the CO_2 concentrations in the MV rooms and the NV rooms can be seen in the winter period (Fig. 4-18 and Tbl. 4-9), where 28% of the MV values exceed the 1000 ppm threshold compared with 80% of the NV values. Conversely during the summer months the difference between the MV and NV classrooms is almost insignificant with only 1% of the MV classrooms exceeding the 1000 ppm threshold compared to 6% of the NV classrooms (for summer 2024). Further information regarding the monthly distribution of daily mean CO_2 concentrations can be found in Appendix C.1.2.4.

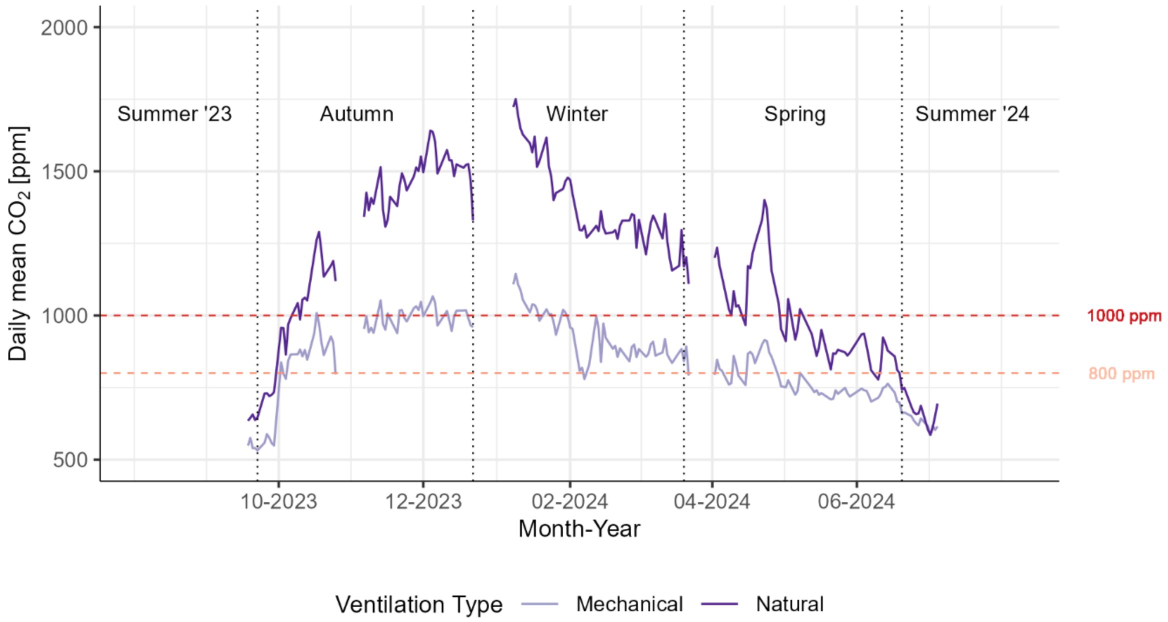


Figure 4-17. Overview of daily mean CO_2 concentrations in Austrian classrooms categorized by ventilation type, highlighting key trends, as well as the CO_2 indoor compliance threshold (1000 ppm, dashed red line) and target threshold (800 ppm, dashed pink line).

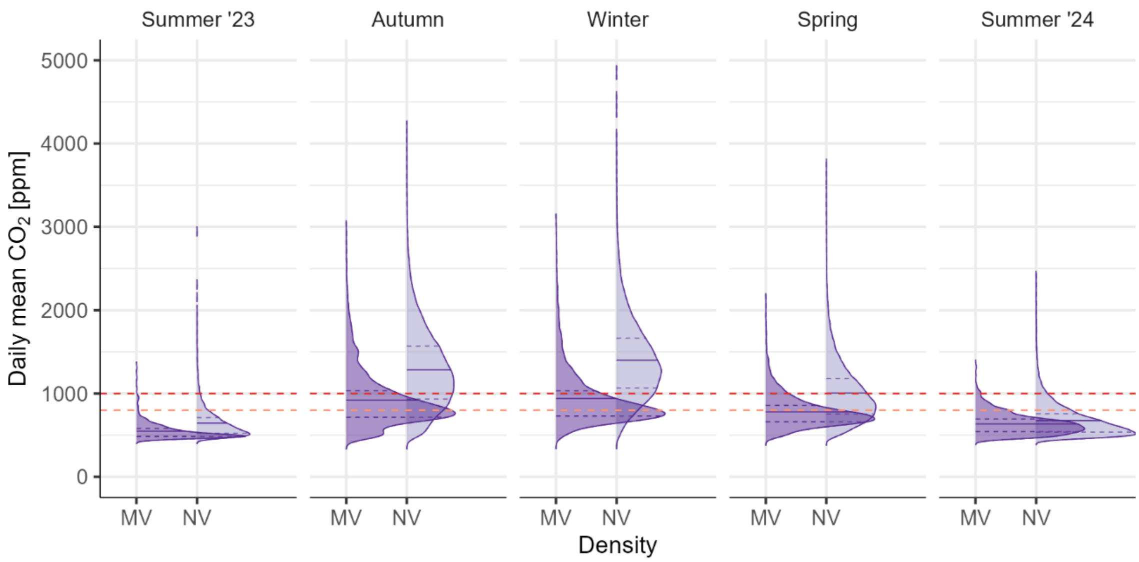


Figure 4-18. Seasonal distribution of daily mean CO_2 concentration in classrooms categorized by ventilation type, including the CO_2 indoor compliance threshold (1000 ppm, dotted red line) and target threshold (800 ppm, dotted pink line). The solid line within each distribution indicates the mean, whereas the dashed lines mark the 25^{th} and 75^{th} percentiles.

A statistical summary comparing the seasonal and annual differences between the MV and NV classrooms, at different percentiles of the probability density function, including the daily mean, minimum and maximum values is summarised in Tbl. 4-9. Overall it can be seen that MV systems perform significantly better than NV systems, and that the benefit is most pronounced during the winter period and in relation to reducing the frequency of high CO_2 values.

Table 4-9. Seasonal statistics of daily mean CO_2 concentrations in classrooms categorized by ventilation type, including frequency of CO_2 indoor threshold exceedances relative to 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances.

Season	Ventilation type	Min [ppm]	Max [ppm]	Percentile [ppm] 25th	50th	75th	IQR [ppm]	Mean [ppm]	Limit exceedance >1000 ppm [%]	>800 ppm [%]
Summer '23	MV	460	1310	484	513	579	96	547	1 %	3 %
	NV	460	2947	523	596	710	186	644	4 %	14 %
Autumn	MV	460	2950	714	837	1032	318	920	28 %	57 %
	NV	460	4184	933	1224	1568	635	1283	69 %	85 %
Winter	MV	463	3036	729	841	1032	303	940	28 %	58 %
	NV	461	4856	1065	1340	1665	600	1400	80 %	93 %
Spring	MV	460	2121	659	740	856	198	779	11 %	34 %
	NV	460	3759	754	938	1182	428	1006	43 %	69 %
Summer '24	MV	460	1316	542	612	694	151	634	1 %	11 %
	NV	460	2401	536	625	757	221	675	6 %	20 %
Year	MV	460	3036	676	784	950	275	856	21 %	46 %
	NV	460	4856	819	1103	1456	637	1178	59 %	77 %

Compliance with the threshold limiting values (e.g. 800 ppm and 1000 ppm) can also be looked at the individual school level. The following tables classify the percentage of schools which comply with the respective daily mean thresholds across the entire school year (Tbl. 4-10) and also during the winter period (Tbl. 4-11). It can be seen that 82% of the mechanically ventilated schools manage to maintain a mean daily CO_2 level below 1000 ppm across the entire year, whilst fewer than 18% of the naturally ventilated schools manage to stay below that level (Tbl. 4-10).

Whilst 82% of the mechanically ventilated schools are still able to stay below the 1000 ppm compliance threshold in winter, less than 5% of the naturally ventilated schools are able to do so. Moreover, almost one-third (32.1%) of naturally ventilated schools have a daily mean CO_2 level above 1500 ppm in wintertime (Tbl. 4-11). In relation to the 'health-based' target of 800 ppm, only 27% of mechanically ventilated schools can maintain this target throughout the winter whilst less than 1% of naturally ventilated schools are able to do so Tbl. 4-11).

Table 4-10. Percentage of schools where the daily mean CO_2 concentration complies with a given threshold, year-round

Ventilation type	CO_2 < 800 ppm [%]	CO_2 < 1000 ppm [%]	1000 < CO_2 < 1500 ppm [%]	CO_2 > 1500 ppm [%]	CO_2 > 2000 ppm [%]
Mechanical	63.6	81.8	18.2	0.0	0.0
Natural	2.8	17.9	79.2	2.8	0.0
Mixed	20.0	60.0	40.0	0.0	0.0
All types	9.0	25.4	72.1	2.5	0.0

Table 4-11. Percentage of schools where the daily mean CO_2 concentration complies with a given threshold, winter period

Ventilation type	CO_2 < 800 ppm [%]	CO_2 < 1000 ppm [%]	1000 < CO_2 < 1500 ppm [%]	CO_2 > 1500 ppm [%]	CO_2 > 2000 ppm [%]
Mechanical	27.3	81.8	18.2	0.0	0.0
Natural	0.9	4.7	63.2	32.1	0.9
Mixed	0.0	20.0	60.0	20.0	0.0
All types	3.3	12.3	59.0	28.7	0.8

4.2.2.5 CO_2 concentration according to school type

Marked differences can be seen (Fig. 4-19) between the mean CO_2 concentrations found in different school types. These differences are most pronounced in the winter season and are much less pronounced during the summer. Special schools (SS)[18] reported significantly lower CO_2 concentrations compared to all other school types (Figs. 4-19 and 4-20 and Appendix C.1.2.5) The daily mean values in the SS rarely surpasses the 1000 ppm threshold, with the highest exceedance frequency (of 18%) occurring during the winter months. Although 43% of the daily mean values exceed the 800 ppm threshold this is much lower than for all other naturally ventilated school types. This finding is likely to reflect, in part, the lower occupant densities typical of this school type (Fig. 4-9). Volksschule (VS) also reported lower CO_2 concentrations than other school types (with a 61% exceedance of the 1000 ppm threshold in winter), however this may be due to the lower exhaled CO_2 volumes in this younger age group (6–10 years) compared to schools housing older children (Persily, 2022) (Section 3.4.1).

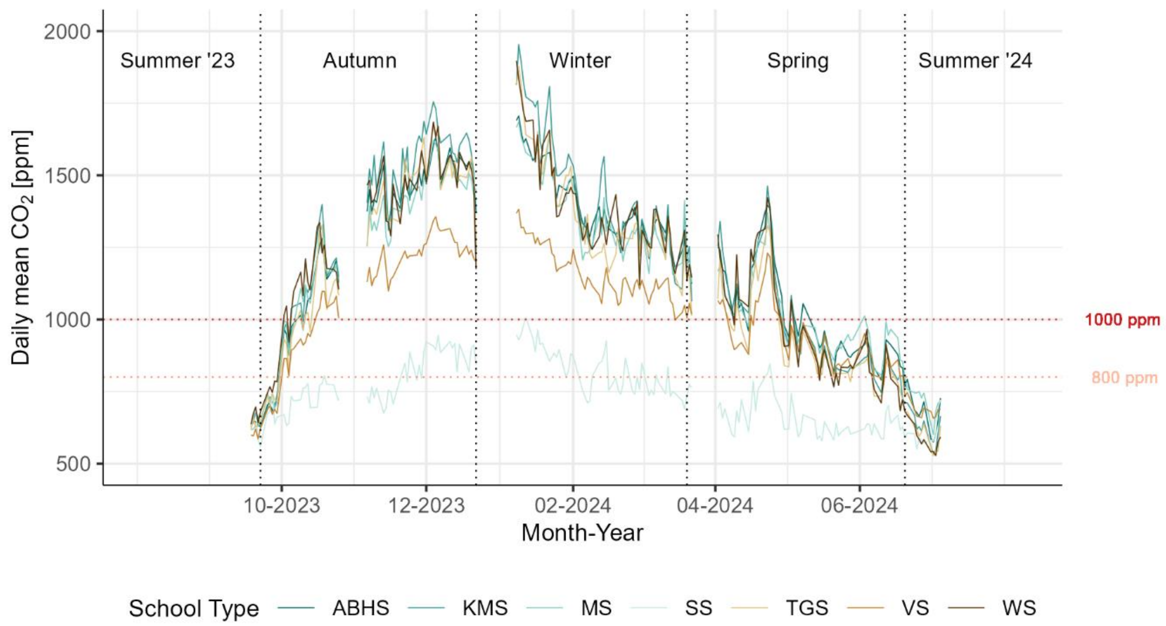


Figure 4-19. Overview of daily mean CO_2 concentrations in Austrian classrooms categorized by school type, highlighting key trends, as well as the CO_2 indoor compliance threshold (1000 ppm, dashed red line) and target threshold (800 ppm, dashed pink line).

The differences in daily mean CO_2 concentrations between the different school types are most pronounced in winter and diminish greatly during the summer period (Fig 4-20 and Appendix C.1.2.5). Overall ABHS, KMS and MS school types suffer from the highest CO_2 concentrations with SS schools, followed by VS schools[19], consistently reporting the lowest CO_2 concentrations.

[18] Caution should be taken when extrapolating these findings to all special schools (SS) since there were only 2 SS schools included in the ImpAQS study.
[19] Caution should be taken when interpreting this finding since younger children have lower CO_2 emission rates than older children (see Section 3.4.1)

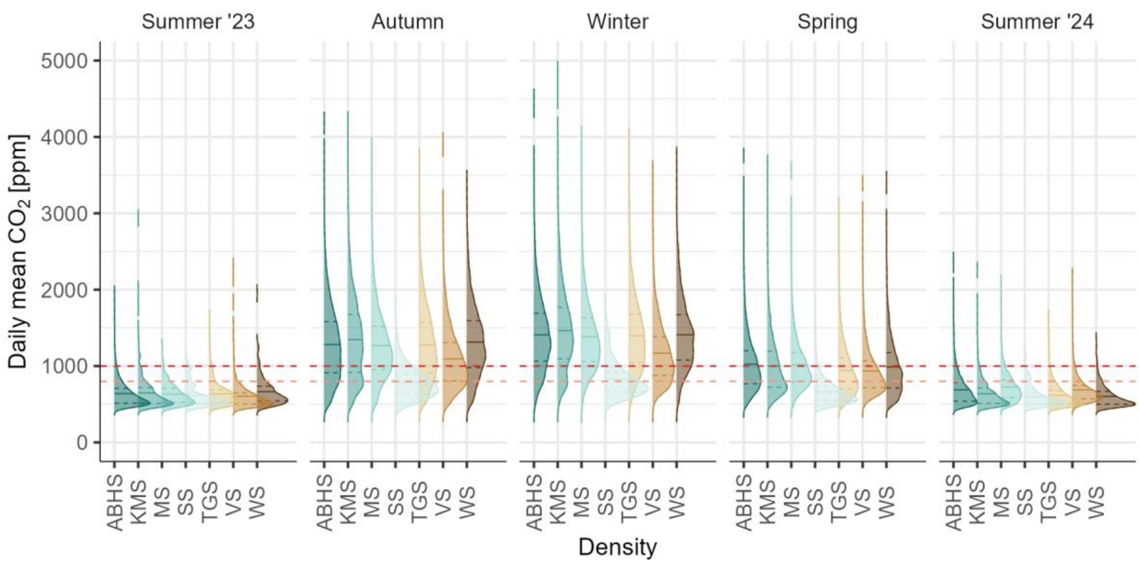


Figure 4-20. Seasonal distribution of daily mean CO_2 concentration in classrooms categorized by school type, including the CO_2 indoor compliance threshold (1000 ppm, dotted red line) and target threshold (800 ppm, dotted pink line). The solid line within each distribution indicates the mean, whereas the dashed lines mark the 25th and 75th percentiles.

In summer the daily mean compliance threshold (of 1000 ppm) is comfortably met, for 91% or more of the time, by schools in each school category. Whilst in spring, for the majority of the time (55% or more), all school types are able to comply with that threshold. The situation changes noticeably in the autumn where the daily mean threshold is exceeded by the majority of schools with the exception of SS. In winter the SS[20] schools are still able to comply with the 1000 ppm threshold the majority (82%) of the time, whilst the majority of all other school types consistently exceed this threshold, including WS (82% of the time) ABHS, KMS and MS school types (80% of the time), TGS (79% of the time) and VS (61% of the time). Collectively these results indicate (with the exception of SS) a widespread failure to meet the 1000 ppm compliance target in almost all school types (Appendix C.1.2.5).

With the exception of SS schools, the majority of all other school types fail to comply with the 'health-based' threshold target value of 800 ppm on an annual basis, with the frequency of daily mean exceedances ranging from 68% (VS) to 80% (MS) (Appendix C.1.2.5). This finding indicates a widespread failure to comply with the 800 ppm target threshold.

4.2.2.6 CO_2 concentration according to urban or rural location

Moderate differences in CO_2 concentrations are observed between rural and urban areas (Fig. 4-21). Schools in rural villages generally present higher daily mean CO_2 levels compared to those in urban environments. In part this finding may be attributed to the more conservative ventilation practices prevalent in rural schools, as highlighted by the directors' survey (Section 5.1). Additionally, larger cities, such as Vienna, implemented a number of policies during the COVID-19 pandemic (Szendi and Sárosi-Blága, 2022), which may have led to greater acceptance of the use of CO_2 sensors and the need for enhanced ventilation protocols, by both staff and students.

Urban areas are further categorized into city outskirts and central city locations, with centrally located schools showing higher daily mean CO_2 concentrations than those in the outskirts. The higher CO_2 levels in centrally located schools are likely due to the increased traffic noise and air pollution typically

[20] Note, this figure should be treated with caution since it is only based on the 2 SS schools in this study.

found in city centres, which alongside temperature, have been identified as the biggest deterrents to teachers ventilating classrooms (Section 5.2).

As noted in previous sections, these differences are most pronounced during the colder seasons. In contrast, during the warmer months, the differences in daily mean CO_2 concentrations are minimal, as shown by the overlapping seasonal distributions for spring and the summer periods (Figs. 4-21 and 4-22). Throughout the school year, rural areas show the highest frequency of CO_2 threshold exceedances (Tbl. 4-12), with the compliance threshold of 1000 ppm being exceeded 59% of the time (75% above 800 ppm). Conversely, urban areas demonstrate lower exceedance rates, with the 1000 ppm threshold being exceeded 55% of the time in central areas and 53% in outskirt areas. Monthly distributions and statistics of daily mean CO_2 concentrations by area type can be found in Appendix C.1.2.6.

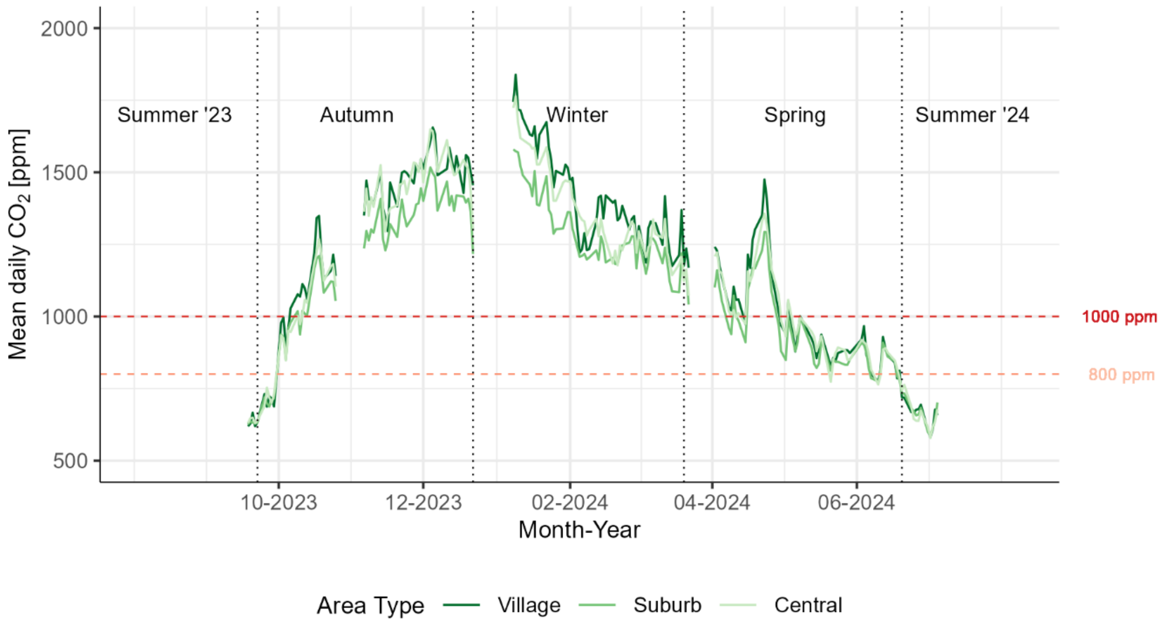


Figure 4-21. Overview of daily mean CO_2 concentrations in Austrian classrooms categorized by area type (rural: village, urban: central, outskirt), highlighting key trends, as well as the CO_2 indoor compliance threshold (1000 ppm, dashed red line) and target threshold (800 ppm, dashed pink line).

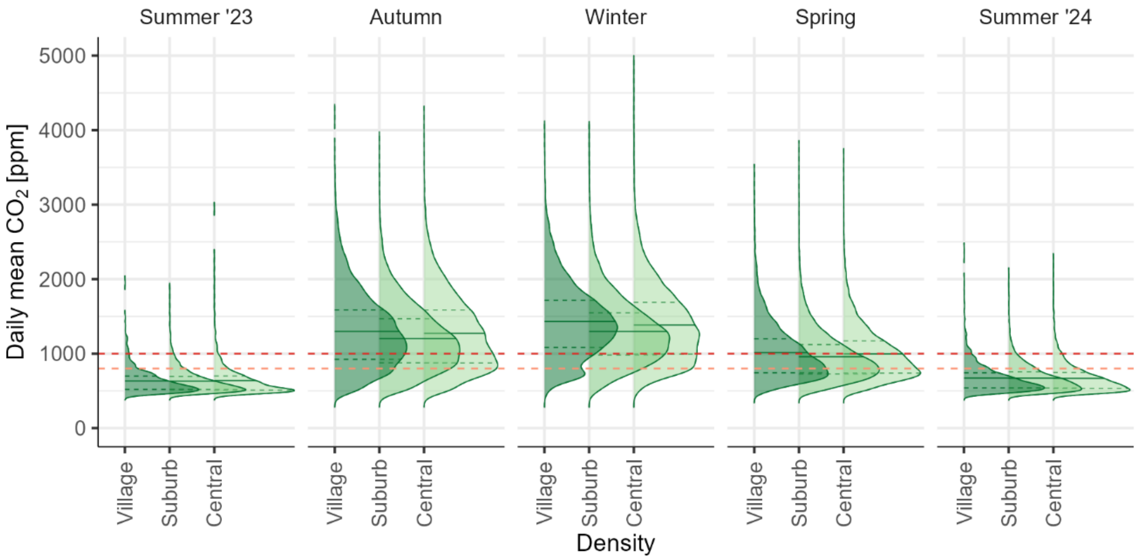


Figure 4-22. Seasonal distribution of mean daily CO_2 concentration in classrooms categorized by area type (rural: village; urban: central, outskirt) including the CO_2 indoor compliance threshold (1000 ppm, dotted red line) and target threshold (800 ppm, dotted pink line). The solid line within each distribution indicates the mean, whereas the dashed lines mark the 25th and 75th percentiles.

Table 4-12. Seasonal statistics of daily mean CO_2 concentrations in classrooms categorized by area type, including frequency of CO_2 indoor threshold exceedances relative to the 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances.

Season	Area type	Min [ppm]	Max [ppm]	Percentile [ppm] 25th	50th	75th	IQR	Mean [ppm]	Limit exceedance >1000 ppm [%]	>800 ppm [%]
Summer '23	Village	461	1951	520	586	700	180	633	4	12
	Suburb	460	1862	519	585	694	175	631	3	12
	Central	460	2947	511	587	700	190	639	5	13
Autumn	Village	462	4184	924	1230	1588	664	1299	69	84
	Suburb	460	3831	877	1148	1469	592	1203	64	82
	Central	460	4165	874	1199	1587	713	1273	65	82
Winter	Village	461	3954	1084	1387	1717	633	1433	80	90
	Suburb	461	3954	982	1244	1548	566	1298	73	89
	Central	462	4856	994	1317	1689	695	1384	74	89
Spring	Village	460	3431	743	931	1199	456	1015	43	67
	Suburb	460	3759	727	894	1121	394	959	37	64
	Central	460	3650	738	925	1171	433	997	41	66
Summer '24	Village	460	2401	540	620	742	203	673	6	18
	Suburb	460	2069	539	628	756	217	672	5	20
	Central	460	2258	533	620	747	214	668	6	18
Year	Village	460	4184	800	1115	1493	693	1197	59	75
	Suburb	460	3954	778	1032	1359	580	1108	53	73
	Central	460	4856	787	1066	1459	672	1169	55	74

4.2.2.7 CO_2 concentration according to region

Pronounced regional differences were identified in the daily mean CO_2 concentrations with schools in Carinthia recording the highest annual daily mean exceedances of the 1000 ppm compliance threshold at 67%, whilst Burgenland had the fewest exceedances at 36%. These inter-regional differences were even more pronounced during the winter period (Figs. 4-23 and 4-24), where both Carinthia and Upper Austria failed to meet the compliance threshold 88 % of the time compared to Burgenland which exceeded the threshold 46% of the time. In winter the health-based target threshold of 800 ppm was unobtainable for the vast majority of schools, with Carinthian schools failing to meet this target 97% of the time, whilst Burgenland schools failed to meet it 61% of the time. Further information regarding regional differences can be found in Appendix C.1.2.7.

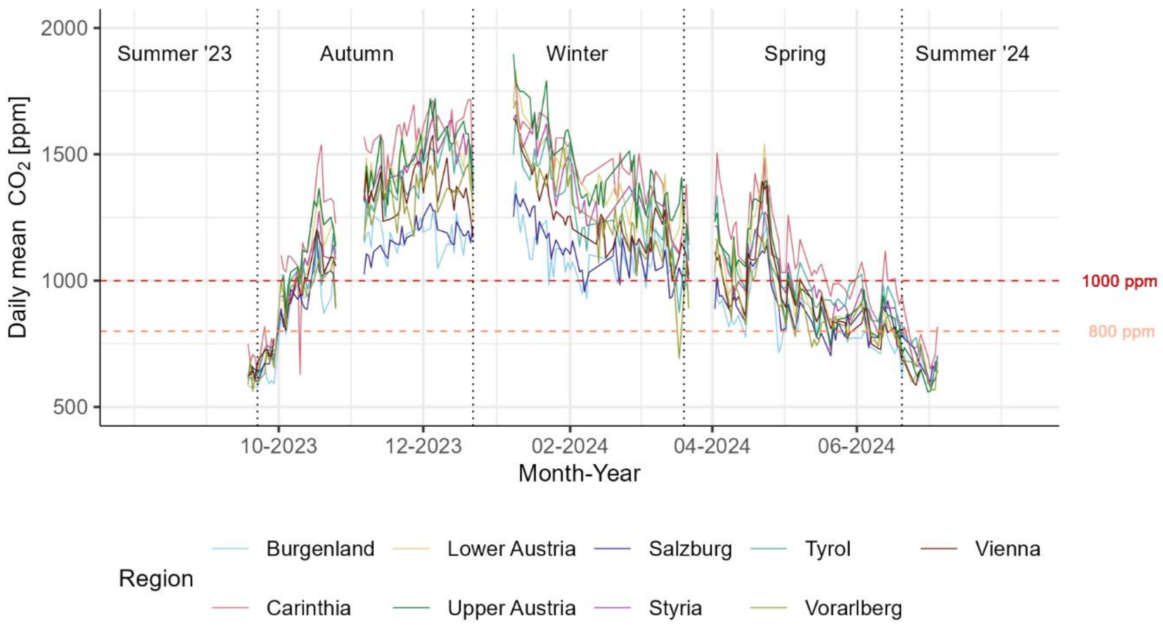


Figure 4-23. Overview of daily mean CO_2 concentrations in Austrian classrooms categorized by region, highlighting key trends, as well as CO_2 indoor compliance threshold (1000 ppm, dashed red line) and target threshold (800 ppm, dashed pink line).

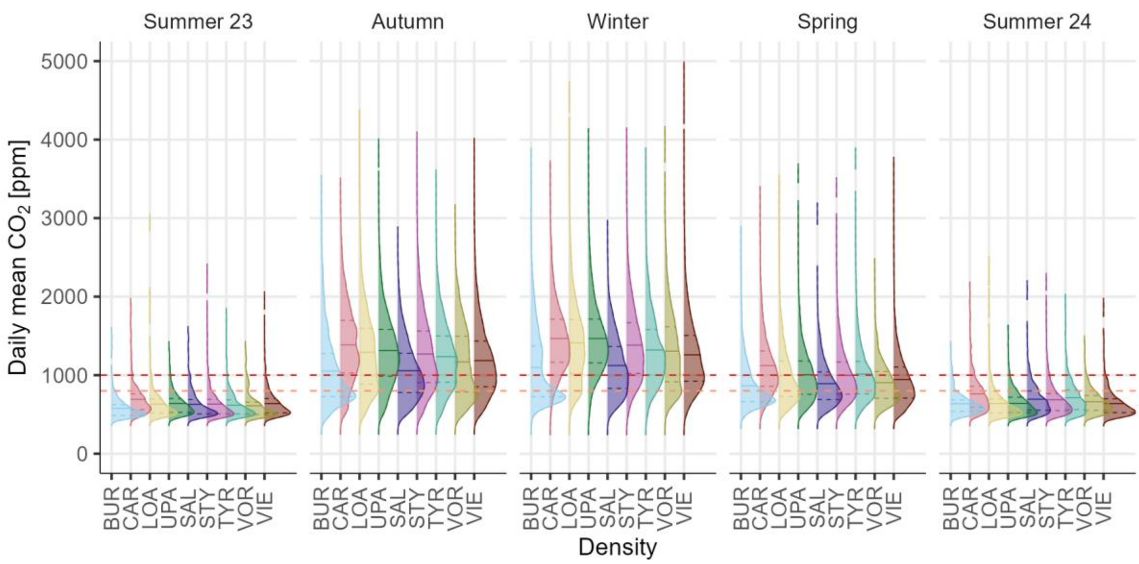


Figure 4-24. Seasonal distribution of daily mean CO_2 concentration in classrooms categorized by region, including CO_2 indoor compliance threshold (1000 ppm, dotted red line) and target threshold (800 ppm, dotted pink line). The solid line within each distribution indicates the mean, whereas the dashed lines mark the 25th and 75th percentiles.

4.2.2.8 CO_2 concentrations comparing the best performing vs worst performing schools

Out of the total of 120 ImpAQS schools 118 were ranked in order from best to worst in relation to their daily mean CO_2 concentration, during the winter period. This was done in order to illustrate the variance which occurs either side of the median value (Fig. 4-25), with consequential implications for health and attainment inequalities. Two schools (school number 21 and 59) were omitted from the ranking because they mainly operate as evening schools, and their inclusion would bias the comparison with the other schools, since they are often unoccupied during the core period of the day (from 8:00 until 14:00). It should also be noted that identifying information, such as the school type and location, is deliberately omitted from this ranking plot in order to avoid publicly identifying individual schools.

The schools which have the lowest daily mean CO_2 concentration are found in the lower quartile (Q1) and are coloured dark blue, schools in the second quartile (Q2) are light blue, whilst the third quartile (Q3) are orange, and the highest quartile (Q4) are red (Fig. 4-25). Strikingly it can be seen that the daily mean CO_2 concentration during winter in the best performing school (averaged over the 10 participating classrooms in each school) is approximately 1400 ppm lower than in the worst performing school. It can also be seen that the largest variance occurs at the tail ends of Q1 and Q4, where the 10 best-performing and the 10 worst-performing schools can be visually identified. This finding suggests that there may be unique factors, or a combination thereof, explaining why the top 10 schools outperform the rest of their quartile and why the bottom 10 schools underperform the rest of their quartile.

A key factor contributing to this ranking is the ventilation system type, since many of the schools using mechanical ventilation outperform those with natural ventilation. Mechanical ventilation systems are designed to provide controlled airflow and can (if properly maintained and correctly operated) significantly reduce the mean CO_2 concentration as shown in Fig. 4-28 by ensuring consistent air exchange. This capability, and the possibility to provide additional filtration of the outdoor air, is particularly important in environments where the outdoor air quality may be compromised (Section 4.3.2).

However, the ranking also shows that solely relying on mechanical ventilation does not guarantee a place in the top 10. Even though natural ventilation can be less acceptable as a means of controlling indoor air quality during periods of cold outside temperatures, the occupant density in the classroom also plays a significant role. In this regard the two SS schools, and other naturally ventilated schools with lower occupant densities, outperform many of the mechanically ventilated schools (Section 4.2.1.7).

Another factor benefiting primary schools (and leading to four primary schools being ranked amongst the top 10 best performing schools) is the fact that younger children have lower CO_2 emission rates compared to older children, which makes it easier for naturally ventilated primary schools to achieve comparatively lower steady-state CO_2 concentrations (Section 3.4.1). However this does not necessarily imply that they are providing better ventilation (Section 4.2.3).

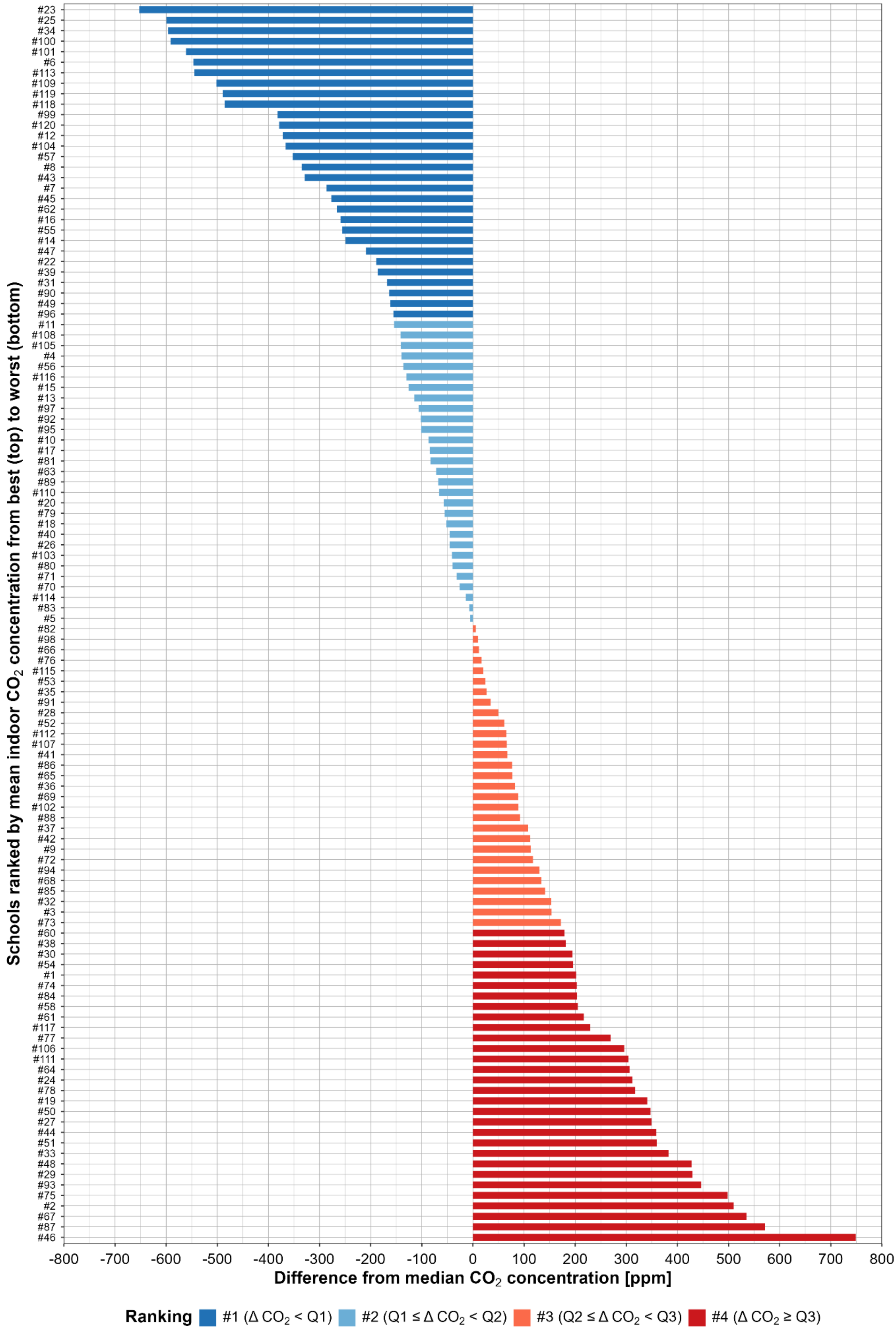


Figure 4-25. Horizontal bar chart - Ranking of 118 ImpAQS schools (best to worst) in winter by daily mean CO_2 level

4.2.3 Ventilation rates in Austrian classrooms

The airflow rate is an important variable since it describes the volume of fresh air that is provided to each occupant in a space [m^3/(h·person)] or [l/(s·person)]. In naturally ventilated rooms it is a complex procedure to measure airflow rates directly, partly because of the transient nature of the forces driving natural airflow (Mustafa et al., 2025) as well as the fact that air can flow into and out of a window opening at the same time. Various methods exist based on mass balance equations, which are predicated on assumptions regarding the rate of CO_2 exhaled by the occupants and the outdoor CO_2 concentration (Batterman, 2017).

The daily mean airflow rates were derived using a steady-state approach, as defined in Wood et al. (2024), for all 1200 classrooms (Section 3.4). This approach allowed for estimates of the ventilation rates during class times without the need for complex air flow measurements. Since only the core periods when classrooms were occupied were relevant for this analysis, only the data recorded between 08:00 and 14:00 on school days was considered. Weekends, holidays, and other days (where the daily average CO_2 concentration was below 600 ppm during this period) were excluded from this analysis, as such low concentrations indicate limited occupancy or non-operation of the classes. Including partially occupied or unoccupied rooms in the ventilation analysis (without knowing the actual occupancy at these times) would potentially result in unrealistically high estimates of the ventilation rates.

The results of these calculations are presented, in the following sections, as density plots of the seasonally aggregated daily mean ventilation airflow rate (per person) and as extended time series plots, to illustrate seasonal trends in the combined mean ventilation airflow rates.

4.2.3.1 Ventilation rates in classrooms

Figure 4-26 shows the daily mean ventilation rate [l/(s·person)], along with the corresponding daily mean CO_2 concentrations [ppm] over the measurement period, from September 2023 to July 2024. The CO_2 measurements were averaged across all 1200 sensors installed in the classrooms. Ventilation rates are shown on the primary y-axis. The black line represents the daily mean ventilation rates across all 1200 classrooms, with the grey ribbon indicating the interquartile range (25^{th} to 75^{th} percentiles) of the ventilation rates. Similarly, the blue line shows the daily mean CO_2 concentration, with the blue ribbon representing the interquartile range of CO_2 measurements. From summer 2023 to early winter 2024, there is a noticeable decline in the daily mean ventilation rates and a corresponding increase in CO_2 concentrations. This is likely due to reduced ventilation frequency, because of falling outdoor temperatures. In spring and summer 2024, the pattern reverses, with increasing ventilation rates and decreasing CO_2 concentrations. From May to July, the average daily ventilation rates mostly exceed 10 l/(s·person), likely due to more frequent ventilation as the weather warmed.

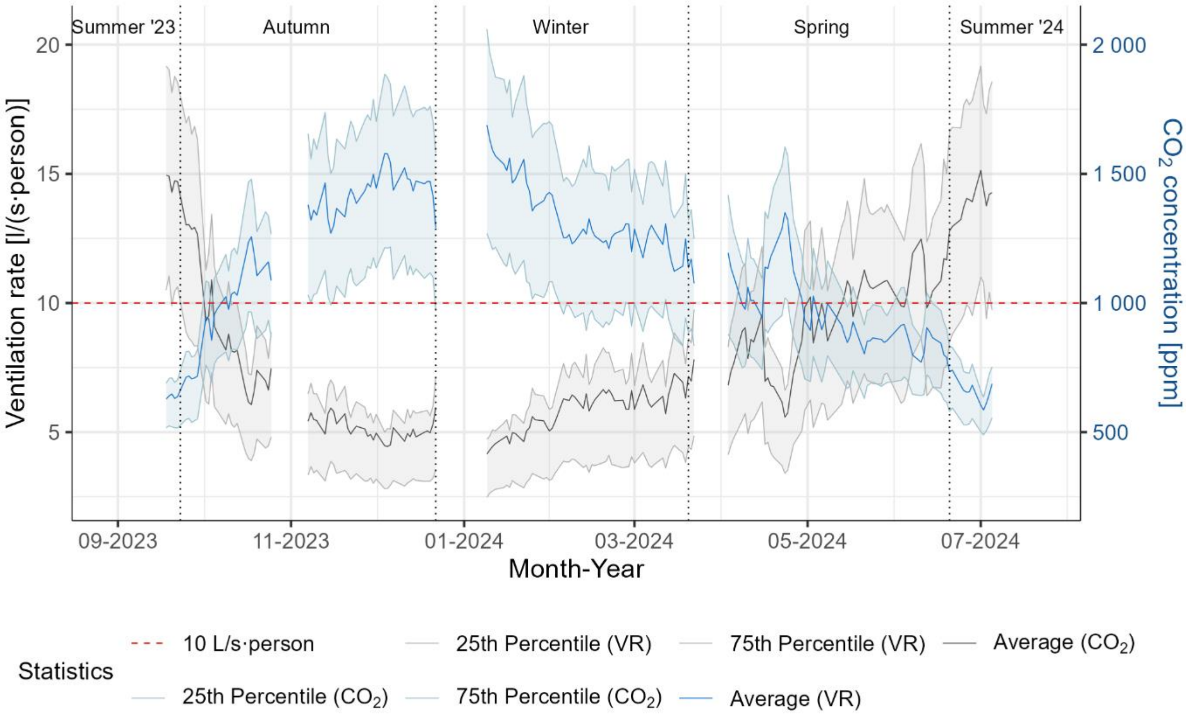


Figure 4-26. Time series– hypothetical mean ventilation rate and IQR range of all classrooms over whole school year

4.2.3.2 Ventilation rate by season

The probability density function and the statistical distribution of the daily average ventilation rates across the 1200 classrooms according to the season are shown in Fig. 4-27 and Tbl. 4-13. Analysing the data at the 75th percentile it can be seen (Tbl. 4-13) that the majority of daily mean values are below 9.5 l/(s·person) thus not fulfilling standard values of 10 l/(s·person) set for category IEQ_I in EN 16798-1:2019 (CEN, 2019). The median ventilation rate is 5.9 l/(s·person), while the arithmetic mean ventilation rate is significantly higher, at 7.4 l/(s·person), reflecting a right skewed distribution (likely because of the higher values recorded in the summer season). Of particular concern, the 25th percentile indicates that for 25% of the time classrooms showed airflow rates less than or equal to 4 l/(s·person), which is the minimum rate recommended by EN 16798-1:2019 (CEN, 2019). This distribution highlights the large variation in ventilation practices across Austrian classrooms, wherein the IQR of the annual daily mean ventilation rate ranges from 4.0 to 9.5 l/(s·person) (Table 4-13).

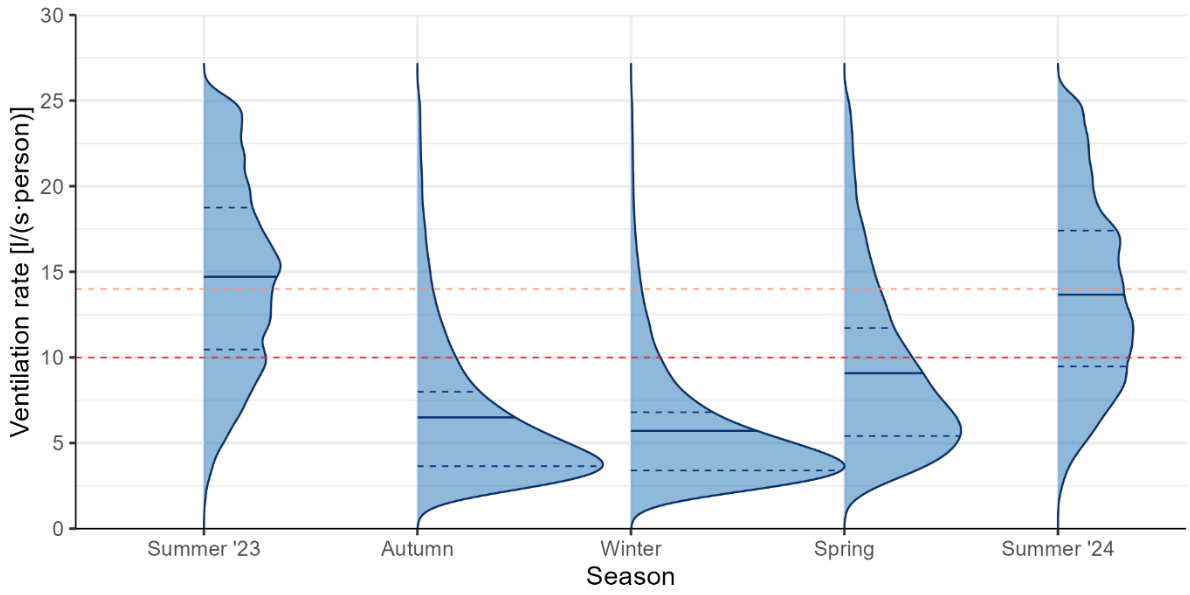


Figure 4-27. Seasonal distribution of VR in l/(s·person) from the combined Test and Control sensors including the EN 16798-1 threshold (10 l/(s·person), IEQ_I, dotted red line). The solid line within each distribution indicates the mean, whereas the dashed lines indicate the 25th and 75th percentiles.

Table 4-13 further quantifies the seasonal variations depicted in Fig. 4-27. A significant increase of approximately 140% in average ventilation rates, occurs between the winter months (5.7 l/(s·person)) to the early summer (13.7 l/(s·person)). On average, 77% of the daily mean ventilation rates across all 1200 classrooms fall below 10 l/(s·person) and therefore do not meet the Category 1 standard of EN 16798-1 (CEN, 2019). Furthermore, from a health-based perspective, for 89% of the time the classrooms exhibit ventilation rates lower than 14 l/(s·person), thereby not meeting the non-infectious air delivery rate (NADR) target set by the Lancet COVID-19 Commission (2022).

Table 4-13. Seasonal statistics of VR including percentage of VR threshold subceedances

Season	Min	Max	Percentile 25	Percentile 50	Percentile 75	Mean	Subceedance <14l/(s·p.)	Subceedance <10l/(s·p.)
	[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[%]	[%]
Summer '23	1.7	25.4	10.5	14.6	18.7	14.7	45.8	22
Autumn	0.9	25.4	3.7	5.2	8.0	6.5	93	84
Winter	1.0	25.4	3.4	4.7	6.8	5.7	96	89
Spring	1.0	25.4	5.4	7.9	11.7	9.1	84	66
Summer '24	1.8	25.4	9.5	13.2	17.4	13.7	55	28
Year	0.9	25.4	4.0	5.9	9.5	7.4	89	77

4.2.3.3 Ventilation rate according to ventilation system type

The seasonal distribution of ventilation rates between mechanically ventilated (MV) and naturally ventilated (NV) classrooms are compared in Fig. 4-28 and Tbl. 4-14. The data indicate that mean ventilation rates in MV classrooms are consistently higher than in NV classrooms. However, MV classrooms exhibit greater variability in the airflow rates provided (Tbl. 4-14), particularly during in colder months. This finding suggests that schools may be following different guidance and standards, resulting in a broad range of set-point targets in relation to the operation of mechanical systems.

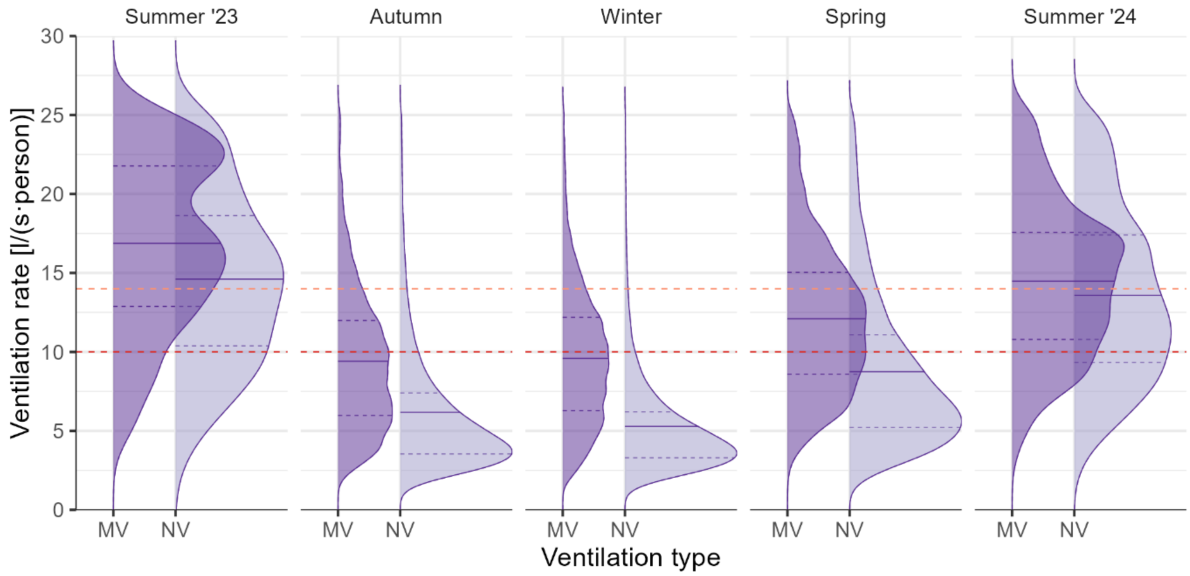


Figure 4-28. Seasonal distribution of VR in l/(s·person) for mechanical (MV) and natural (NV) ventilation systems including EN 16798-1 IEQ$_I$ threshold (10 l/(s·person), dotted red line). The solid line within each distribution indicates the mean, and the dashed lines indicate the 25th and 75th percentiles.

In summer 2024, the daily mean ventilation rates between MV and NV classrooms are relatively similar, with MV classrooms averaging 14.5 l/(s·person) and NV classrooms 13.6 l/(s·person). Both ventilation types perform well during this season, with NV classrooms falling below the 10 l/(s·person) threshold for only 29% of the time, whilst MV classrooms subceed the threshold only 20% of the time. These findings suggests that natural ventilation can achieve comparable performance to mechanical systems under warmer conditions.

In winter, a more pronounced disparity is observed. MV classrooms maintain a daily mean ventilation rate of 9.6 l/(s·person) on average, while NV classrooms fall significantly to 5.3 l/(s·person) (Tbl. 4-14). The proportion of daily mean ventilation rates failing to meet the 10 l/(s·person) standard is substantially higher for NV classrooms (93%) compared to MV classrooms (57%) (Tbl. 4-14). This difference underscores the limitations of NV systems in colder months, where reduced air exchange is likely to be driven by the occupants' response to lower air temperatures, resulting in inadequate ventilation rates.

Furthermore, both MV and NV classrooms frequently fall below the recommended minimum outdoor airflow rate specified in EN 16798-1, which advises that ventilation rates should not drop below 4 l/(s·person) to account for human-generated pollutants (CEN, 2024). This issue is particularly pronounced in colder months, where the 25th percentile values for NV classrooms are 3.5 l/(s·person) in autumn and 3.3 l/(s·person) in winter, indicating inadequate ventilation for more than a quarter of all occupied periods during this time.

In addition, daily mean ventilation rates in many MV classrooms do not meet the requirement set by the Austrian Workplace Regulations (AStVO), which mandate a minimum of 35 m^3 of outdoor air per person per hour (equivalent to approximately 9.7 l/(s·person)) for rooms where light physical work is conducted. In autumn, the daily median ventilation rate in MV classrooms is 8.9 l/(s·person), falling short of this threshold, with similar rate of non-compliance in winter where median rates are 9.3 l/(s·person). Whilst the upper quartile of the MV values comply with the AStVO requirement year-round, a large percentage MV classrooms fail to meet the AStVO requirements during the colder months (Tbl. 4-14).

Table 4-14. Seasonal statistics of VR including percentage of VR threshold subceedances for mechanical (MV) and natural (NV) ventilation separately.

Season	Vent.-type	Min	Max	Percentile 25	Percentile 50	Percentile 75	Mean	Subceedance <14l/(s·p.)	Subceedance <10l/(s·p.)
		[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[%]	[%]
Summer '23	MV	4.9	25.4	12.9	16.8	21.8	16.9	29	12
	NV	1.7	25.4	10.4	14.5	18.6	14.6	47	23
Autumn	MV	1.7	25.4	6.0	8.9	12.0	9.4	85	59
	NV	0.9	25.4	3.5	4.9	7.4	6.2	94	87
Winter	MV	1.7	25.3	6.3	9.3	12.2	9.6	86	57
	NV	1.0	25.4	3.3	4.4	6.2	5.3	97	93
Spring	MV	1.8	25.4	8.6	11.7	15.0	12.1	68	36
	NV	1.0	25.4	5.2	7.5	11.1	8.7	86	69
Summer '24	MV	3.5	25.3	10.8	14.5	17.6	14.5	46	20
	NV	1.8	25.4	9.3	13.0	17.4	13.6	56	29
Year	MV	1.7	25.4	6.9	10.0	13.4	10.5	78	50
	NV	0.9	25.4	3.8	5.6	8.8	7.1	91	80

4.2.3.4 Ventilation rate according to school type

The seasonal distribution of ventilation rates across various school types is compared in Fig. 4-29 and Tbl. 4-15. The data reveal a consistent pattern that was also observed in previous analyses, with lower ventilation rates in colder months and higher rates during warmer periods.

In winter, the mean ventilation rates for most school days fall between 5.5 and 5.7 l/(s·person), however the median rates are approximately 1 l/(s·person) lower than the mean values, suggesting that a smaller number of better ventilated classrooms are skewing the distribution. Notably, special needs schools (SS) perform significantly better, with a mean ventilation rate of 12.5 l/(s·person), suggesting better air quality in these schools during colder months[21]. As temperatures increase, ventilation rates improve across all school types. By summer 2024, the average of the daily mean ventilation rates ranges from 11.1 l/(s·person) in primary schools (VS) to 15.9 l/(s·person) in WS, with ventilation levels becoming more consistent across the different school types.

It is notable that VS schools, despite having relatively low CO_2 concentrations (relative to other school types) (Section 4.2.2), are one of the worst performing school types in relation to ventilation rates (Fig. 4-29 and Tbl. 4-15); this apparent paradox is explained by the fact that younger children emit less CO_2 than older children (Tbl. 3-1). This is why comparing room CO_2 concentrations without considering the occupancy characteristics of a room (including the age and metabolic rate of the occupants) can be misleading. In general ventilation airflow rates per person [l/(s·person)] provide a more reliable indicator of the ventilation and indoor air quality.

[21] Caution is advised in generalising the results of the special needs schools (SS), since there were only two SS in the study.

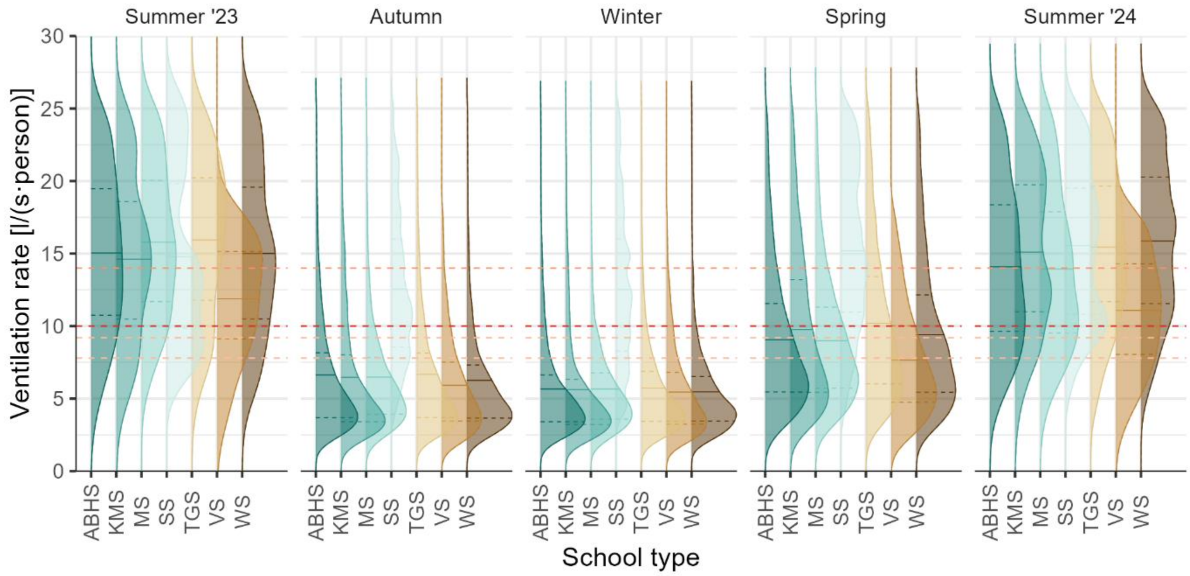


Figure 4-29. Seasonal distribution of VR in l/(s·person) for different school types separately including the EN 16798-1 IEQ$_I$ threshold (10 l/(s·person), dotted red line). The solid line within each distribution indicates the mean, and the dashed lines indicate the 25th and 75th percentiles.

In relation to ÖNORM H 6039:2023, which specifies 28 m³/(h·person) (equivalent to 7.8 l/(s·person)) for students under 10 years and 33 m³/(h·person) (equivalent to 9.2 l/(s·person)) for students from 11 to 18 years, primary schools (VS) would be expected to meet the threshold target of 7.8 l/(s·person). In winter, VS classrooms fall below this threshold 81% of the time, with a mean ventilation rate of 5.5 l/(s·person). Although ventilation is improved in the summer 2024, VS classrooms still fall below the 7.8 l/(s·person) requirement 24% of the time, despite having a mean ventilation rate of 11.1 l/(s·person).

Special needs schools (SS), which accommodate students aged approximately 6 to 15, must consider both the 7.8 l/(s·person) threshold for younger students and the 9.2 l/(s·person) threshold for older students[22]. In winter, SS classrooms fail to meet the 9.2 l/(s·person) threshold 31% of the time, despite a mean ventilation rate of 12.5 l/(s·person). However, compliance improves significantly in summer 2024, where classrooms fail to meet this threshold less than 10% of the time, with a mean ventilation rate of 15.6 l/(s·person).

For other school types, including ABHS, KMS, MS, TGS, and WS, which serve students aged 11 to 18, ÖNORM H 6039:2023, recommends a minimum ventilation threshold of 9.2 l/(s·person). In winter, a high proportion (86–90%) of the daily mean ventilation rates in classrooms of these school types fail to meet this standard, with mean ventilation rates ranging between 5.5 and 5.7 l/(s·person). However, ventilation improves markedly in summer, with mean airflow values ranging from 13.9 to 15.9 l/(s·person).

[22] This implies that mixed age classes would need to ventilate at the higher rate to comply with the ÖNORM.

Table 4-15. Seasonal statistics of daily mean VR, including percentage of threshold subceedances for different school types.

Season	School type	Min	Max	Percentile			Mean	Subceedance			
				25	50	75		<14 l/(s·p.)	<10 l/(s·p.)	<9.2 l/(s·p.)	<7.8 l/(s·p.)
		[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[l/(s·p.)]	[%]	[%]	[%]	[%]
Summer '23	ABHS	2.8	25.4	10.8	15.0	19.5	15.0	45	21	17	10
	KMS	1.7	25.3	10.5	14.5	18.6	14.6	47	25	21	13
	MS	5.3	25.4	11.7	15.5	20.0	15.8	40	17	10	6
	SS	6.9	25.3	9.9	13.7	19.8	14.8	55	27	23	9
	TGS	3.6	25.4	11.8	16.3	20.2	15.9	35	18	14	7
	VS	1.7	18.2	9.1	12.3	15.1	11.9	63	32	25	17
	WS	2.8	25.3	10.5	14.8	19.6	15.0	45	21	18	12
Autumn	ABHS	1.2	25.4	3.7	5.2	8.2	6.6	93	83	80	73
	KMS	1.2	25.3	3.4	4.9	8.0	6.5	92	82	80	74
	MS	1.3	25.4	3.9	5.4	7.8	6.5	95	87	83	75
	SS	3.4	25.3	8.6	11.5	16.0	12.6	64	36	30	19
	TGS	1.3	25.4	3.7	5.3	8.1	6.7	93	83	80	73
	VS	0.9	18.2	3.5	5.0	7.5	5.9	97	88	84	77
	WS	1.5	25.3	3.7	5.0	7.3	6.3	94	87	84	78
Winter	ABHS	1.1	25.4	3.4	4.6	6.6	5.7	96	90	87	82
	KMS	1.0	25.3	3.2	4.4	6.3	5.6	95	88	86	82
	MS	1.2	25.3	3.6	4.9	6.8	5.7	97	92	90	83
	SS	3.4	25.4	8.3	12.0	16.0	12.5	63	36	31	23
	TGS	1.2	25.4	3.4	4.7	6.9	5.7	97	90	88	81
	VS	1.0	18.2	3.2	4.6	6.8	5.5	98	90	87	81
	WS	1.3	25.3	3.5	4.6	6.5	5.5	97	93	90	85
Spring	ABHS	1.3	25.4	5.5	7.8	11.6	9.1	85	67	61	50
	KMS	1.3	25.4	5.4	8.4	13.2	9.8	78	60	55	46
	MS	1.4	25.4	5.7	8.0	11.3	9.0	87	67	61	48
	SS	3.2	25.4	11.0	14.7	20.0	15.2	44	20	16	9
	TGS	1.6	25.3	6.0	8.9	13.4	10.2	78	58	52	42
	VS	1.0	18.2	4.8	6.9	10.0	7.7	92	75	70	59
	WS	1.4	25.4	5.4	8.1	12.2	9.4	81	65	59	47
Summer '24	ABHS	2.2	25.4	9.6	13.6	18.4	14.1	52	28	22	14
	KMS	2.4	25.3	11.0	14.7	19.7	15.1	47	20	17	9
	MS	2.6	25.4	9.5	13.4	17.9	13.9	53	28	21	13
	SS	6.1	25.1	10.8	15.7	19.5	15.6	41	18	10	3
	TGS	3.6	25.2	11.7	15.3	19.7	15.5	42	17	13	7
	VS	1.8	18.2	8.0	11.1	14.3	11.1	73	41	35	24
	WS	4.8	25.3	11.6	16.2	20.3	15.9	39	15	11	6
Year	ABHS	1.1	25.4	4.0	5.9	9.5	7.5	89	77	73	66
	KMS	1.0	25.4	3.7	5.7	10.2	7.6	87	75	71	65
	MS	1.2	25.4	4.3	6.2	9.4	7.5	90	78	74	65
	SS	3.2	25.4	9.1	12.6	17.2	13.3	58	31	26	17
	TGS	1.2	25.4	4.1	6.1	10.0	7.8	87	75	71	64
	VS	0.9	18.2	3.7	5.6	8.7	6.6	94	82	78	70
	WS	1.3	25.4	4.0	5.7	9.1	7.3	89	79	76	68

4.2.3.5 Ventilation rate according to region

Regional differences were identified in the daily mean ventilation rates across schools, with schools in Carinthia (Kärnten) recording the lowest annual daily mean values, and schools in Burgenland showing better performance overall (Fig. 4-30 and Tbl. 4-16).

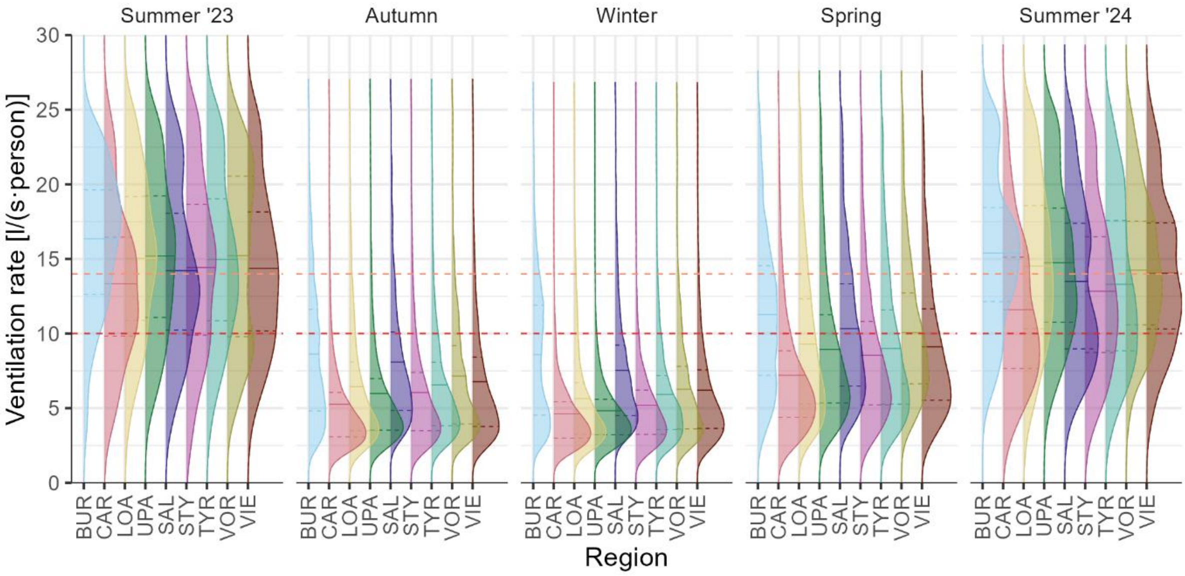


Figure 4-30. Seasonal distribution of VR in l/(s·person) for different regions separately including EN 16798-1 threshold (10 l/(s·person), IEQ_I, dotted red line). The solid line within each distribution indicates the mean, whereas the dashed lines indicate the 25th and 75th percentiles

These regional differences were most pronounced in winter, where Carinthian schools showed daily mean ventilation rates failing to meet the recommended 10 l/(s·person) threshold 96% of the time, with a mean ventilation rate of 4.6 l/(s·person). In contrast, Burgenland subceeded this threshold the least, with 62% of mean daily classroom ventilation rates falling below the threshold and a mean ventilation rate of 8.6 l/(s·person).

Ventilation rates improved in summer 2024, with daily mean values ranging from 11.6 l/(s·person) in Carinthia to 15.4 l/(s·person) in Burgenland. Most regions showed values above the 10 l/(s·person) threshold, with Carinthia recording daily averages below the threshold for 43% of the time, compared to only 19% of the time in Burgenland.

Table 4-16. Seasonal statistics of VR including percentage of VR threshold subceedances for different regions.

Season	Region	Min	Max	Percentile			Mean	Subceedance	
				25	50	75		<14 l/(s·p)	<10 l/(s·p)
		[l/(s·p)]	[l/(s·p)]	[l/(s·p)]	[l/(s·p)]	[l/(s·p)]	[l/(s·p)]	[%]	[%]
Summer '23	BUR	4.1	23.9	12.6	16.8	19.6	16.4	28	10
	CAR	3.0	25.2	9.8	12.9	16.5	13.3	55	27
	LOA	1.7	25.4	10.9	15.2	19.2	15.0	42	21
	UPA	4.0	25.4	11.1	15.4	19.2	15.2	43	20
	SAL	4.0	25.3	10.2	13.6	18.1	14.2	54	24
	STY	1.7	25.3	9.9	14.7	18.7	14.4	47	25
	TIR	3.3	25.1	10.9	14.7	19.0	15.0	46	19
	VOR	4.9	25.3	9.8	15.1	20.5	15.2	42	29
	VIE	2.8	25.4	10.2	14.0	18.2	14.4	50	24

Autumn	BUR	1.5	25.4	4.8	7.6	11.6	8.6	86	66
	CAR	1.3	25.2	3.1	4.2	6.1	5.3	96	92
	LOA	1.2	25.4	3.5	5.0	8.1	6.4	93	83
	UPA	1.2	25.4	3.5	4.8	7.0	6.0	95	88
	SAL	1.9	25.4	4.8	6.8	10.1	8.1	89	75
	STY	0.9	25.4	3.5	4.9	7.4	6.0	95	88
	TIR	1.3	25.3	3.8	5.4	8.1	6.6	94	85
	VOR	1.7	25.3	3.9	5.8	9.2	7.2	92	79
	VIE	1.2	25.3	3.8	5.5	8.4	6.8	93	82
Winter	BUR	1.3	25.3	4.5	7.9	11.9	8.6	87	62
	CAR	1.2	24.9	3.0	4.0	5.4	4.6	99	96
	LOA	1.1	25.3	3.2	4.4	6.7	5.6	96	88
	UPA	1.2	25.3	3.2	4.2	5.6	4.8	98	96
	SAL	1.9	25.4	4.5	6.4	9.2	7.5	91	79
	STY	1.0	25.1	3.2	4.5	6.2	5.2	98	94
	TIR	1.3	25.2	3.6	5.0	7.2	5.9	97	89
	VOR	1.2	25.4	3.6	5.2	7.8	6.3	96	86
	VIE	1.0	25.4	3.6	5.1	7.6	6.2	95	87
Spring	BUR	1.9	25.4	7.2	10.9	14.5	11.3	72	44
	CAR	1.2	25.3	4.4	6.2	8.8	7.2	93	82
	LOA	1.4	25.4	5.3	8.1	12.3	9.3	82	63
	UPA	1.4	25.4	5.3	7.7	11.3	8.9	85	68
	SAL	1.6	25.4	6.5	9.3	13.3	10.3	78	56
	STY	1.0	25.3	5.2	7.4	10.8	8.5	88	70
	TIR	1.3	25.4	5.3	7.8	11.6	9.0	84	66
	VOR	1.8	25.3	6.6	9.1	12.7	10.1	81	58
	VIE	1.2	25.4	5.5	7.9	11.7	9.1	84	66
Summer '24	BUR	4.9	25.2	12.1	15.3	18.4	15.4	40	19
	CAR	1.9	25.3	7.7	10.8	15.1	11.6	68	43
	LOA	2.2	25.3	10.3	14.2	18.6	14.5	49	23
	UPA	3.0	25.3	10.8	14.2	18.4	14.8	48	20
	SAL	2.6	25.3	9.0	12.8	17.4	13.5	55	32
	STY	1.8	25.4	8.7	12.3	16.5	12.8	61	34
	TIR	2.7	25.2	8.8	12.6	17.6	13.3	58	33
	VOR	3.5	25.4	10.6	13.9	17.5	14.2	51	21
	VIE	3.0	25.3	10.3	13.6	17.4	14.0	53	24
Year	BUR	1.3	25.4	5.4	9.1	13.0	9.7	80	56
	CAR	1.2	25.3	3.4	4.9	7.4	6.2	94	86
	LOA	1.1	25.4	3.8	5.7	9.7	7.3	89	76
	UPA	1.2	25.4	3.8	5.4	8.6	7.0	90	81
	SAL	1.6	25.4	5.2	7.6	11.5	8.9	84	68
	STY	0.9	25.4	3.8	5.7	8.7	7.0	92	81
	TIR	1.3	25.4	4.2	6.1	9.6	7.6	89	77
	VOR	1.2	25.4	4.4	7.0	10.7	8.2	87	71
	VIE	1.0	25.4	4.2	6.2	9.6	7.6	89	77

4.2.3.6 Ventilation rates comparing the best performing vs worst performing schools and classrooms

Out of the total of 120 ImpAQS schools 118 were ranked in order from best to worst in relation to their daily mean ventilation rate, during the winter period. This was done in order to illustrate the variation which occurs either side of the median (Fig. 4-31). As per Section 4.2.2.8, two schools (school number 21 and 59) were omitted from the ranking because they mainly operate as evening schools, and this would bias the comparison with the other schools since they are often unoccupied during the core period of the day (i.e. from 8:00 until 14:00). It should be noted that identifying information such as the school type and location is deliberately omitted from this figure in order to avoid publicly identifying individual schools.

The schools which have the lowest daily mean ventilation rate are found in the lower quartile (Q1) and are coloured red, schools in the second quartile (Q2) are orange, whilst the third quartile (Q3) are light blue, and the highest quartile (Q4) are dark blue (Fig. 4-31). Strikingly, it can be seen that the daily mean ventilation rate in the best performing school (averaged over the 10 participating classrooms in each school) is more than 10 l/(s·person) higher than in the worst performing school. It can also be seen that the largest variance occurs at the tail ends of Q1 and Q4, where the 10 best-performing and the 10 worst performing schools can be visually identified. This finding suggests that there may be unique factors, or a combination thereof, explaining why the top schools outperform the rest of their quartile and the bottom schools underperform the rest of their quartile. Irrespective of the underlying reasons, this finding points to the potential for significant health and attainment inequalities in Austrian schools as a result of the pronounced variation in ventilation rates.

A key factor contributing to this ranking is the ventilation system type, since the majority of schools using mechanical ventilation outperform those with natural ventilation. Mechanical ventilation systems are designed to provide controlled airflow and can (if properly maintained and correctly operated) significantly increase the median ventilation rate as shown in Figure 4-37 by ensuring consistent air exchange. This capability, and the possibility to provide additional filtration of the outdoor air, is particularly important in environments where the outdoor air quality may be compromised (Section 4.3.2).

However, the ranking also shows that solely relying on mechanical ventilation does not guarantee a place in the top 10. Even though natural ventilation can be less acceptable as a means of controlling indoor air quality during periods of cold outside temperatures, the occupant density in the classroom also plays a significant role. In this regard, the SS schools outperform many of the mechanically ventilated schools as their spatial density is much higher in relation to other schools (Section 4.2.1.7).

Contrary to the mean CO_2 concentration ranking, a factor penalizing primary schools with respect to their ventilation rate is the lower CO_2 emission rates for children under 11 (compared to over 11) . This means that to achieve the same steady state CO_2 concentration a primary school (VS) class will require a lower ventilation rate than a classroom with older children (on account of their lower metabolic rate). This makes it harder for naturally ventilated primary schools to achieve comparatively high ventilation rates without setting more stringent CO_2 targets (Section3.4.1) . Hence, only two primary schools (albeit mechanically ventilated) rank in the top 10 best performing schools compared with four when ranked on the basis of CO_2 (Fig. 4-25).

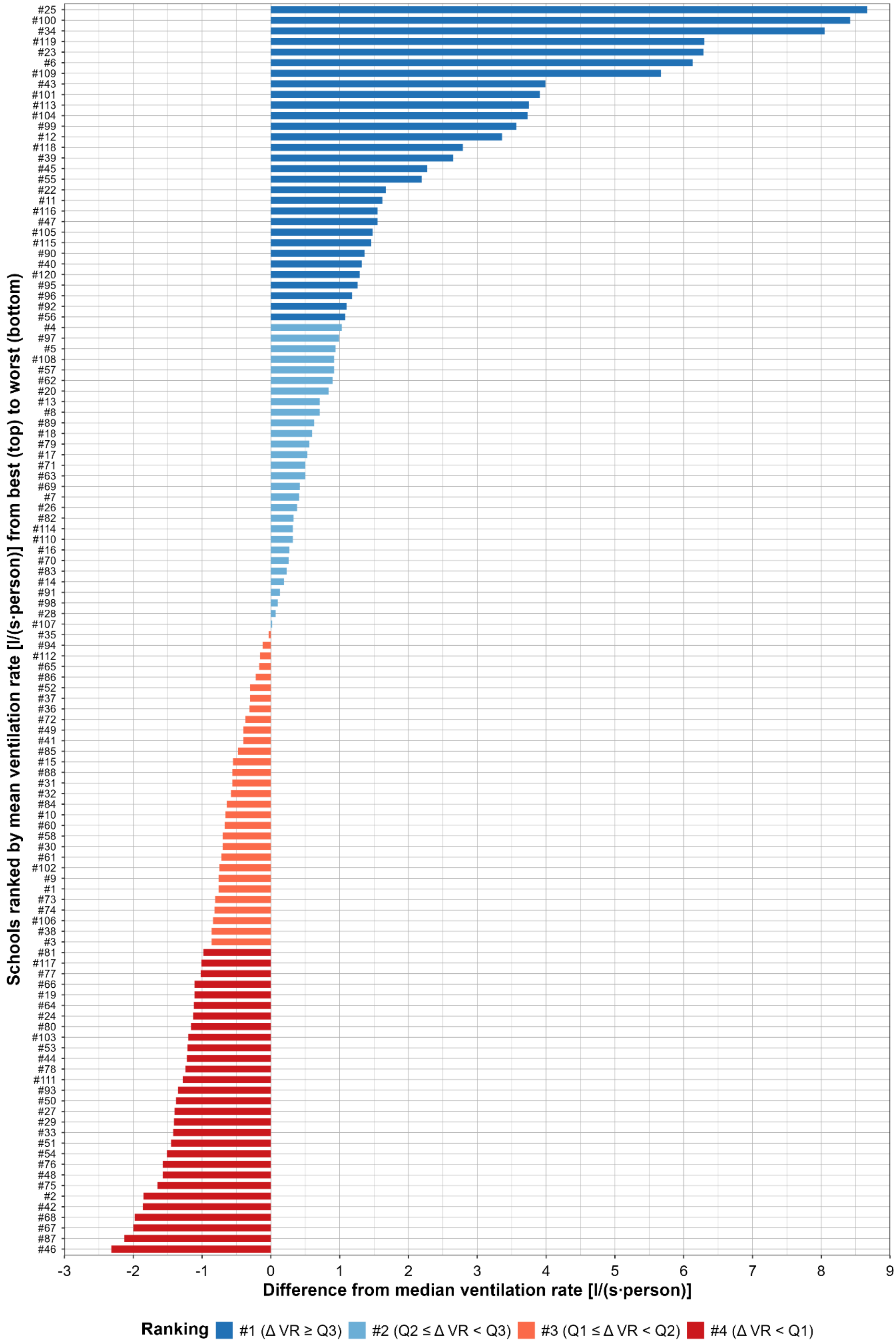


Figure 4-31. Horizontal bar chart - Ranking of 118 ImpAQS schools (best to worst) in winter by mean ventilation rate

4.3 Impact of local environmental quality factors on indoor CO_2 concentrations

This section aims to answer **research question 2** *"Are the results for the CO_2 concentration and ventilation practices dependent upon the season and/or other local environmental factors (e.g. thermal comfort, air pollution etc)?*

In order to understand the possible effect that environmental factors (occurring outside of the classroom) have on the resultant CO_2 and ventilation rates inside the classrooms, it is important to evaluate environmental data in proximity to the schools. First, the outdoor CO_2 measurements recorded at the site of the individual schools are analysed (Section 4.3.1). Second, four principle air pollutants ($PM_{2.5}$, PM_{10}, NO_2,and O_3) measured in proximity to the schools are investigated (Section 4.3.2). Finally, the relationship between indoor CO_2 concentrations and other environmental factors affecting thermal comfort, including outdoor and indoor air temperature, are evaluated (Section 4.3.3). Additional subjective analysis of the effects of outdoor noise on the ability of teachers to ventilate their classrooms is found in Section 5.2.2 and 5.2.4.

4.3.1 Outdoor CO_2 measurements

Variation in the outdoor CO_2 measurements at the ImpAQS schools, over the 2023–24 period, are shown in Fig. 4-32. It should be noted that the values in Fig. 4-32 have been compensated to correct for differences in altitude between the schools (Appendix B.3). The outdoor values can be seen to vary across the year according to the seasonal CO_2 trend, which is influenced by seasonal biomass carbon sequestration in the spring to autumn period as well as higher fossil fuel burning due to the use of heating systems in wintertime (Fig. 4-32). In addition there are localised influences where CO_2 concentrations are often elevated in more urban areas due to higher densities of vehicle traffic and industry. Local airflow patterns and seasonal weather trends can also influence CO_2 concentrations. Variations in the daily mean outdoor CO_2 concentration of the ImpAQS schools (Fig. 4-32) can be compared to the background CO_2 concentrations at the Sonnblick observatory (which are typically lower than elsewhere in Austria) and the urban CO_2 concentration at the Arsenal Tower in Vienna, which are indicative of the higher concentrations typically found in an urban context (Fig. 3-11).

The fluctuation in daily mean ambient CO_2 concentrations (Figs. 3-11 and 4-32) (and also in higher resolution data) can vary by up to 75 ppm (or more) over a relatively short time frame, and this has implications for the consistent measurement of normative CO_2 concentrations indoors, which is why EN 16798-1 (CEN, 2019) and ISO 17772 (ISO, 2017) adopt relative threshold reference values, which are specified as a function of the localised ambient CO_2 concentration (Tbl. 2-6). However, since other widely used standards (e.g. BMK, ISO 16000-41) and previous studies have used absolute threshold values the indoor CO_2 concentrations (Section 4.2.2) were assessed in this way.

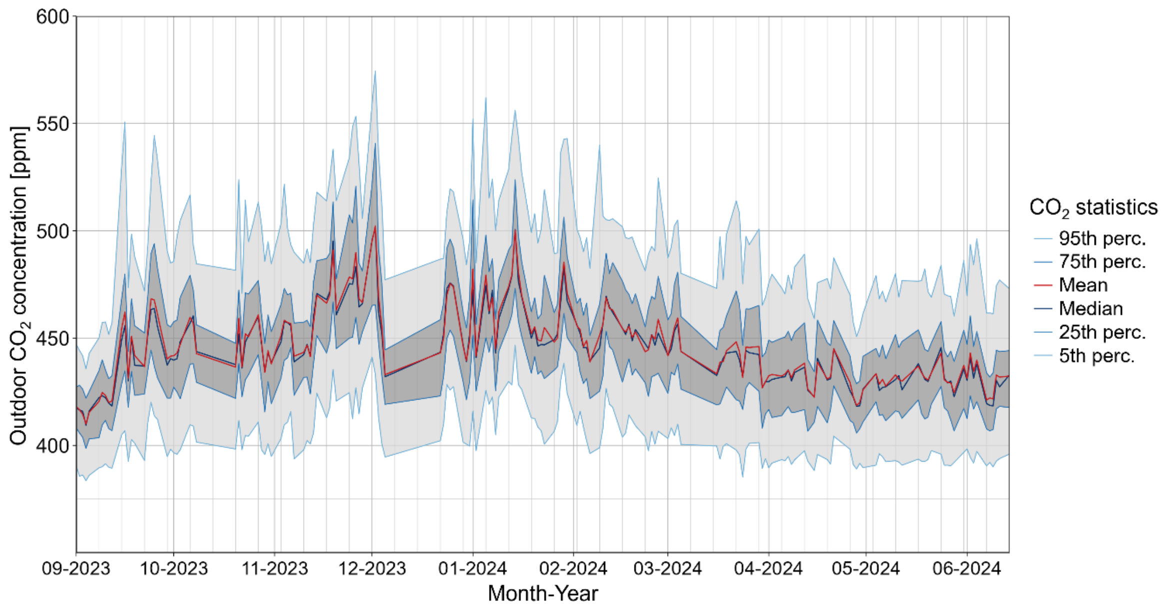


Figure 4-32. Daily mean outdoor CO_2 concentrations at the ImpAQS schools[23] for the school year 2023–24

4.3.2 Outdoor air pollutant ($PM_{2.5}$, PM_{10}, NO_2, O_3) concentrations

The nearest UBA outdoor pollutant measuring station was mapped to the corresponding school (Fig. 3-12) using expert advice from UBA Austria staff. The values shown in the following analysis can be linked to the individual schools using Tbl. A-3 in Appendix B.9. In interpreting the following data (Figs. 4-33 to 4-36) the values provided should be seen as indicative of local background concentrations in the region of the schools, since the measurements presented were not taken at the specific site of each school. Additionally, since the number of monitoring stations in the network is limited, the distance to the nearest monitoring station and prevailing wind directions should be considered when evaluating these results at the individual school level (Tbl. A-3 in Appendix B.9).

4.3.2.1 Outdoor $PM_{2.5}$ concentrations

A summary of the impacts of $PM_{2.5}$ on human health and the relevant EU and WHO thresholds are described in Section 3.7.2. In this section monitored data for the 2023–24 school year, is presented from the Federal Environmental Agency (UBA) monitoring station nearest to each school. The purpose of this analysis is to evaluate typical background levels of $PM_{2.5}$ in the region of the participating schools.

The WHO guidelines state that annual mean concentration of $PM_{2.5}$ should not exceed 5 µg/m^3. The daily (24 hour) threshold of 15 µg/m^3 also applies, at the 99th percentile of the annual distribution (equivalent to three to four exceedance days per year) (WHO, 2021b). The majority (98%) of the UBA stations in this study (with the exception of UBA station ZOE2) exceed the annual mean $PM_{2.5}$ concentration limit. In one case (UBA station 0170) the annual mean value is more than three times the air quality guideline (AQG) threshold limit. In relation to the daily limit all (100%) of the stations

[23] The CO_2 values recorded at the ImpAQS schools include altitude compensation, however the data has not been adjusted to compensate for air temperature and pressure fluctuations. This is because the air pressure measurements recorded by the devices were found to be unreliable in many cases.

show 3 or more exceedances of the AQG $PM_{2.5}$ limit value per year (Fig. 4-33). These results suggest that almost every school in the ImpAQS study (other than one school in Lower Austria, located near to the UBA station ZOE2) is likely to be exceeding the WHO $PM_{2.5}$ exposure limit. Further measurements at the site of the individual schools are needed to confirm this finding.

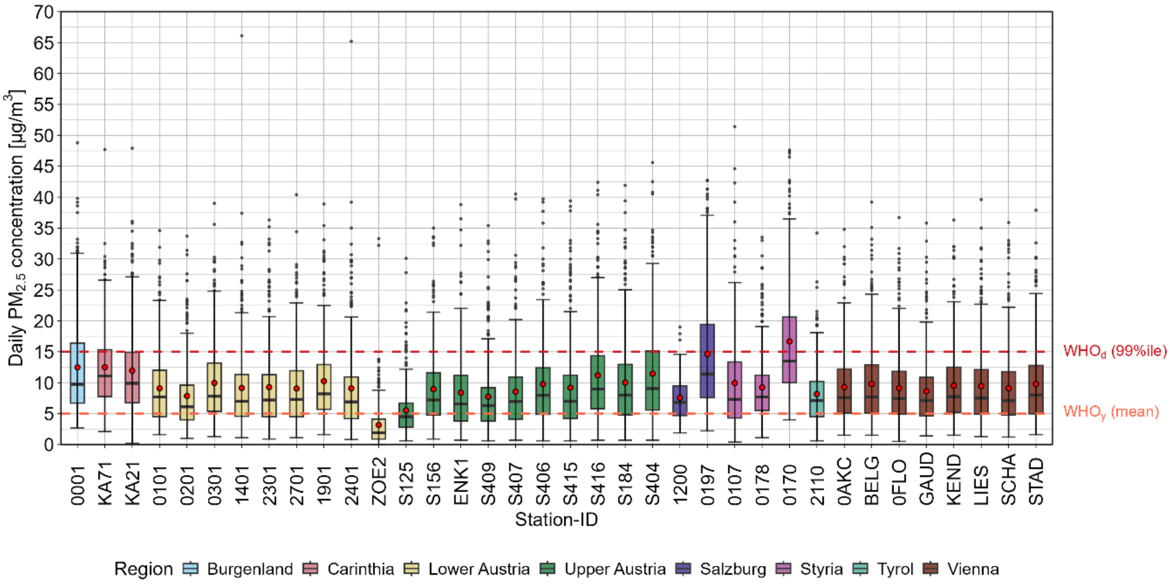


Figure 4-33. Boxplot showing annual variation in daily mean $PM_{2.5}$, concentration by nearest UBA measuring station compared to WHO daily and yearly mean AQG thresholds, red dots represent the annual mean

4.3.2.2 Outdoor PM_{10} concentrations

A summary of the impacts of PM_{10} on human health, and the relevant EU and WHO thresholds, are described in Section 3.7.3. In this section monitored data for the 2023–24 school year, taken from the nearest Federal Environmental Agency (UBA) monitoring station to each school, is presented. The purpose of this analysis is to evaluate typical background levels of PM_{10} in the region of the participating schools. The distances between schools and their respective monitoring stations are described in Tbl. A-3 in Appendix B.9.

The WHO PM_{10} annual mean AQG level is 15 µg/m³, in addition a daily (24 hour) threshold of 45 µg/m³ applies at the 99th percentile (which is equivalent to 3–4 exceedance days per year). It can be seen (Fig. 4-34) that approximately half (49%) of the stations exceed the annual mean AQG threshold. Whilst the daily AQG threshold is exceeded on more than 3 occasions by more than half (59%) of the stations. Although this represents fewer exceedances than for PM2.5, it suggests that the majority of Austrian schools are likely to exceed the WHO PM_{10} exposure limits. Further measurements at the site of the individual schools would be needed to confirm this finding.

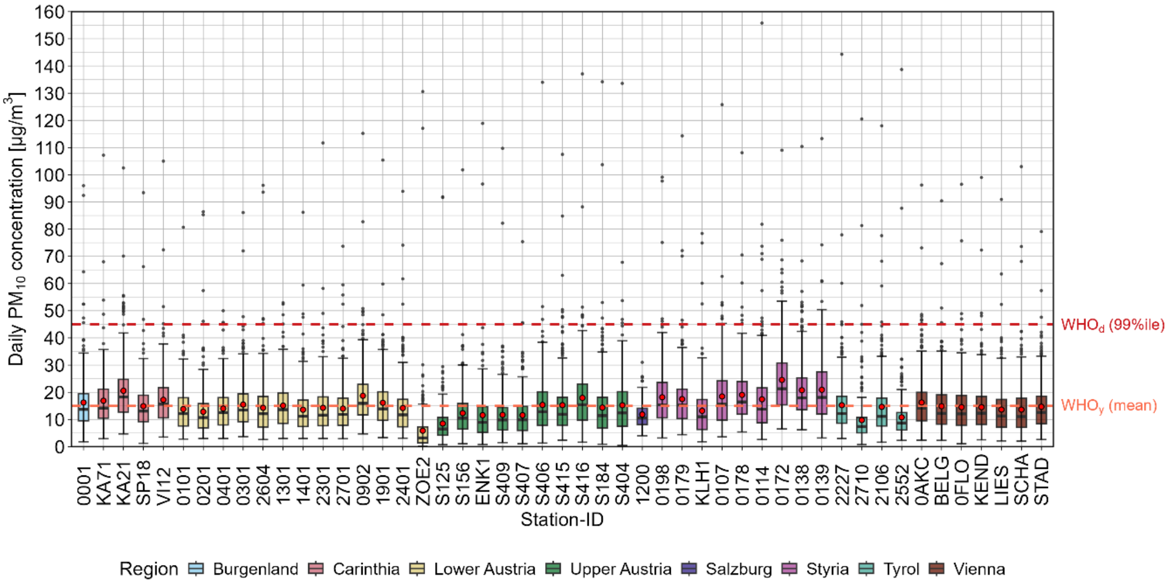


Figure 4-34. Boxplot showing annual variation in daily PM_{10}, concentration by nearest UBA measuring station compared to WHO daily and yearly mean AQG thresholds, red dots represent the annual mean

4.3.2.3 Outdoor NO_2 concentrations

A summary of the impacts of NO_2 on human health and the relevant EU and WHO thresholds are described in Section 3.7.4. In this section monitored data for the 2023–24 school year, taken from the nearest Federal Environmental Agency (UBA) monitoring station to each school, is presented. The purpose of this analysis is to evaluate typical background levels of NO_2 in the region of the participating schools. The distances between schools and their respective monitoring stations are shown in Tbl. A-3 in Appendix B.9.

Three WHO AQG level levels are provided for NO_2, an annual limit of 10 µg/m³, a daily limit of 25 µg/m³, and a one-hour limit of 200 µg/m³, wherein the daily limit applies at the 99th percentile and the annual limit as the mean value. Hourly exceedances are not reported here since measurements at this resolution need to be made at the school's precise location to ensure that short term local influences are captured. In relation to the annual mean limit of 10 µg/m³, it can be seen (Fig. 4-35) that the majority (82%) of the stations exceed the AQG threshold. Whilst the daily limit of 25 µg/m³ is exceeded at the 99th percentile by 94% of the stations. This suggests that almost every school in the study (with the exception of three schools) is likely to be exposed to NO_2 levels which are above the WHO limits. Further measurements at the site of the individual schools would be needed to confirm this finding.

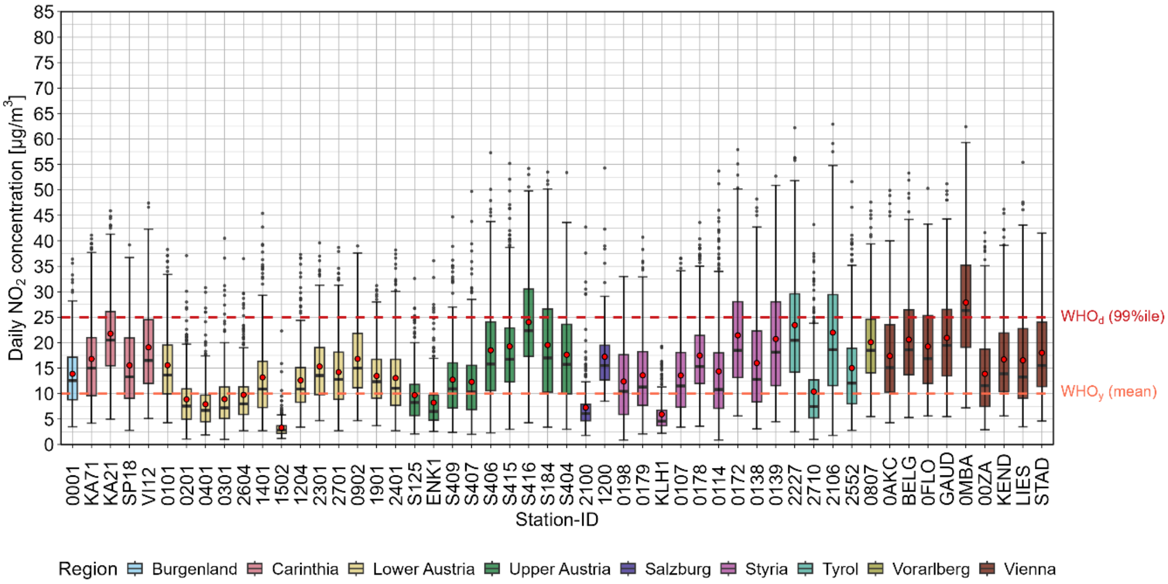


Figure 4-35. Boxplot showing annual variation in external NO_2, concentration by nearest measuring station per region compared to WHO daily and yearly mean thresholds, red dots represent the annual mean

4.3.2.4 Outdoor O_3 concentrations

A summary of the impacts of O_3 on human health and the relevant EU and WHO thresholds are described in Section 3.7.5. In this section monitored data for the 2023–24 school year, taken from the nearest Federal Environmental Agency (UBA) monitoring station to each school, is presented. The purpose of this analysis is to evaluate typical background levels of O_3 in the region of the participating schools. The distances between schools and their respective monitoring stations are shown in Tbl. A-3 in Appendix B.9.

The WHO guidelines provide two AQG thresholds for ozone: a maximum daily 8-hour mean of 100 µg/m³, assessed at the 99th percentile, and a peak season value of 60 µg/m³. The peak season value is defined as the average of the daily maximum 8-hour mean concentration in the six consecutive months with the highest six-month running average O_3 concentration. In relation to the maximum daily 8-hour mean it can be seen (Fig. 4-36) that every UBA station significantly exceeds the daily 8-hour mean of 100 µg/m³ at the 99th percentile, which suggests that all schools in the proximity to these stations would likely fail to comply with the WHO AQG limit.

To assess O_3 peak levels, the daily 8-hour maximum averages were calculated by taking the highest average concentration over any consecutive 8-hour period within each day. A 6-month running mean value is then computed for each month by averaging the daily 8-hour maximums over the current month and the previous 5 months. This assessment provides a stable, long-term view of sustained ozone exposure, and enables the identification of the peak month. Ozone levels were found to peak in September, based on the 6-month running mean (which averages the daily maximums over the warmest months from April to September). The peak values derived are considerably above the WHO peak season limit of 60 µg/m³ for all stations (Appendix C.1.3.), with 6-month moving average values ranging from 85.1 to 103.2 µg/m³ in September 2023. Therefore it can be concluded that the peak season value for O_3 is 42–72% above the WHO limit in the proximity to each school. As expected, ozone levels decline significantly during the winter months due to reduced sunlight and cooler temperatures, although only around half (55%) of all stations fall below the WHO peak season during the winter period. Further measurements, at the site of the individual schools, would be needed to confirm these findings.

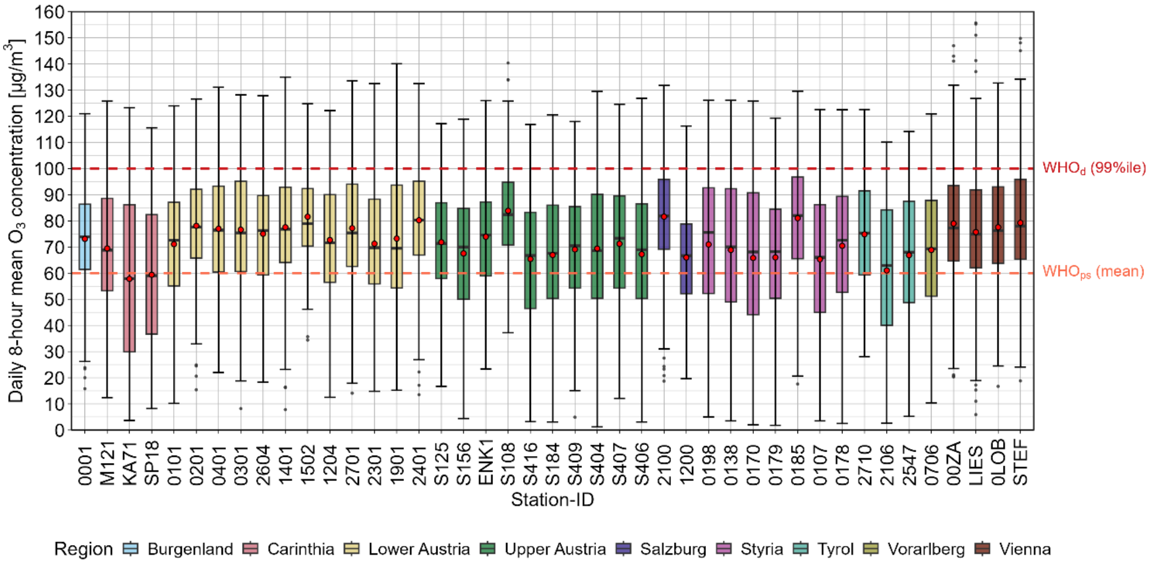


Figure 4-36. Boxplot showing annual variation in external O_3, concentration by nearest measuring station per region compared to WHO daily and peak season thresholds, red dots represent the annual mean

4.3.3 Relationship between CO_2 concentrations and outdoor and indoor temperatures

The relationship between indoor CO_2 concentrations and outdoor and indoor temperatures in Austrian classrooms is illustrated in Fig. 4-37, with data aggregated across all 120 schools to provide a single daily representation for the entire dataset. The first plot (Fig. 4-37, left) shows the association between the daily mean indoor CO_2 concentration and outdoor air temperature, with separate smooth lines for naturally and mechanically ventilated classrooms. As outdoor temperatures rise, CO_2 levels decline in classrooms using both types of ventilation. However, at lower temperatures there is a significant difference between the two ventilation types. This gap starts to become pronounced as outdoor temperatures fall below 20 °C, at which point the CO_2 levels in naturally ventilated buildings rise steeply, while the mechanically ventilated schools maintain more consistent CO_2 levels. Mechanically ventilated schools are able to maintain much lower CO_2 concentrations in winter, with a gap of over 500 ppm between the two ventilation types when daily mean outdoor temperatures fall below 5 °C. As temperatures rise towards summer, the CO_2 levels for both ventilation types converge, likely due to increased window openings during warmer periods, which create similar ventilation conditions.

In the second plot (Fig. 4-37, right), which examines the relationship between indoor CO_2 concentration and indoor temperature, a similar trend is observed, but the difference between the two ventilation types is less pronounced at warmer temperatures. This is likely because most of the warmest indoor temperatures occur during the summer when natural ventilation is better tolerated. Nonetheless, there is still a clear difference in CO_2 concentrations, particularly at lower indoor temperatures. At indoor temperatures below 22 °C, naturally ventilated classrooms show CO_2 levels that are 200–400 ppm higher than mechanically ventilated classrooms. This indicates that during the heating season mechanical ventilation systems offer a significant advantage in maintaining lower CO_2 levels, although the difference narrows as indoor temperatures increase. Overall, while mechanical ventilation is consistently better at controlling CO_2 levels, the magnitude of the difference is more pronounced during colder months. When the daily mean outside air temperature is 10 °C or lower, mechanically ventilated classrooms have on average 450–600 ppm lower daily mean CO_2 concentrations (Fig. 4-37). This finding is important in the context of Austria where the average air temperature was 9.3 degrees Celsius in 2024 (which is around 1.9 degrees above the 1991-2020 average) (Statista, 2025) and given that schools are typically closed during the warmest months (July and August).

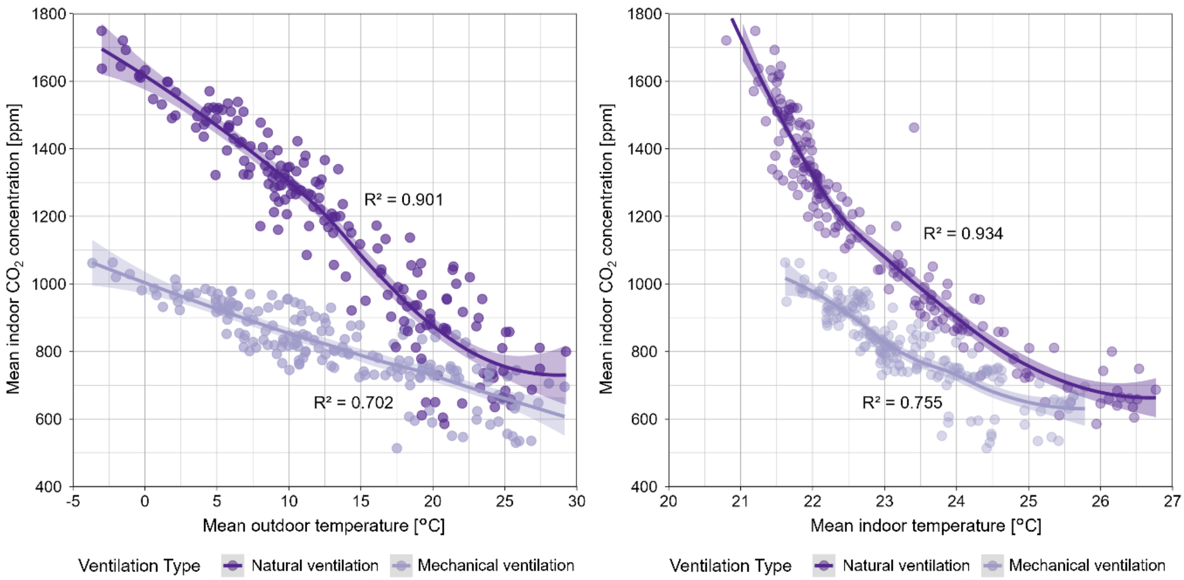


Figure 4-37 (left). Scatterplot correlation of outdoor air temperature and indoor CO_2 concentration with MV and NV, and (right) scatterplot correlation of indoor air temperature and indoor CO_2 concentration with MV and NV

4.4 Impact of CO_2 monitors and ventilation guidance on classroom ventilation outcomes

This section aims to answer **research question 3** *"Do classrooms equipped with CO_2 monitors, and basic ventilation guidance, achieve better ventilation outcomes (reduced CO_2 concentrations) than those without monitors?"*

In order to answer this question direct comparisons are made between the control and test classrooms as matched pairs (Section 3.5.4.1). This includes assessing the difference between the annual performance of the paired-classrooms as well as looking at these differences on a seasonal and monthly basis, to assess whether the benefits of visible sensors are more pronounced at certain time of the year (Section 4.4.1).

The analysis in this section focuses on the benefits of using CO_2 monitors in naturally ventilated schools. Since the occupants of mechanically ventilated classrooms typical have little or no control over the ventilation (particularly in wintertime when CO_2 concentrations are highest) including them in this comparison would skew the results. Daily and hourly data are cleaned and aggregated, as described in Section 3.4.2, to ensure a fair comparison between control and test classrooms. Specifically, a dynamic cut-off threshold (Section 3.4.2) is employed to exclude paired test and control classrooms that are likely to be unoccupied or only partially occupied.

To assess the performance of classrooms with control and test sensors, we derive two metrics that capture the signed difference and relative signed difference between the matched pairs. The metrics are defined as follows:

$$CTD = C - T \tag{4-1}$$

$$CTO = \frac{C - T}{O} \cdot 100 \tag{4-2}$$

Where C represents the CO_2 concentration of a control sensor, T denotes the CO_2 concentration of the matched test sensor, and O is the CO_2 concentration of the outdoor sensor installed in the relevant school. CTD indicates the signed difference between the matched control and test sensor, measured in ppm. Positive values indicate that the C sensor registers higher CO_2 levels compared to the matched T sensor. CTO is the percentage signed difference between the matched control and test sensor relative to the ambient outdoor CO_2 concentration, expressed as a percentage.

Matched differences are analysed in absolute term, based on the CTD metric, in Section 4.4.1, and in relative terms, based on the CTO metric, in Section 4.4.2.

Both hourly and daily data are investigated. At the hourly level, CO_2 concentrations refer to hourly mean values aggregated from the 15-min resolution data. At the daily level, CO_2 concentrations represent daily mean values aggregated from hourly data, thus encompassing the mean CO_2 levels captured by a sensor during the core classroom hours (Section 3.4.2).

First, daily data are depicted to provide an overview of the matched differences at the daily level. Then, summary statistics and statistical test results are provided for both the daily and hourly data. Since the data are not normally distributed, as confirmed by the Shapiro test (Appendix C.1.4., Tbl. A-15), the assumptions of the paired t-test are not met, therefore this parametric test could not be applied. Instead, the non-parametric Wilcoxon signed-rank test was adopted, which does not require data normality. The Wilcoxon signed-rank test is used to assess whether the median of the signed differences (CTD metric) is equal to 0 and the median of the signed relative differences (CTO metric) is equal to 0%.

4.4.1 Comparative analysis of signed differences over time (annual, seasonal and monthly)

The signed differences between matched control and test sensors at the daily level (CTD metric) are depicted in Fig 4-38. It highlights that the mean paired differences (red solid line) consistently exceed 0 ppm (red dashed line) across the school year, except during the summer months where the mean paired differences approach 0 ppm. Summary statistics (including the monthly, seasonal and yearly means) are reported in Tbl. 4-17, where the smallest monthly mean difference of 34 ppm is observed in July and the largest mean difference of 224 ppm is measured in November. Similar considerations apply to the median differences (50th percentile). The Wilcoxon signed-rank test, which is used to infer the median difference, estimates that the yearly median of the paired difference is 152 ppm (95% CI: 149 ppm to 155 ppm). As demonstrated by the low p-value, there is enough evidence to state that the yearly median of the paired differences significantly differs from 0. Additionally, median values significantly differ from zero for every season and month. The largest median value is observed in Autumn, where during the month of November it is estimated to be 225 ppm (95% CI: 216 to 234). Similar results are found in tests carried out on the hourly data, both in terms of the mean and median values, as well as the signed-rank test results (Fig. 4-39 and Tbl. 4-18). The minimum and maximum values for the hourly data indicate a range of values that is wider compared to that of the daily data, which reflects the effects of the aggregation process.

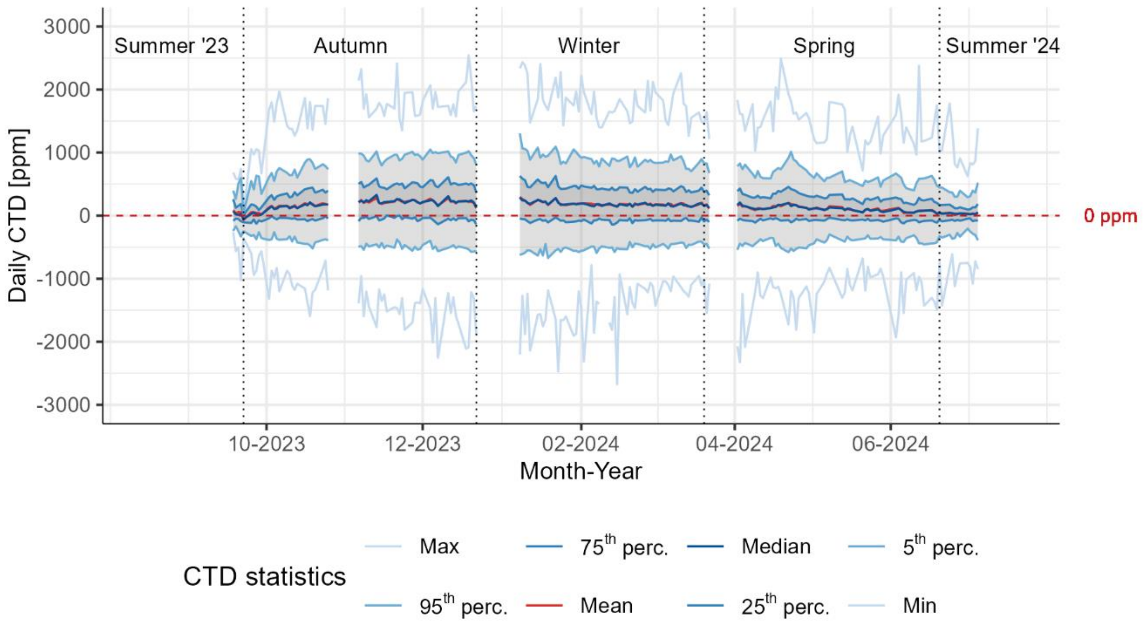


Figure 4-38. Overview of signed paired differences ($\boldsymbol{CTD}$ metric) in daily mean CO_2 concentrations, highlighting key trends and the zero ppm difference (dashed red line)

Table 4-17. Monthly, seasonal and yearly statistical summary of signed differences ($\boldsymbol{CTD}$ metric) for daily mean CO_2 concentrations, including the results of the non-parametric Wilcoxon signed-rank test, such as the p-value, the estimate of the median, and its 95% confidence interval

Month / Season / Year	Min [ppm]	Max [ppm]	Percentile [ppm] 25th	50th	75th	IQR [ppm]	Mean [ppm]	Wilcoxon signed-rank test p-value	Estimate [ppm]	95% CI [ppm]	
Sep	-1023	1054	-83	22	146	229	44	< 0.001	31	16	46
Oct	-1596	1969	-45	147	351	396	158	< 0.001	152	146	159
Nov	-1810	2414	-41	227	490	531	224	< 0.001	225	216	234
Dec	-2254	2542	-71	215	496	567	215	< 0.001	216	206	226
Jan	-2470	2434	-76	210	506	582	213	< 0.001	212	202	222
Feb	-3501	2221	-80	173	426	506	177	< 0.001	175	166	184
Mar	-1544	2259	-76	162	403	479	168	< 0.001	164	155	173
Apr	-2322	2490	-71	140	351	421	143	< 0.001	141	135	148
May	-1854	1803	-70	95	271	341	100	< 0.001	98	92	105
Jun	-1932	2379	-81	57	204	285	61	< 0.001	59	54	64
Jul	-1079	1387	-66	28	126	193	34	< 0.001	31	22	41
Summer '23	-1023	740	-64	15	160	225	49	0.007	37	9	68
Autumn	-2254	2542	-51	186	439	490	197	< 0.001	193	188	198
Winter	-3501	2434	-77	183	449	526	188	< 0.001	186	180	191
Spring	-2322	2490	-75	106	299	374	114	< 0.001	110	106	114
Summer '24	-1427	1780	-70	34	141	211	34	< 0.001	34	29	40
Year	-3501	2542	-69	142	380	449	159	< 0.001	152	149	155

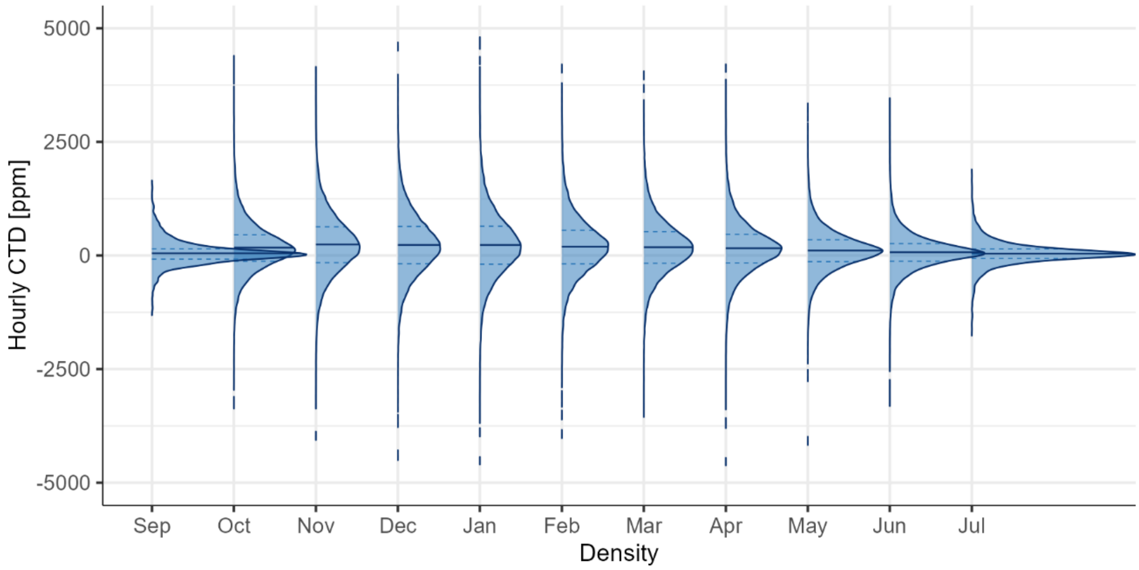


Figure 4-39. Monthly distribution of signed differences ($\boldsymbol{CTD}$ metric) for hourly mean CO_2 concentrations.

Table 4-18. Monthly, seasonal and yearly statistical summary of signed differences ($\boldsymbol{CTD}$ metric) for hourly mean CO_2 concentrations, including the results of the non-parametric Wilcoxon signed-rank test, such as the p-value, the estimate of the median, and its 95% confidence interval

Month / Season / Year	Min [ppm]	Max [ppm]	Percentile [ppm]			IQR [ppm]	Mean [ppm]	Wilcoxon signed-rank test			
			25th	50th	75th			p-value	Estimate [ppm]	95% CI [ppm]	
Sep	-1163	1492	-79	24	148	227	49	< 0.001	33	23	43
Oct	-3287	4311	-128	149	455	583	174	< 0.001	161	157	166
Nov	-3964	4046	-157	225	632	789	244	< 0.001	236	230	241
Dec	-4422	4592	-182	216	640	822	233	< 0.001	226	219	232
Jan	-4521	4715	-191	216	645	836	232	< 0.001	225	219	231
Feb	-3924	4110	-184	185	555	739	195	< 0.001	188	182	194
Mar	-3466	3961	-171	171	525	696	183	< 0.001	176	170	182
Apr	-4529	4125	-163	148	466	629	160	< 0.001	152	148	157
May	-4081	3264	-135	103	347	481	109	< 0.001	105	101	109
Jun	-3227	3368	-127	62	264	391	72	< 0.001	67	64	70
Jul	-1620	1755	-63	32	144	207	43	< 0.001	37	32	42
Summer '23	-1023	1492	-60	19	150	210	46	< 0.001	35	17	53
Autumn	-4422	4592	-150	190	570	720	217	< 0.001	205	202	208
Winter	-4521	4715	-184	192	582	766	206	< 0.001	198	195	202
Spring	-4529	4125	-148	113	388	536	127	< 0.001	119	116	121
Summer '24	-2120	2816	-91	38	172	263	41	< 0.001	40	37	43
Year	-4529	4715	-154	146	493	647	177	< 0.001	163	162	165

4.4.2 Comparative analysis of signed relative differences over time (annual, seasonal and monthly)

The signed differences relative to the outdoor CO_2 concentrations (CTO metric) on a daily basis are depicted in Fig. 4-40. The 25th percentile trend remains close to 0% (red dashed line) throughout the school year, indicating that 75% of the time, the relative differences between matched control and test sensors are close to or greater than 0%. Table 4-19 summarizes the statistical outcomes of the daily data analysis. It shows that a mean CTO value of 50% is observed in November, signifying that the mean signed difference amounts to 50% of the outdoor CO_2 levels. Therefore, for an outdoor CO_2 concentration of 420 ppm, the mean $C - T$ difference corresponds to 210 ppm. It is also important to note that from November to January, the 75th percentile values exceed 100%, highlighting that 25% of the observations (the upper tail of the CTO distribution) have control and test differences that are twice the outdoor CO_2 levels. Figure 4-41 depicts and Tbl. 4-20 summarises the results of the analysis of the hourly data. Here, the CTO metric reaches values of up to 55% (mean) and 141% (75% percentile) in November.

Statistical tests indicate that the median CTO value is 36% throughout the school year and significantly different from 0%. Similarly, there is enough evidence to state that the median CTO value is statistically different from 0% for each season and month.

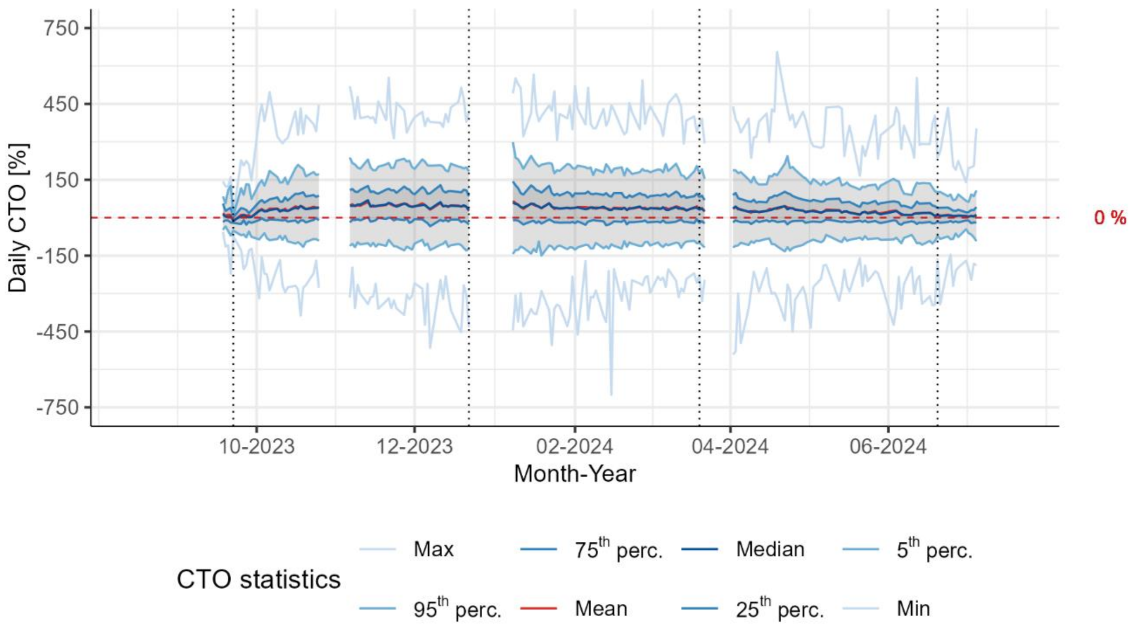


Figure 4-40. Overview of signed relative differences (CTO metric) in daily mean CO_2 concentrations, highlighting key trends and the 0% value (dashed red line)

Table 4-19. Monthly, seasonal and yearly statistical summary of signed relative differences (CTO metric) for daily mean CO_2 concentrations, including the results of the non-parametric Wilcoxon signed-tank test, such as the p-value, the estimate of the median, and its 95% confidence interval

Month / Season / Year	Min [%]	Max [%]	Percentile [%] 25th	50th	75th	IQR [%]	Mean [%]	Wilcoxon signed-rank test p-value	Estimate [%]	95% CI [%]	
Sep	-222	227	-17	5	31	48	9	< 0.001	7	3	10
Oct	-388	497	-10	33	79	89	36	< 0.001	34	33	36
Nov	-385	555	-9	51	109	118	50	< 0.001	50	48	52
Dec	-515	514	-15	46	106	121	46	< 0.001	46	44	48
Jan	-504	566	-16	45	109	126	46	< 0.001	46	44	48
Feb	-779	543	-17	38	93	110	39	< 0.001	38	36	40
Mar	-331	488	-17	36	89	106	37	< 0.001	36	34	38
Apr	-541	655	-16	32	81	97	33	< 0.001	33	31	34

May	-436	439	-16	22	63	79	24	< 0.001	23	22	25
Jun	-445	553	-19	13	47	66	14	< 0.001	14	12	15
Jul	-246	353	-15	7	30	46	8	< 0.001	7	5	10
Summer '23	-222	160	-14	3	34	48	10	< 0.001	8	2	14
Autumn	-515	555	-11	41	97	108	43	< 0.001	42	41	44
Winter	-779	566	-17	40	98	115	41	< 0.001	41	39	42
Spring	-541	655	-17	24	69	86	26	< 0.001	25	25	26
Summer '24	-344	434	-17	8	33	50	8	< 0.001	8	7	9
Year	-779	655	-15	32	85	100	36	< 0.001	34	33	35

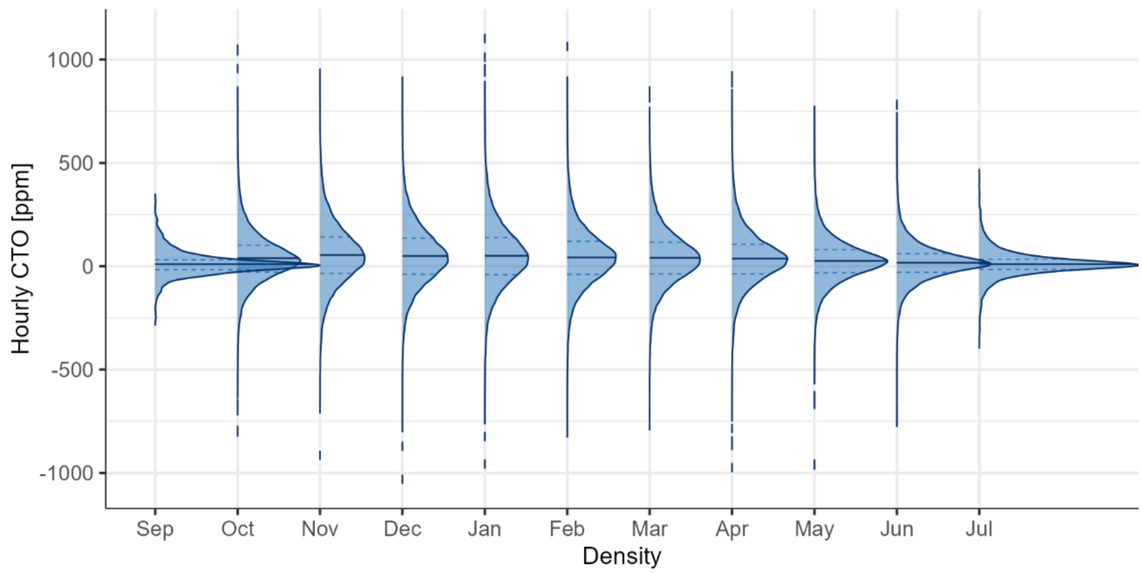


Figure 4-41. Monthly distribution of signed relative differences ($\boldsymbol{CTO}$ metric) for hourly CO_2 concentrations

Table 4-20. Monthly, seasonal and yearly statistical summary of signed relative differences ($\boldsymbol{CTO}$ metric) for hourly CO_2 concentrations, including the results of the non-parametric Wilcoxon signed-tank test, such as the p-value, the estimate of the median, and its 95% confidence interval

Month / Season / Year	Min [%]	Max [%]	Percentile [%] 25th	50th	75th	IQR [%]	Mean [%]	Wilcoxon signed-rank test p-value	Estimate [%]	95% CI [%]	
Sep	-248	313	-17	5	31	48	10	< 0.001	7	5	9
Oct	-797	1050	-28	33	101	129	39	< 0.001	36	35	37
Nov	-915	935	-35	50	141	176	55	< 0.001	53	51	54
Dec	-1030	895	-39	46	135	174	50	< 0.001	48	46	49
Jan	-958	1102	-41	46	139	180	50	< 0.001	49	47	50
Feb	-804	1064	-39	40	121	160	43	< 0.001	41	40	42
Mar	-772	846	-38	38	116	154	41	< 0.001	39	38	40
Apr	-973	924	-37	34	106	144	37	< 0.001	35	34	36
May	-959	749	-31	24	81	112	26	< 0.001	24	24	25
Jun	-753	782	-29	14	61	90	17	< 0.001	15	15	16
Jul	-369	440	-15	8	34	49	10	< 0.001	9	8	10
Summer '23	-222	313	-13	4	32	45	10	< 0.001	7	4	11
Autumn	-1030	1050	-33	42	125	158	48	< 0.001	45	44	46
Winter	-958	1102	-40	42	127	167	45	< 0.001	43	43	44
Spring	-973	924	-34	26	89	123	30	< 0.001	27	27	28
Summer '24	-507	718	-21	9	40	62	10	< 0.001	9	9	10
Year	-1030	1102	-34	33	109	144	39	< 0.001	36	36	37

4.5 Impact of indoor air quality on airborne disease risk

This section aims to answer **research question 4** *Does improving indoor air quality (in classrooms equipped with CO_2 monitors) provide a statistically significant advantage in terms of reducing the risk of airborne disease infection?*

In the absence of continuous testing for SARS-CoV-2, Influenza-A, Measles and other airborne diseases information to answer this question must be drawn from analytical models and statistical inference. The influence of occupancy and ventilation on the long-range airborne transmission risk of SARS-CoV-2 is investigated using an analytical model (Section 4.5.1). By subsequently coupling this model to the individual classroom ventilation rates the temporal variation in the relative infection risk in individual classrooms is explored (Section 4.5.2). Finally the relationship between the absenteeism and environmental variables (such as the CO_2 concentration and ventilation rate) is assessed along with the relationship between absenteeism and the community prevalence of SARS-CoV-2 (using national waste-water data) (Section 4.5.3).

4.5.1 Airborne infection risks and ventilation

The following section aims to provide an analysis of the risk of long-range airborne transmission of SARS-CoV-2 using an analytical model developed by researchers from the Max Planck Institute for Chemistry (MPIC), Germany, and the Cyprus Institute, Cyprus (Lelieveld et al., 2020).

In this analysis the group infection risk is assessed under varying conditions of occupancy, ventilation rates, and exposure duration. In this context, the term ‘group risk’ refers to the probability that at least one person within a group will become infected, through airborne viral transmission, assuming the presence of one infectious person in the room. The model used here was parameterised to model the transmission characteristics of the original Omicron variant of SARS-CoV-2 under the assumption of a well-mixed air volume, with uniform viral concentration throughout the space. The analysis does not include short-range transmission, or fomite transmission from surfaces and therefore the overall risk could be considerably higher than the modelled analysis suggests.

4.5.1.1 Influence of occupancy and ventilation on long-range airborne transmission risk

Figure 4-43 shows the relationship between group infection risk and occupancy over varying exposure durations (ranging from 0–10 h) under a constant ventilation rate of 250 l/s. For 25 occupants this results in a ventilation rate of 10 l/(s·person) corresponding to IEQ class I, as defined by EN 16798-1:2019 (CEN, 2019). The results demonstrate a rising risk of infection with increasing occupancy and time of exposure. For example, teaching a small group of 15 people over a 6-hour period results in a group infection risk of about 35%. In contrast, a larger group of 30 people under the same conditions results in a risk of about 60%.

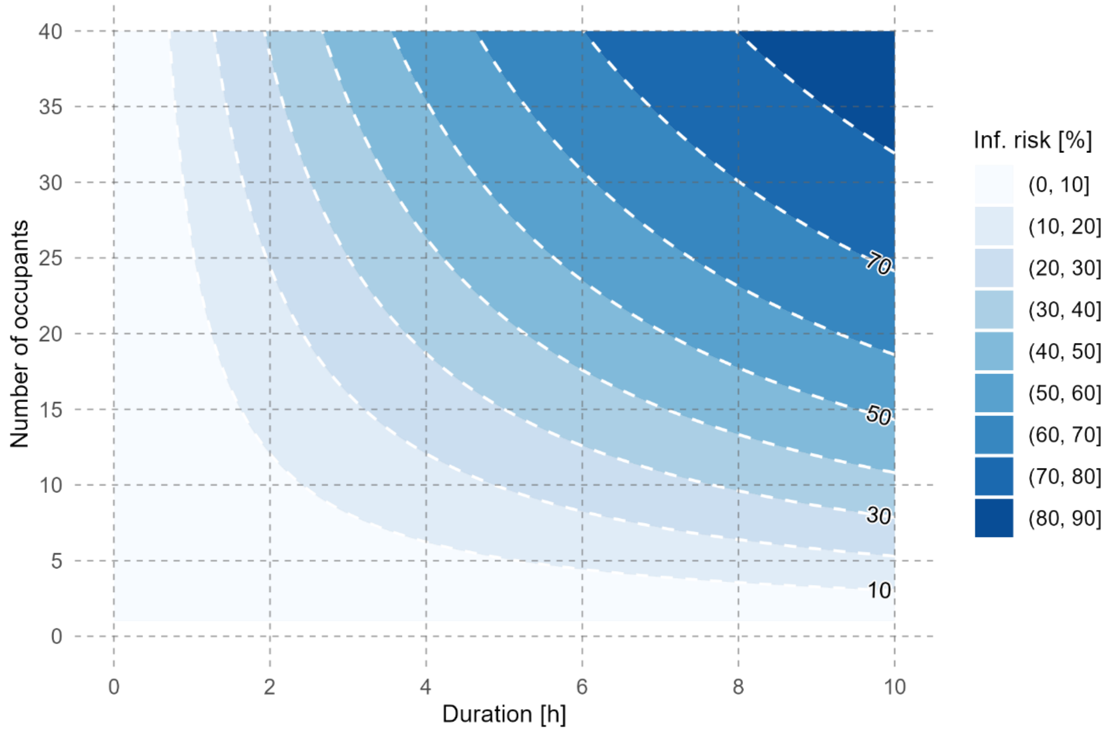


Figure 4-42. Example showing group infection risk (SARS-CoV-2) vs. exposure time (for a ventilation rate of 10 l/(s·person))

The group infection risk as a function of the ventilation rate and exposure duration is shown in Fig. 4-43, assuming a constant room occupancy of 25 people. The plot illustrates how higher ventilation rates lead to a reduction in the airborne infection risk.

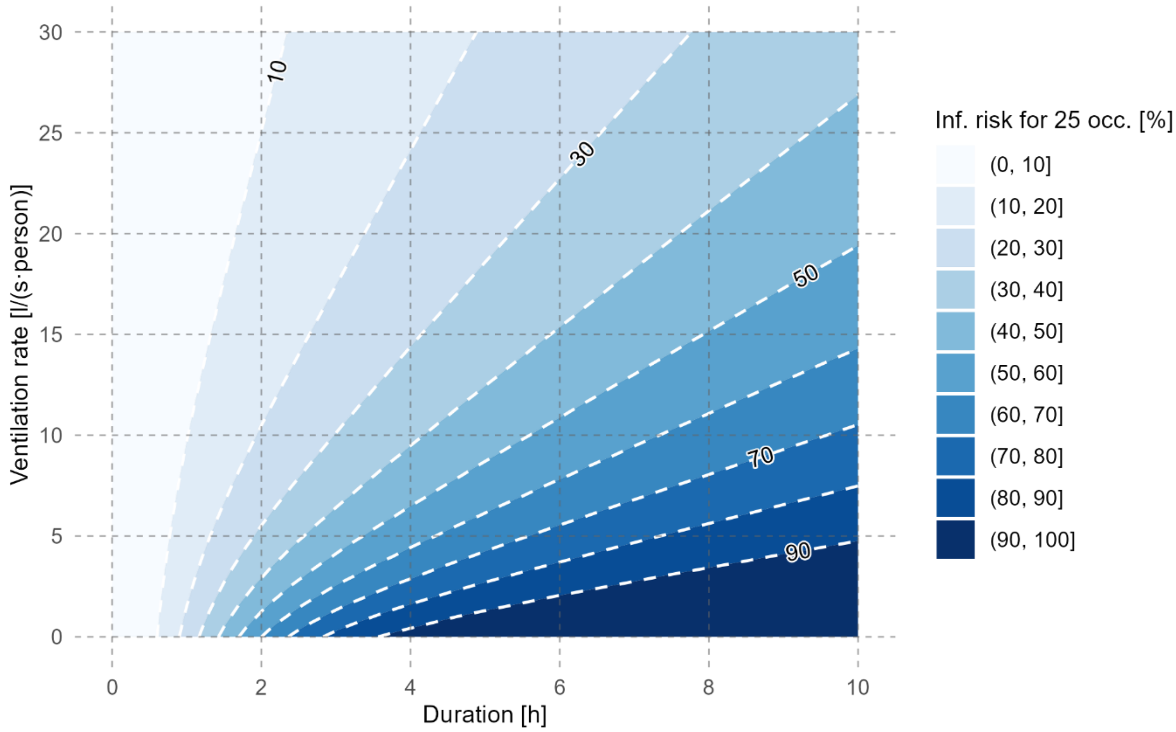


Figure 4-43. Example showing long-range airborne transmission risk (SARS-CoV-2) under different ventilation airflow rates

For example, category IEQ_{III} from EN 16798-1:2019 (CEN, 2019), with an airflow rate of 4 l/(s·person) results in a group infection risk of around 74 % after 6 hours of exposure. Whilst category IEQ_{II}, with 7 l/(s·person) reduces the risk to 60% and category IEQ_{I}, at 10 l/(s·person), further reduces the risk to 50%. In comparison, the Lancet Commission's Non-infectious Air Delivery Rates (NADR) recommendation of 14 l/(s·person) lowers the group infection risk to 43% (The Lancet COVID-19 Commission, 2022), and the ASHRAE Standard 241:2023 recommendation, for the control of infectious aerosols, of 20 l/(s·person) reduces the risk to 32%.

To illustrate the connection between CO_2 concentrations, ventilation and infection risk: assuming a standard CO_2 emission rate of 20 l/(h·person), as defined in EN 16798-1:2019 (CEN, 2019) and CEN/TR 16798-2:2019 (CEN, 2019), the corresponding equilibrium CO_2 concentrations for the above mentioned ventilation rates would result in approximately 1810 ppm for 4 l/(s·person), 1210 ppm for 7 l/(s·person), 980 ppm for 10 l/(s·person), 820 ppm for 14 l/(s·person) and 700 ppm for 20 l/(s·person). However, note that in a school context, the CO_2 emission rate from younger occupants may be lower than 20 l/(h·person) ranging from 11.16 l/(h·person) for primary school students to 15.55 l/(h·person) for secondary school students (Section 3.4.1).

These results illustrate that increasing ventilation in indoor spaces is a key measure in minimizing the risk of airborne disease transmission. Moreover, Figs. 4-42 and 4-43 show that a reduction in the time of exposure further lowers the infection risk, highlighting the importance of both sufficient ventilation and shorter exposure durations in controlling airborne disease transmission.

4.5.2 Temporal variation of infection risk derived from CO_2 monitoring data

Seasonal trends in the modelled daily mean group infection risk rate, in the 1200 ImpAQS classrooms, are analysed in the following section. The group infection risk is calculated using the infection risk model (Section 3.8) coupled with the daily mean ventilation rate for each classroom (Section 3.4.1). A reference scenario is provided by way of a comparator based on a constant ventilation rate of 10 l/(s·person) for 25 occupants, which results in a 52% risk that at least one person will become infected with SARS-CoV-2 (with an assumed exposure duration of 6 h per day). It should be noted that the reference scenario described here is intended to model a 'peak wave scenario' and not a typical day and is based on an approach described in the Positionspapier zur Bewertung von Innenräumen in Hinblick auf das Infektionsrisiko durch SARS-CoV-2 (BMK, 2021), see Appendix B.11 for more information.

4.5.2.1 Infection risk in classrooms

The hypothetical daily average individual infection risk for the 1200 ImpAQS classrooms (from September 2023 to July 2024) is shown in Fig. 4-44. This data is derived from the ventilation rate coupled infection risk model, which is then compared to a reference scenario.

The black line represents the average daily group infection risk across all 1200 classrooms, assuming an occupancy of 25 people. The grey ribbon indicates the interquartile range (25^{th} to 75^{th} percentiles) of the daily mean group infection risks. The dashed red line represents the reference scenario.

Similarly to the ventilation rate data (Section 3.4.1), the infection risk follows a seasonal pattern, with higher risk in colder months and lower risk in warmer months. From autumn to winter, there is a clear increase in the group infection risk across all 1200 classrooms, with daily values ranging from approximately 50% to 75%. This rise in infection risk is closely linked to the reduced ventilation rates during colder weather. Conversely, the group infection risk decreases significantly approaching summer. From June to July, the group infection risk mostly falls below the reference scenario (based on a constant ventilation rate of 10 l/(s·person)), reflecting improved ventilation rates as outdoor temperatures increase.

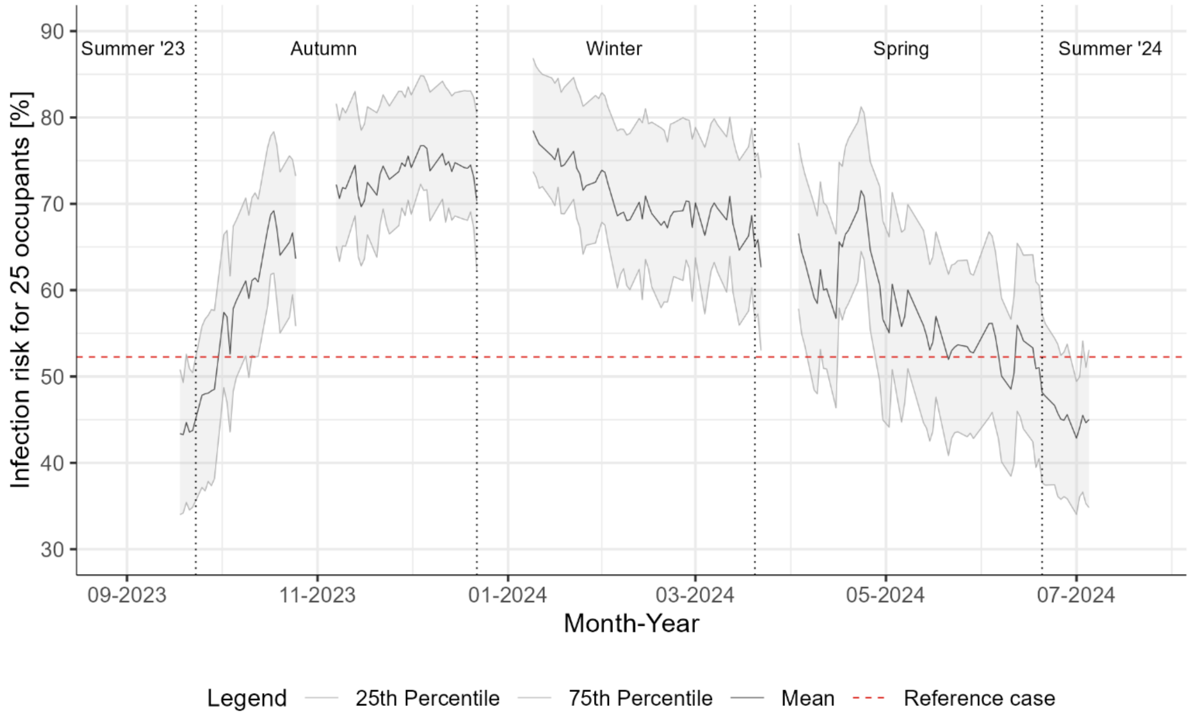


Figure 4-44. Time series - hypothetical mean group infection risk and percentiles of all classrooms over 2023–24 school year

4.5.2.2 Infection risk by season

The probability density function of the hypothetical infection risk by season is shown in Fig. 4-45, and Tbl. 4-21 presents the statistics of the group infection risk across various seasons, based on the daily ventilation conditions occurring across the school year, from September to July.

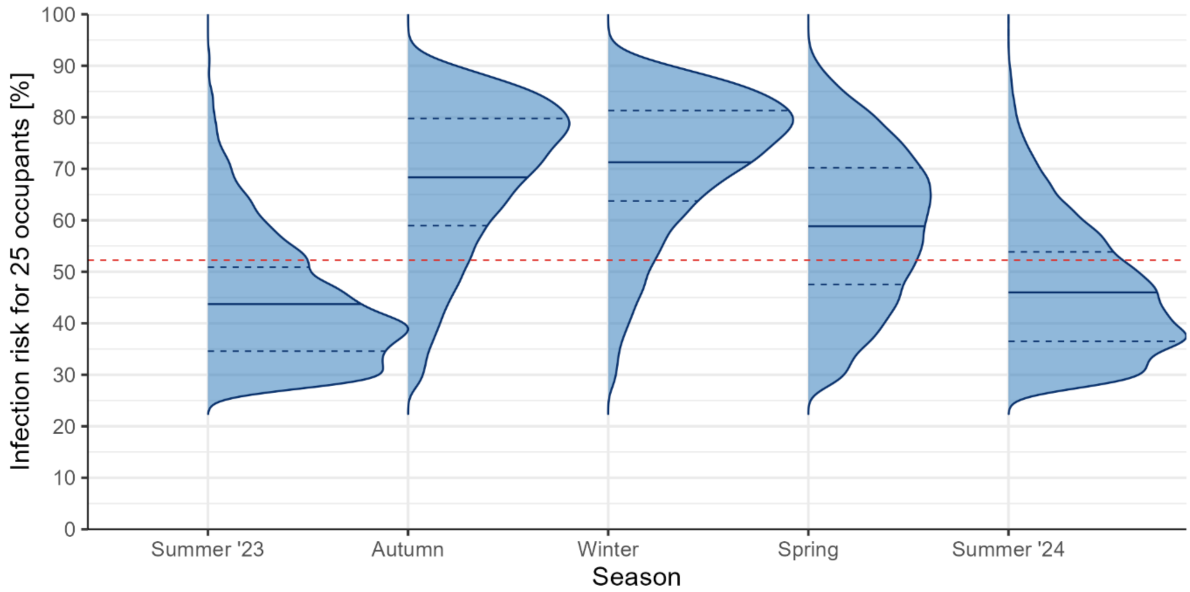


Figure 4-45. Seasonal distribution of the airborne infection risk for all classroom (assuming 25 occupants) compared to a reference scenario with EN 16798-1 threshold (10 l/(s·person), IEQ_1, dotted red line). The solid line within each distribution indicates the mean, whereas the dashed lines indicate the 25th and 75th percentiles.

The 75th percentile shows that the majority of classrooms exhibit a group infection risk higher than 70%, which greatly exceeds the reference risk level of 52%, calculated for a ventilation rate of 10 l/(s·person). In winter the mean infection risk in all 1200 classrooms is 71% with 89% of classrooms exceeding the reference scenario. In contrast, Summer '24 shows a significant reduction in the infection risk, with a mean of 44% and only 22% of classrooms exceeding the reference scenario. The mean infection risk across all classrooms and all seasons is 65%, indicating that, on average the risk of at least one person becoming infected in a classroom exceeds the reference scenario[24].

Table 4-21. Seasonal statistics of infection risk for a classroom with 25 occupants including percentage of reference case exceedances

Season	Min	Max	Percentile 25	Percentile 50	Percentile 75	Mean	Exceedance > Ref. Scen.
	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Summer '23	27	92	35	41	51	44	22
Autumn	27	96	59	71	80	68	84
Winter	27	95	64	74	81	71	89
Spring	27	95	48	59	70	59	66
Summer '24	27	91	36	44	54	46	28
Year	27	96	54	68	78	65	77

[24] It should be noted that the infection risks calculated here are hypothetical, since they assume that one infectious person is present in each classroom. This level of risk is unlikely to occur in reality other than for relatively brief periods at the peak of an infection wave.

4.5.2.3 Infection risk according by classroom category (C or T)

The daily mean infection risk recorded by the classrooms with control sensors (C) tend to be slightly higher than those measured by the classrooms with test sensors (T), particularly during the colder months. The seasonal distributions in Figure 4-46 and Table 4-22 reveal relatively modest differences between the control and test sensors, with the reference case exceedance frequencies differing by a few percentage points.

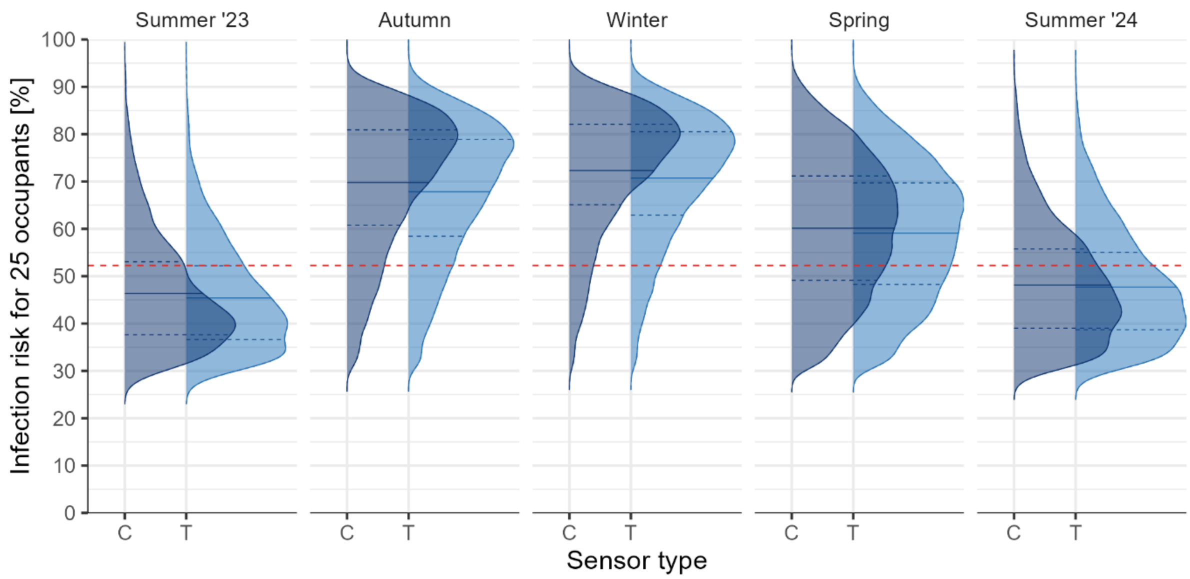


Figure 4-46. Seasonal distribution of infection risk for a classroom with 25 occupants for Test (T) and Control (C) sensors separately including reference scenario with EN 16798-1 standard threshold (10 l/(s·person), IEQ1, dotted red line). The solid line within each distribution indicates the mean, whereas the dashed lines indicate the 25th and 75th percentiles.

In winter, classrooms with control sensors show a mean value of the daily infection risk of 72% (which exceeds the reference scenario) compared to 70% for the rooms with test sensors. The lowest overall infection risks are seen in the summer months, where the average ventilation rates are comparable between control and test sensors: Summer '24 exhibits an average daily mean infection risk of 46% for classrooms with control sensors and test sensors respectively. However, as noted earlier, this analysis does not account for other compounding factors that could influence the differences in ventilation rates found between classrooms with and without visible CO_2 sensor (including partial occupancy and ventilation system type) which are explored in more detail in Section 4.4.

Table 4-22. Seasonal statistics of infection risk for a classroom with 25 occupants including percentage of reference case exceedances for classrooms with Test (T) and Control (C) sensors separately

Season	Sensor - type	Min	Max	Percentile 25	Percentile 50	Percentile 75	Mean	Exceedance > Ref. Scen.
		[%]	[%]	[%]	[%]	[%]	[%]	[%]
Summer '23	C	27	92	35	41	51	44	23
	T	27	91	34	41	51	43	22
Autumn	C	27	95	60	73	81	69	85
	T	27	96	58	70	79	67	83
Winter	C	27	95	65	75	82	72	90
	T	27	95	63	73	80	70	89
Spring	C	27	95	48	60	71	59	67
	T	27	94	47	59	69	58	65
Summer '24	C	27	91	36	44	54	46	29
	T	27	90	36	44	53	46	27
Year	C	27	95	54	69	79	66	78
	T	27	96	53	67	77	64	76

4.5.2.4 Infection risk according to ventilation system type

The seasonal distributions of the infection risk between mechanically ventilated (MV) and naturally ventilated (NV) classrooms are shown in Figure 4-47 and the corresponding Table 4-23. Table 4-23Overall the data (Tbl. 4-23) indicate that the mean infection risk in NV classrooms is consistently higher than in MV classrooms. Additionally, NV classrooms exhibit greater variability in their infection risk level, particularly during colder months.

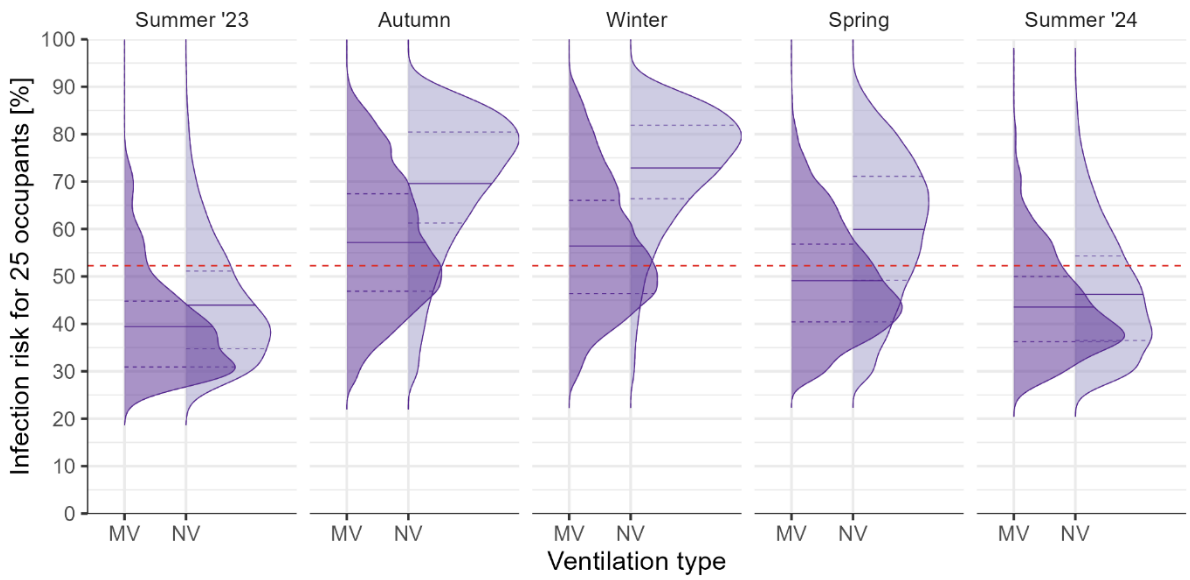


Figure 4-47. Seasonal distribution of infection risk for a classroom with 25 occupants for mechanical (MV) and natural (NV) ventilation separately, including a reference scenario with EN 16798-1 threshold (10 l/(s·person), IEQ_I, dotted red line). The solid line within each distribution indicates the mean, whereas the dashed lines indicate the 25th and 75th percentiles.

Table 4-23. Seasonal statistics of infection risk for a classroom with 25 occupants including percentage of reference case exceedances for mechanical (MV) and natural (NV) ventilation separately.

Season	Vent.-type	Min	Max	Percentile 25	50	75	Mean	Exceedance > Ref. Scen.
		[%]	[%]	[%]	[%]	[%]	[%]	[%]
Summer '23	MV	27	73	31	37	45	39	12
	NV	27	92	35	41	51	44	23
Autumn	MV	27	91	47	56	67	57	59
	NV	27	96	61	73	80	70	87
Winter	MV	27	92	46	55	66	56	57
	NV	27	95	66	75	82	73	93
Spring	MV	27	91	40	48	57	49	36
	NV	27	95	49	61	71	60	69
Summer '24	MV	27	81	36	41	50	44	20
	NV	27	91	36	44	54	46	29
Year	MV	27	92	44	52	63	54	50
	NV	27	96	56	69	79	66	80

4.5.2.5 Infection risk according to school type

The seasonal distribution of group infection risks across various school types are compared in Fig. 4-48 and Tbl. 4-24. The data shows a consistent pattern, as observed in previous analyses, with higher infection risks in colder months and lower risks during warmer periods. The differences in daily group infection risk across various school types are most pronounced in winter, with reductions during the summer months. Overall, most school types display similar group infection risks, with SS schools showing comparatively lower risks in winter and VS schools experiencing slightly higher risks in summer.

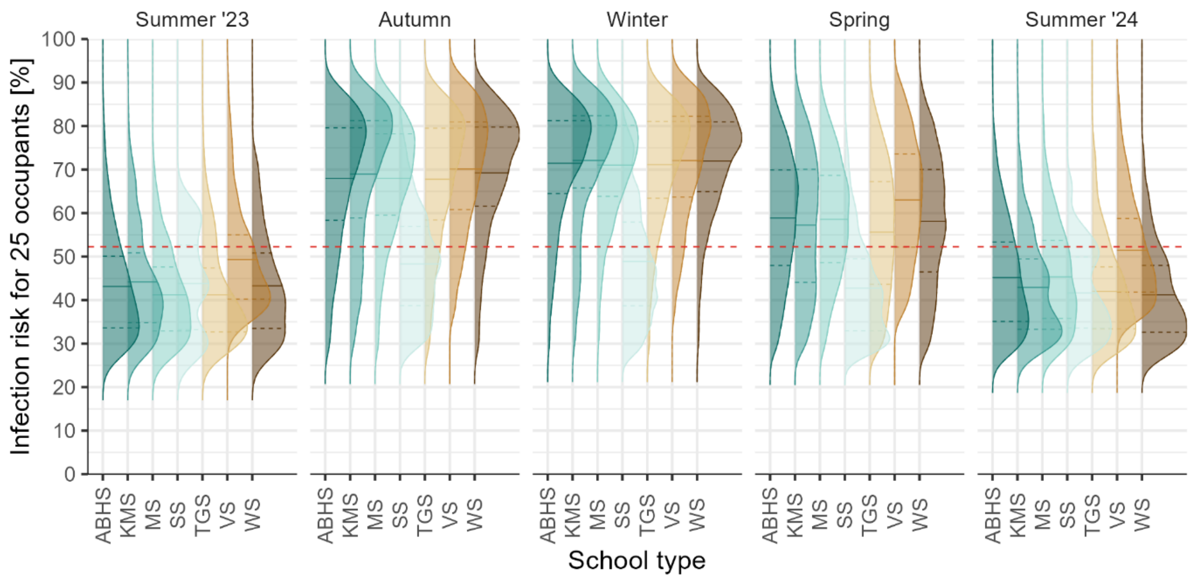


Figure 4-48. Seasonal distribution of infection risk for a classroom with 25 occupants for different school types separately including reference scenario with EN 16798-1 standard threshold (10 l/(s·person), IEQ_I, dotted red line). The solid line within each distribution indicates the mean, whereas the dashed lines indicate the 25th and 75th percentiles.

In winter, the average value of the daily mean group infection risk ranges from 71 to 72% for school types such as ABHS, KMS, MS, TGS, VS, and WS, whereas classrooms in SS schools show a much lower daily average risk of 49%, as a result of their better ventilation rates. By summer 2024, these values converge, with the average of the daily mean values ranging between 41 to 45% for ABHS, KMS, MS, SS, TGS, and WS schools. However, classrooms in VS schools exhibit slightly more elevated infection risks, with an average value of 51% during the summer.

Table 4-24. Seasonal statistics of the infection risk for a classroom with 25 occupants, including the percentage of reference case exceedances for different school types.

Season	School type	Min	Max	Percentile 25	Percentile 50	Percentile 75	Mean	Exceedance > Ref. Scen.
		[%]	[%]	[%]	[%]	[%]	[%]	[%]
Summer '23	ABHS	27	85	34	40	50	43	21
	KMS	27	91	35	41	51	44	25
	MS	27	71	33	40	48	41	17
	SS	27	63	33	43	53	44	27
	TGS	27	80	33	38	47	41	18
	VS	35	92	40	46	55	49	32
	WS	27	85	33	41	51	43	21
Autumn	ABHS	27	95	58	71	80	68	83
	KMS	28	95	59	73	81	69	82
	MS	27	94	60	70	78	68	87
	SS	28	81	39	48	57	48	36
	TGS	27	94	58	71	80	68	83
	VS	35	96	61	72	81	70	88
	WS	27	93	62	72	80	69	87
Winter	ABHS	27	95	64	74	81	71	90
	KMS	27	95	66	76	82	72	88
	MS	27	94	64	73	80	71	92
	SS	27	81	39	47	58	49	36
	TGS	27	94	63	74	81	71	90
	VS	35	95	64	74	82	72	90
	WS	27	94	65	75	81	72	93
Spring	ABHS	27	94	48	60	70	59	67
	KMS	27	94	44	58	70	57	60
	MS	27	93	49	59	69	59	67
	SS	27	82	33	41	50	43	20
	TGS	27	92	44	56	67	56	58
	VS	35	95	52	63	74	63	75
	WS	27	93	46	59	70	58	65
Summer '24	ABHS	27	89	35	43	53	45	28
	KMS	27	88	33	41	49	43	20
	MS	27	86	36	44	54	45	28
	SS	28	67	34	39	50	42	18
	TGS	28	80	33	40	48	42	17
	VS	35	91	42	49	59	51	41
	WS	27	74	33	38	48	41	15
Year	ABHS	27	95	54	68	78	65	77
	KMS	27	95	52	69	79	65	75
	MS	27	94	54	66	76	64	78
	SS	27	82	37	45	55	47	31
	TGS	27	94	52	67	77	64	75
	VS	35	96	57	69	79	67	82
	WS	27	94	55	69	78	66	79

4.5.2.6 Infection risk according to region

The seasonal distribution of infection risks across different regions is compared in Fig. 4-49 and the corresponding Table 4-25. The data reveal seasonal variations, with the highest infection risks generally observed during the colder months with significantly lower risks occurring during the summer.

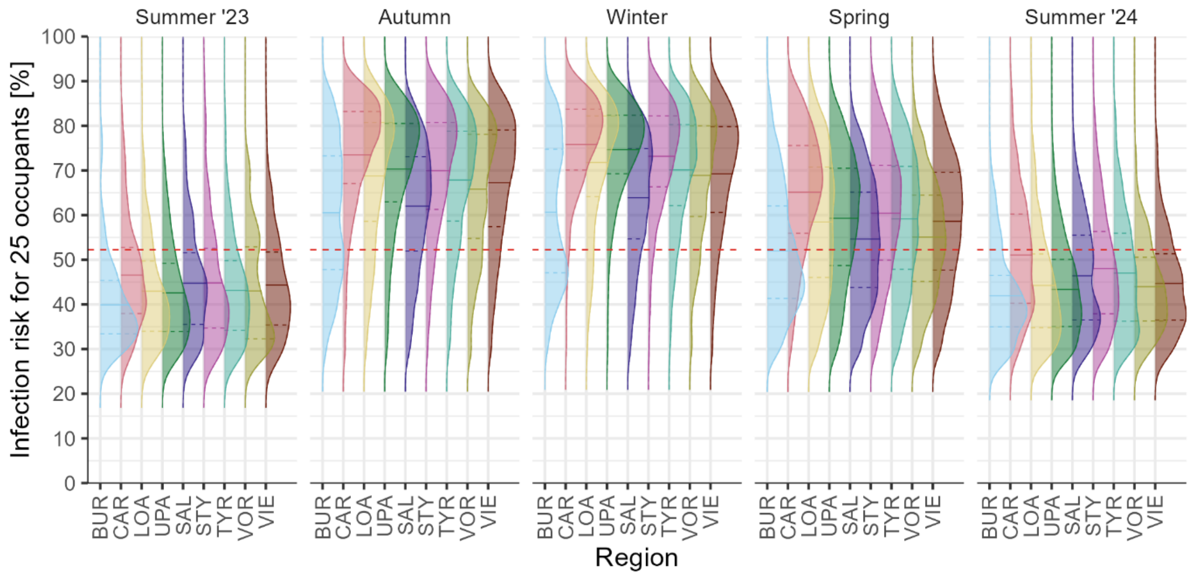


Figure 4-49. Seasonal distribution of infection risk for a classroom with 25 occupants for different regions separately including reference scenario with EN 16798-1 threshold (10 l/(s·person), IEQ1, dotted red line). The solid line within each distribution indicates the mean, whereas the dashed lines indicate the 25th and 75th percentiles.

In winter, the highest value of the mean daily infection risk is seen in Carinthia, with an average risk of 76% and classrooms exceeding the reference scenario threshold 96% of the time. In contrast, classrooms in Burgenland perform the best, with a mean daily risk value of 61% and classrooms exceeding the risk of the reference scenario 62% of the time, indicating relatively better air quality and infection control during this period.

By summer 2024, infection risks are significantly lower across all regions. The mean values of the daily infection risk ranges from 42% in Burgenland to 51% in Carinthia, with the majority of regions showing improved ventilation and infection control. In Carinthia, classrooms still exceed the risk of the reference scenario 43% of the time, while Burgenland records the fewest exceedances, with classrooms surpassing the threshold only 19% of the time.

Table 4-25. Seasonal statistics of infection risk for a classroom with 25 occupants including percentage of reference case exceedances for different regions.

Season	Region	Min	Max	Percentile 25	Percentile 50	Percentile 75	Mean	Exceedance > Ref. Scen.
		[%]	[%]	[%]	[%]	[%]	[%]	[%]
Summer '23	BUR	29	77	33	37	45	40	10
	CAR	28	84	38	45	53	47	27
	LOA	27	91	34	40	50	43	21
	UPA	27	78	34	40	49	43	20
	SAL	27	78	36	43	52	45	24

	STY	27	92	35	41	53	45	25
	TIR	28	82	34	41	50	43	19
	VOR	28	73	32	40	53	43	29
	VIE	27	85	35	42	52	44	24
Autumn	BUR	27	93	48	61	73	61	66
	CAR	28	94	67	77	83	73	92
	LOA	27	95	59	72	81	69	83
	UPA	27	95	63	73	81	70	88
	SAL	27	90	52	64	73	62	75
	STY	27	96	61	73	81	70	88
	TIR	28	94	59	70	79	68	85
	VOR	27	91	55	68	78	66	79
	VIE	28	94	57	70	79	67	82
Winter	BUR	27	94	47	59	75	61	62
	CAR	28	94	70	78	84	76	96
	LOA	27	95	64	75	82	72	88
	UPA	27	94	69	77	82	75	96
	SAL	27	91	55	66	75	64	79
	STY	28	95	66	75	82	73	94
	TIR	28	94	62	72	80	70	89
	VOR	27	94	60	71	80	69	86
	VIE	27	95	61	72	80	69	87
Spring	BUR	27	91	41	50	62	52	44
	CAR	27	94	56	67	76	65	82
	LOA	27	93	46	59	71	58	63
	UPA	27	93	49	60	70	59	68
	SAL	27	92	44	54	65	55	56
	STY	27	95	50	61	71	60	70
	TIR	27	94	48	60	71	59	66
	VOR	27	91	45	55	64	55	58
	VIE	27	94	48	59	70	59	66
Summer '24	BUR	28	73	35	40	47	42	19
	CAR	28	90	40	50	60	51	43
	LOA	27	89	35	42	51	44	23
	UPA	27	84	35	42	50	43	20
	SAL	27	86	37	45	56	46	32
	STY	27	91	38	46	56	48	34
	TIR	28	86	36	45	56	47	33
	VOR	27	81	36	43	51	44	21
	VIE	27	84	36	43	51	45	24
Year	BUR	27	94	44	55	70	57	56
	CAR	27	94	61	73	81	70	86
	LOA	27	95	53	69	79	66	76
	UPA	27	95	57	70	79	67	81
	SAL	27	92	48	60	71	59	68
	STY	27	96	56	69	79	67	81
	TIR	27	94	53	67	77	64	77
	VOR	27	94	50	63	75	62	71
	VIE	27	95	53	66	77	64	77

4.5.2.7 Infection risk comparing the best, mean and worst performing classrooms

Figure 4-50 and Figure 4-51 illustrate the CO_2 concentrations and viral load dynamics, respectively, under three different 'real-world' scenarios: best, average, and worst-case days. These scenarios were selected from the monitored data to represent a range of typical operating conditions experienced in classrooms. The selection of these days was based on their alignment with the 25th percentile (best), mean (average), and 95th percentile (worst) of the daily mean CO_2 concentrations observed in 1200 classrooms.

Figure 4-50 presents the daily evolution of the 2-minutely CO_2 concentrations for each scenario, with the dashed red line representing the mean CO_2 concentration for each case.

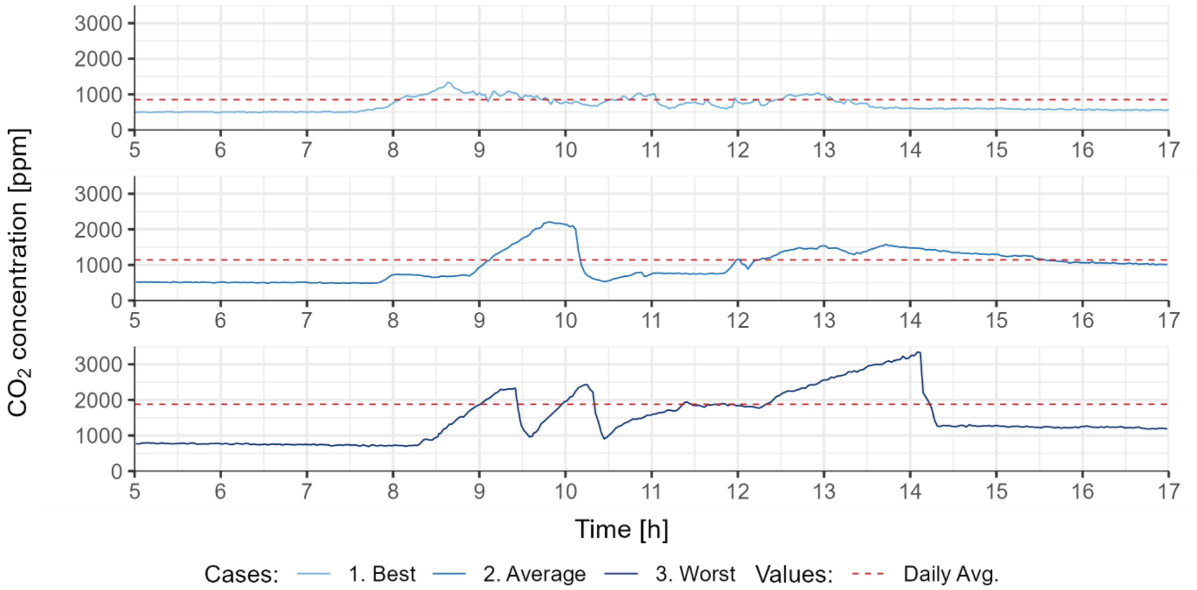


Figure 4-50. Time series example showing representative CO_2 concentration profiles in the best (25th percentile), average (mean), and worst (95th percentile) reference case classrooms

Figure 4-51 illustrates the corresponding viral concentrations ($c_v(t)$) in the three representative classrooms (primary y-axis) and the cumulative number of inhaled viral particles ($n_v(t)$) by students (secondary y-axis). These values were calculated based on the daily average ventilation rate for each scenario. As shown in Fig. 4-51, a steady-state balance between the viral emission and removal rates is reached within 0.5 to 2 hours in all three cases, depending on the ventilation rate.

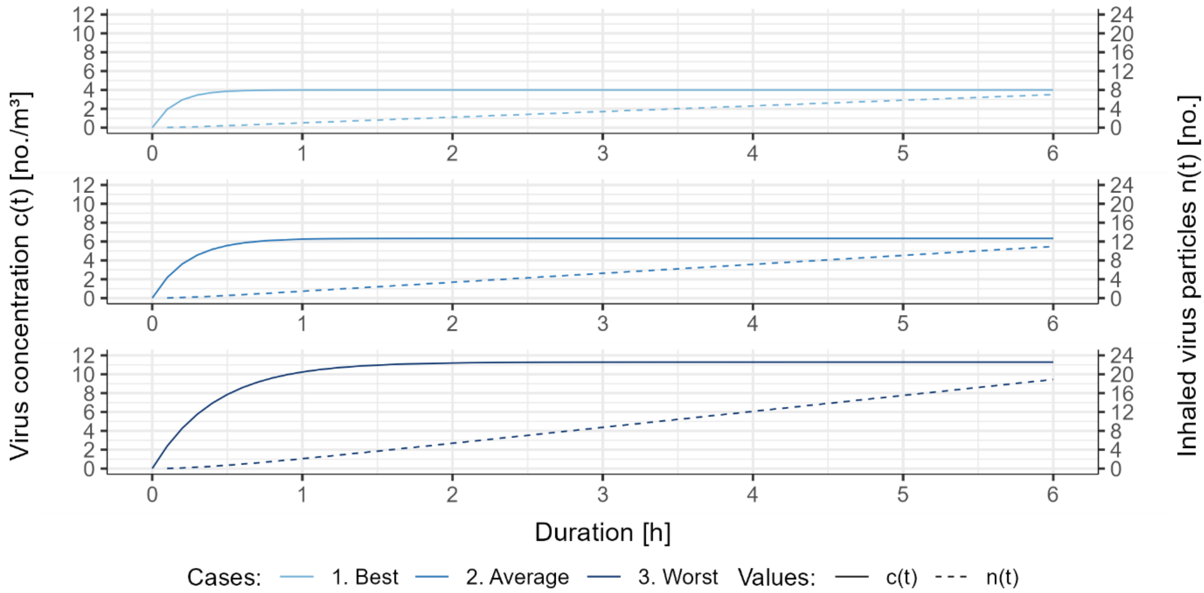


Figure 4-51. Time series - example showing viral concentration $c(t)$ and the number of inhaled virus particles $n(t)$ corresponding to the best-, average- and worst- case classrooms

The CO_2 concentration, ventilation rate, virus concentration, number of inhaled virus particles and group infection risk for the respective cases are shown in Tbl. 4-26. In the best-case scenario, characterised by a ventilation rate of 10.2 l/(s·person), the CO_2 concentration remains relatively low at 852 ppm on average. This effective air exchange helps minimize the virus concentration in the air, stabilizing at 4 virus particles/m³. As a result, the group infection risk is kept at 53%. The average-case scenario, with 6.1 l/(s·person) ventilation, shows a moderate increase in CO_2 levels to a daily average of 1140 ppm and a virus concentration of 6 particles/m³. This leads to a higher group infection risk of 69%, reflecting how reduced ventilation affects air quality and transmission risk. In the worst-case scenario, with only 3.0 l/(s·person) ventilation, CO_2 levels rise significantly to an average of 1877 ppm, and the virus concentration reaches 11 particles/m³. Under this scenario the infection risk increases to 87%, demonstrating how insufficient ventilation rapidly elevates the risk of airborne viral transmission.

Table 4-26. Daily infection risk examples - a classroom with 25 occupants under 3 different ventilation regimes (best, mean and worst case).

Cases	Daily average values				
	CO_2 conc. [ppm]	VR [l/(s·person)]	Virus conc. c(t) [no./m³]	Inhaled particles n(t) [no.]	Group infection risk [%]
Best	852	10.2	4	7	53
Average.	1140	6.1	6	11	69
Worst	1877	3.0	11	19	87

4.5.3 Association between absenteeism and environmental variables

Since the ImpAQS project is predominantly an observational study (with the only intervention being the controlled matched-paired testing of CO_2 sensors), relationships between variables can be explored using measures of association, such as Pearson correlation (r), Spearman correlation and cross correlation. However, it is important to remember that correlation does not imply causation: two variables may show an association without a direct cause-and-effect relationship and may be influenced by additional unmeasured variables. Thus, drawing definitive causal conclusions about these relationships is beyond the scope of the ImpAQS project.

None-the-less, understanding the nature of any moderate or strong associations occurring between air quality, ventilation and absenteeism is of interest from the perspective of investigating causal relationships in future research studies. When categorising the strength of correlations in a health-based or epidemiological context, for absolute values of r, 0–0.19 is typically regarded as very weak, 0.2–0.39 as weak, 0.40–0.59 as moderate, 0.6–0.79 as strong and 0.8–1 as a very strong correlation (BMJ, 2024), but these are arbitrary limits, and the context of the results should always be considered.

4.5.3.1 Pearson Correlation Analysis

The Pearson correlation method was used to assess the strength of linear relationships between absenteeism and environmental factors, such as indoor CO_2 concentration, outdoor temperature, outdoor $PM_{2.5}$, SARS-CoV-2 waste-water genome copies, ventilation rates, and infection risk, aggregated across 120 schools. The correlations were calculated using the weekly aggregated means for these variables. This approach provides a broad overview of how these variables relate on a national level, smoothing out day-to-day fluctuations and individual school variability.

Pearson correlation assesses the strength of linear relationships between two variables, where an increase or decrease in one variable corresponds to a proportional change in the other. This method contrasts with Spearman correlation, which examines monotonic relationships—situations where variables move in the same relative direction, though not necessarily at a constant rate. Pearson correlation offers a snapshot of the overall linear relationship between two variables, without accounting for time dependencies or lagged effects, making it useful for understanding how variables move together at the aggregated (i.e. national) level, regardless of the timing of those changes.

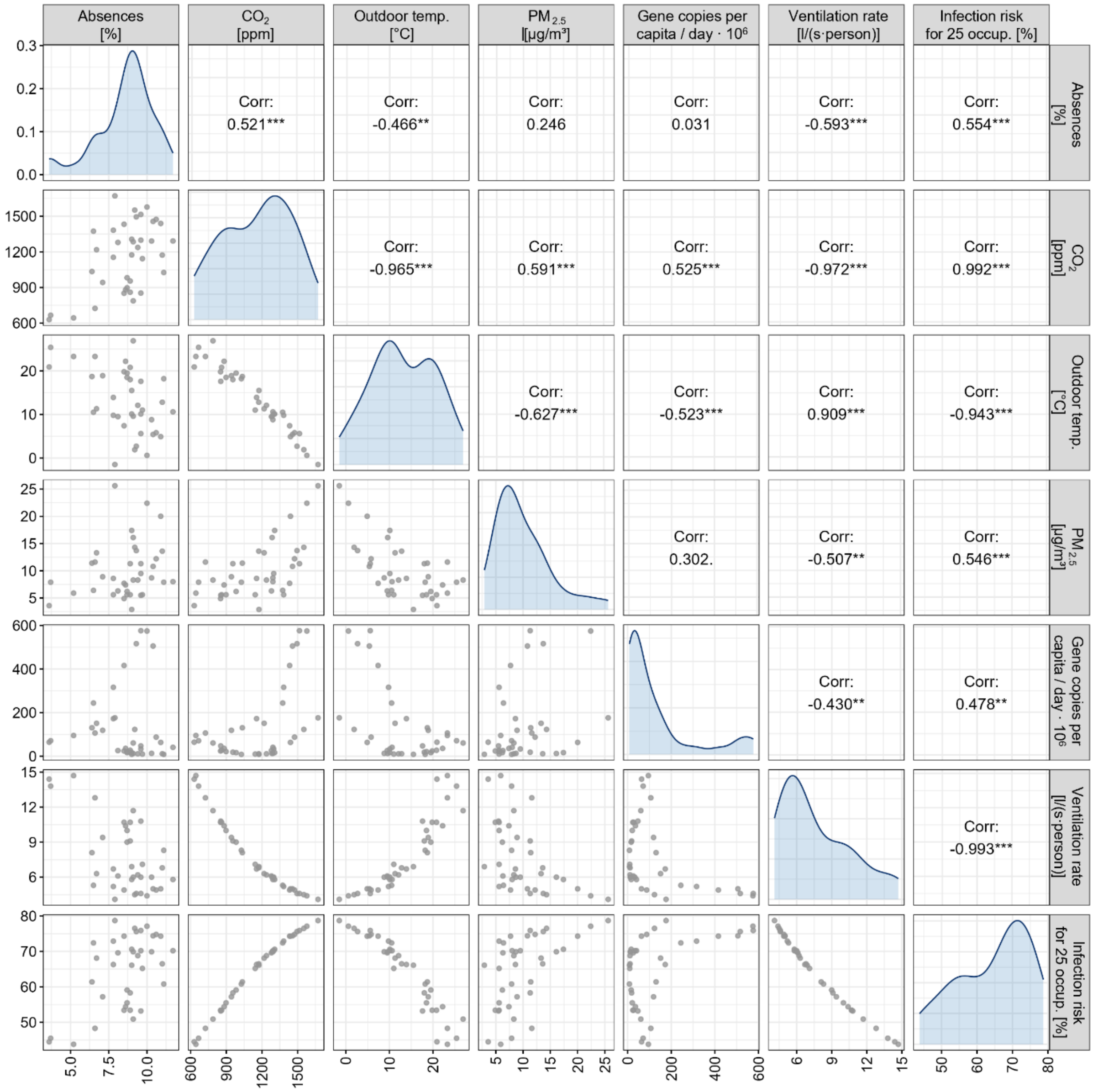


Figure 4-52. Pearson correlation analysis between absenteeism and environmental variables

The Pearson correlation analysis (Fig. 4-52) revealed a moderate positive correlation (r = 0.521) between indoor CO_2 levels and absenteeism, suggesting that higher CO_2 levels, a sign of poor ventilation, are linked to an increase in student absences. In contrast, a moderate negative correlation (r = -0.466) was observed between outdoor temperature and absenteeism, indicating that colder weather tends to be associated with higher rates of absenteeism, possibly due to a rise in seasonal illnesses during colder periods. Ventilation rates showed a moderate to strong negative correlation with absenteeism (r = -0.593), reinforcing the idea that better ventilation helps reduce absences by improving indoor air quality and minimising the spread of airborne illnesses. Finally, there was a moderate positive correlation (r = 0.554) between the theoretically derived infection risk (Appendix B.10.) and absenteeism, highlighting that when infection risks increase, so do student absences, likely reflecting the impact of illness outbreaks at this time.

4.5.3.2 Cross-Correlation Function (CCF) analysis

Cross-correlation (CC) measures the similarity between two time series over time, this allows the potential lead-lag relationships between variables to be explored. To investigate potential lead-lag relationships between absenteeism and environmental variables (such as indoor CO_2 concentration, outdoor temperature, outdoor $PM_{2.5}$ levels, ventilation rates, and infection risk), we initially applied Cross-Correlation Function (CCF) analysis on the daily data. The CCF allowed us to explore whether changes in these environmental factors precede or follow changes in absenteeism, highlighting any possible time-lagged associations.

The results from this initial analysis suggested some interesting lead-lag relationships. For example, higher CO_2 concentrations appeared to precede increases in absenteeism by a few days, while colder outdoor temperatures were associated with higher absenteeism after a short delay. These findings hinted at possible connections between poor ventilation, seasonal conditions, and student absences. However, these lead-lag relationships likely reflected broader, longer-term trends, such as seasonal variations, rather than direct short-term cause-and-effect relationships.

To better understand these findings, we repeated the CCF analysis on differenced data, i.e. data where long-term trends, such as seasonal patterns, had been removed. Differencing the data allowed us to focus on short-term fluctuations by eliminating the overarching trends that might otherwise mask or exaggerate direct short-term relationships between variables. We conducted this analysis on both daily and weekly differenced data to examine how the environmental variables related to absenteeism once these long-term trends were accounted for.

After applying the CCF to the differenced data, the lead-lag relationships detected in the undifferenced analysis disappeared. None of the examined variables (i.e. indoor CO_2 concentrations, outdoor temperature, outdoor $PM_{2.5}$, ventilation rates, or SARS-CoV-2 infection risk) showed significant short-term lead-lag effects on absenteeism in the differenced analysis.

4.6 Summary and consolidation of the quantitative analysis findings

The quantitative findings analysed in Section 4 (above) have provided evidence to inform the first four research questions posed by the ImpAQS project (Section 1.4). In the following sub-sections a condensed answer is provided in response to each research question.

4.6.1 Answer to research question 1

What percentage of Austrian classrooms are adequately/inadequately ventilated according to existing norms and emerging ‘health-based’ ventilation guidance?

The majority (55%) of the annual daily mean CO_2 values recorded for all schools exceed the 1000 ppm threshold set out in ÖNORM H 6039 (ASI, 2023), EN 16798-1 Category 1 (CEN, 2019) and BMK Class A (BMK, 2024). The median ventilation rate across all schools was 5.9 l/(s·person) which is 41% lower than the 10 l/(s·person) required by Category IEQ_I in EN 16798-1:2019 (CEN, 2019) and 36% lower than the age related airflow rate (for 11–18 year olds) set out in ÖNORM H 6039:2023 (ASI, 2023) (Tbl. 2-3). Notably, for 25% of the school-year classrooms had daily mean airflow rates lower than 4 l/(s·person) indicating that a significant number of Austrian classrooms are providing less than the minimum ventilation rate (of 4 l/(s·person)) recommended by EN 16798-1:2019 (Tbl. 4-11) (CEN, 2019).

In relation to meeting ‘health based’ target ventilation thresholds, over 90% of schools would fail to comply with the relevant guidelines on a daily basis (including the BMK Class A+ target (BMK, 2024b), the REHVA health-based target of 800 ppm (REHVA, 2022), and The Lancet Commission's Non-infectious Air Delivery Rates (NADR) recommended ventilation airflow rate of 14 l/(s·person) (The Lancet COVID-19 Commission, 2022)) (Tbl. 4-10). In wintertime non-compliance with 'health-based' targets increases to over 96%, indicating that less than 4% of Austrian schools are currently able to maintain such targets year-round (Tbl. 4-11).

Collectively this represents a widespread failure to comply with the minimum standards set out in current Austrian, European, and International guidelines for the ventilation of classrooms.

4.6.2 Answer to research question 2

Are classroom CO_2 concentrations and ventilation practices dependent upon the season and/or other local environmental factors (e.g. noise, thermal comfort, external air pollution etc)?

The data indicates a strong dependency of classroom CO_2 concentrations, and ventilation rates, on the season. From the summer of 2023 to the winter 2023-24 there is a noticeable decline in the daily mean ventilation rates and a corresponding increase in CO_2 concentrations. During the winter period the median ventilation rate is 4.7 l/(s·person) with 25% of classrooms recording only 3.4 l/(s·person) or lower. This is likely due to the reduced frequency of window airing as a consequence of colder outdoor temperatures. In spring 2024 the pattern begins to reverse, with increasing ventilation rates and decreasing CO_2 concentrations. During the spring and early summer period the median daily ventilation rates are 7.9 and 13.2 l/(s·person) respectively, likely due to more frequent and extended periods of room airing as a consequence of the warmer weather.

Analysis of the relationship between indoor CO_2 concentrations and their association with outdoor temperatures (Section 4.3.3) showed that as outdoor temperatures rise, CO_2 levels decline for both natural and mechanical ventilation. However, at lower temperatures (corresponding to the winter months), there is a significant difference between the two ventilation types. Mechanically ventilated schools are able to maintain much lower CO_2 concentrations, with a difference of over 450–600 ppm between the two ventilation types, during the coldest period of the year.

External noise was not explicitly measured in this study but is known to have a pronounced influence on window opening behaviour. The subjective issue of noise disturbance in relation to ventilation practices in the classroom is evaluated, from the classroom teachers' perspective, in section 5.2.2.1 (in relation to the winter survey) and 5.2.4.1 (in relation to the summer survey).

4.6.3 Answer to research question 3

Do classrooms equipped with CO_2 monitors, and basic ventilation guidance, achieve better ventilation outcomes (reduced CO_2 concentrations) than those without monitors?

Classrooms with visible CO_2 monitors and ventilation guidance generally performed better than classrooms without any visible information. The results are nuanced however, and in the aggregated annual data (Fig. 4-15) the full benefit of using visible CO_2 sensors is not immediately apparent. This is because of the confounding factors, occurring naturally in a heterogenous dataset, which are masking the full benefit of using CO_2 sensors in the context of fully occupied naturally ventilated classrooms. A major confounding factor is the inclusion of partially occupied or unoccupied rooms in the matched-paired comparison of T and C classrooms. This is because classrooms with a low occupancy cannot be fairly compared to fully occupied classrooms, without skewing the results. For this reason additional screening methods were applied to the T and C data (Section 4.4) to avoid biasing the comparison. Additionally mechanically ventilated T and C classrooms were removed from the matched-pair analysis (since the occupants of a mechanically ventilated room with a T sensor do not typically need to interact with the CO_2 sensor and windows to maintain acceptable CO_2 levels).

By cleaning the data in this way a true comparison of the benefits of using visible CO_2 monitors could be seen (Sections 4.4.1 and 4.4.2). What the data shows is that CO_2 monitors provide the greatest benefit during the colder months when the CO_2 levels are highest. In November and December the monthly median difference between the C and T sensors was 227 and 215 ppm respectively, showing a clear advantage to using CO_2 sensors at this time (Tbl. 4-17). In contrast the difference between the C and T sensors was much lower in June and July where the monthly median difference was only 57 and 28 ppm respectively.

The most significant benefit of using visible CO_2 sensors were found in the upper quartile of classrooms (i.e. the most poorly ventilated rooms), where it can be seen (Tbl. 4-17) that in December and January 25% of the T classrooms (with a visible CO_2 sensor) reported approximately 500 ppm lower monthly median CO_2 concentrations (496 and 506 ppm respectively) compared to the corresponding C classrooms.

Collectively these findings suggests that most naturally ventilated classrooms will achieve a noticeable reduction in CO_2 concentration through the use of a visible CO_2 sensor (with clear guidance). Moreover, the benefit of CO_2 sensors is most pronounced during the colder months when ventilation is generally poor. In around a quarter of all classrooms, this benefit results in a reduction of nearly 500 ppm in the daily mean CO_2 concentration during the coldest months of the year. In interpreting these results it is important to bear in mind that no formal training was given to the classroom teachers in relation to the correct usage of a CO_2 sensor or appropriate ventilation strategies (other than two small wall-mounted display posters in the T classrooms, see Appendix B.6).

4.6.4 Answer to research question 4

Does improving the indoor air quality in classrooms provide a statistically significant advantage in terms of reducing the risk of airborne disease infection?

Analytical modelling of the airborne transmission risk of the SARS-CoV-2 virus was used to answer the question of whether improving indoor air quality through better ventilation practices could help to reduce the risk of airborne disease transmission in classrooms. By applying this model (Section 4.5.1) to the daily mean ventilation rates determined for each classroom (Section 4.2.3.1) the relative risk of airborne infection can be compared (Section 4.5.2).

The analysis shows that the class size, length of exposure and ventilation rate all play an influential role in the level of airborne infection risk. For example, teaching a small group of 15 students over a 6-hour period results in a group infection risk (probability of one other person becoming infected in a room with one infectious person) of about 35%. In contrast, teaching a larger group of 30 people under the same conditions results in a risk of 60%.

In the context of this study, where 25% of the classrooms achieve an annual median ventilation airflow rate of 4 l/(s·person) or less, this results in a group infection risk probability of around 74% after 6 hours of exposure. In comparison an identical classroom with an airflow rate of 7 l/(s·person) (Category IEQ_{II}) reduces the risk to 60% (19% relative risk reduction). Whilst a classroom with an airflow rate of 10 l/(s·person) (Category IEQ_I) further reduces the risk to 50% (32% relative risk reduction). In contrast a classroom applying the ASHRAE Standard 241:2023 (ASHRAE, 2023) recommendation for the control of infectious aerosols, with a minimum airflow rate of 20 l/(s·person) would reduce the group infection risk to 32% (57% relative risk reduction).

It should be noted that this analysis does not include short-range (i.e. direct airborne) transmission or fomite transmission from surfaces, therefore the overall infection risk could be considerably higher than the modelled analysis. These findings emphasise the importance of using appropriate ventilation and air cleaning strategies in combination with other prophylactic measures (e.g. masking and distancing) at times of the year when airborne pathogen transmission risks are high.

5 Qualitative survey responses

This section aims to answer **research question 5**, "*Do teachers perceive the installation and use of CO_2 sensors positively, negatively, or indifferently? And if positively or negatively, what are the greatest drivers and barriers to the use of CO_2 monitors and achieving appropriate ventilation practices in classrooms?*".

This section further supports the quantitative information (provided in Section 4.2) with respect to the second part of **research question 2**, "*Are classroom CO_2 concentrations and ventilation practices dependent upon the season and/or other local environmental factors (e.g. thermal comfort, external air pollution, noise etc)?*".

To answer these questions, a total of four surveys were conducted during the course of the ImpAQS project. Two of these surveys were targeted at school directors (Section 5.1), since they play a very influential role in relation to the development and implementation of school policies and the briefing of teachers. In addition, two seasonal (winter and summer) surveys were directed at classroom teachers (Section 5.2) since it is their behaviour and knowledge which plays a decisive role in the day-to-day ventilation practices occurring at the individual classroom level. A summary of the analyses carried out in this chapter is presented in Section 5.3, where an answer to research question 5 is provided along with additional information supporting research question 2 (posed in Section 1.4).

In order to differentiate between direct quotes and indirect quotes in this chapter, the text has been formatted as follows: double speech marks are used in conjunction with italics to indicate direct quotes, whilst single speech marks are used in conjunction with italics to indicate indirect quotes (i.e. where the quoted text may have been paraphrased or redacted for clarity).

5.1 School directors' surveys

5.1.1 First survey – results

The initial survey was designed to be answered by the 120 school directors at the beginning of the 2023 school year. First contact was made with the school directors on the 21.09.2023 (Fig. 5-1), which was the date the survey officially opened. Additional follow-up phone calls took place on the 25.09 and the 26.09, with the closure of the survey on the 27.09.2023. The short timeline of the survey was imposed by the deadline of the interim report, which was due at the end of September 2023, in which the answers to the first survey were included.

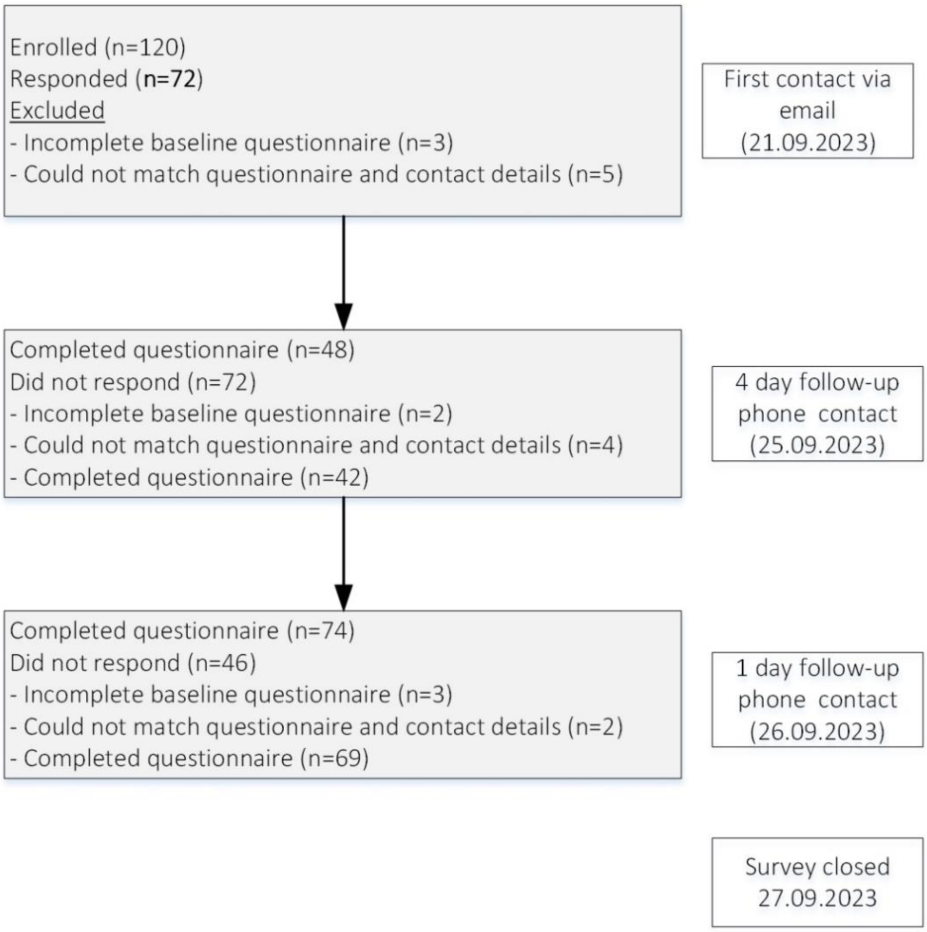


Figure 5-1. Workflow of the first directors' survey, including timescale and contact methods

The results of the survey were analysed in detail to understand whether statistically significant associations existed between the survey responses and other variables (such as school type, gender, region etc.). A more detailed analysis can be found in Appendix C.2.1.1.

As a means of increasing the response rate and quality of responses, establishing rapport with the school directors (before administering the survey) was found to be beneficial. By providing clear instructions, assuring confidentiality, and emphasising the importance of their feedback, maximum participation was encouraged. Initial contact requesting the general participation of schools in the ImpAQS study was generated via email in May 2023. It was found that whilst Graz schools responded relatively swiftly to the mailout (likely due to previous contacts with some of the schools), in schools outside of Styria, answers were less forthcoming, hence the contact strategy was changed to telephone calling.

Recruitment for the first directors' survey started in September 2023 with an initial email invitation. Two telephone calls were subsequently made to increase participation in the short timeframe available (Fig. 5-1). The survey was addressed to the 120 participating school directors, of whom 72 eventually participated with 69 valid responses recorded (Fig. 5-1). Based on a total of 5921 schools in Austria (Statistik Austria, 2024) and 120 participating schools, an 88% confidence level is achieved, with a 12% risk of sampling error, hence achieving a good compromise between certainty and sample size from which to draw conclusions.

All of the pie charts and box plots summarising the survey results can be found in Appendix C.2.1.1. Looking at the survey responses in terms of the importance of ventilation (Question 2), the majority of respondents agreed that ventilation in classrooms is either '*very important*' or '*extremely important*' (97.1%), that it has a '*very high*' or '*extremely high*' influence on the performance of pupils (83.8%) and that IAQ is '*very'* or '*extremely'* important with respect to the transmission of viral aerosols and other airborne contaminants in classrooms (91.1%) (Appendix C.2.1.1).

A number of false answers were deliberately included in Question 3 *("Why do you consider ventilation important?")*, i.e. G ('*better digestion*'), H ('*increased sustainability*'), and I ('*changes in melatonin*'). From the distribution of yes and no responses, one can see that this worked, and indeed, most directors spotted these incorrect associations. However, it was also noticeable that most of them did not understand the physical association between '*ventilation rates and humidity*' (C), '*reduction of internal pollutants like smoke and dust*' (E), and '*removal of toxic compounds and VOCs from internal sources*' (J) (Appendix C.2.1.1).

In terms of existing ventilation patterns (Question 4), the responses were that they ventilate, '*at least once a day*' (13.2%) '*up to every hour*' (22.1%), '*irregularly, such as purge ventilation every hour*' (41.2%), or '*continuously'* (16.2%) (Appendix C.2.1.1). This suggests that only a small minority of school directors understand the importance of continuous ventilation or have the means to implement it.

Challenges and barriers to ventilation (Question 5) were considered to include '*outside noise*' (45.5%) and '*outside air temperature*' (19.7 %). Less problematic was seen to be '*noise from mechanical ventilation*'[25] (1.5%), '*draughts'* (0%), and '*polluted outside air*' (7.6%) (Appendix C.2.1.1). Most noticeable are the following statements: 50% say that '*they have difficulties to use a mechanical or hybrid ventilation system*'; 60.6% answered that '*the school owner requested them to save energy*' (which has had an impact on their ventilation behaviour). The majority (77.6%) of school directors responded that '*they do only what others are doing*', whilst only 38.8% responded that '*they would ventilate regardless of what others are saying*'. In combination, these results suggests that only around a third of school directors are confident in their ventilation strategy and consider this a priority.

Question 6 probed their understanding of CO_2 thresholds, by asking "*What do you think the maximum CO_2 level should be if you want to ensure a healthy working environment in a classroom?".* Directors were asked to choose the maximum permissible CO_2 concentration (ppm) on a sliding scale ranging from 0 ppm up to 5000 ppm. In response to this question: 45% gave values of '*900 ppm or lower*', 35% provided values '*between 1000 ppm and 1800 ppm*'. 19% of all respondents gave values of '*2000 ppm and above',* with the highest value being '*3700 ppm*'. The answer that was given the most frequently (i.e. by 20% of all respondents) was '*1000 ppm*'. This response suggests that the majority of school directors are unaware of what current ventilation guidelines recommend.

In terms of identifying IAQ influencing factors (Question 7) a number of false answers were included again, and these were mostly identified by the respondents (Appendix C.2.1.1). Answers such as, '*teaching equipment*' (16.4%), '*artificial lighting*' (10.4%), '*noise level outside*' (4.5%), '*noise level inside*' (3%) were only selected by the minority. The majority (85.1%) knew that '*the number of people in a room is influential*', as well as '*type of activity in the room*' (74.6%), and the '*type and number of window openings*' (74.6%).

[25] Note that this figure includes responses from schools without mechanical ventilation.

In Question 8, 80.6% of directors agreed that '*pupils should be informed about the consequences of poor air quality*'.

In Question 9, 88.1% stated that they believe that '*pupils should take a much more active role in maintaining the indoor air quality*', with 75% of these stating, that '*there should be a CO_2 champion (i.e. a student acting as CO_2 officer and calling for action) in each class*' (Appendix C.2.1.1). However, it was also seen that this role is age dependent (with the age range suggested by the respondents indicating a rather uniformly spread response). Nonetheless, the majority agreed that '*children aged 12 and above should play an active role in managing the air quality*'.

Question 10 addressed the belief that a CO_2 sensor, with instructions, could potentially improve IAQ. Nobody (0%) responded that '*they do not have any interest in IAQ*', whilst 76.1% stated '*they would find it very helpful*'.

5.1.2 Additional comments – open-ended questions

Most answers provided by the directors, in the open-ended text answers, addressed the topics of responsibility and awareness. Directors stated that "*All pupils should be 'educated' to ventilate regularly"* and that "*awareness and information would lead to all pupils remembering to ventilate regularly"*. However, they also remarked that *"raising awareness among everyone has weaknesses and only helps to a limited extent if not all pupils are convinced of its importance"*.

Some directors confirmed that they already had student *"ventilation officers in the class"* or even conduct a *"ventilation signal… after about half an hour"* of class and that pupils were encouraged to *"support/remind teachers if they forget to air the room"*. The importance of getting everyone on board in this process, i.e. *"all pupils and all teachers"* was emphasised.

One director's response to internal air quality was that *"Every child should be made responsible for reacting to bad air!"* i.e. instead of just one student to have a class full of CO_2 champions.

Whilst another director noted that, *"A traffic light system is helpful. When the traffic light changes from green to orange, the pupils independently point this out to the teacher. There is probably no need for an authorised representative*."

5.1.3 Second survey – results

At the end of the monitoring period, in September 2024, a year after the first survey was conducted, the school directors were approached again and asked the same questions regarding ventilation for a second time. The purpose of this was to understand if their perception of importance had changed, and whether their knowledge about ventilation and threshold IAQ values had improved. The second survey was sent to the 120 school directors on the 13.08.2024, almost a year after the first survey was conducted. Out of the 120 directors 92 responded with 88 valid results, increasing the confidence level to almost 90% with a 10% risk of sampling error (Appendix C.2.1.2).

To maximise the response rate, the survey remained open for four weeks this time and interim reminders were sent out to boost the response rate.

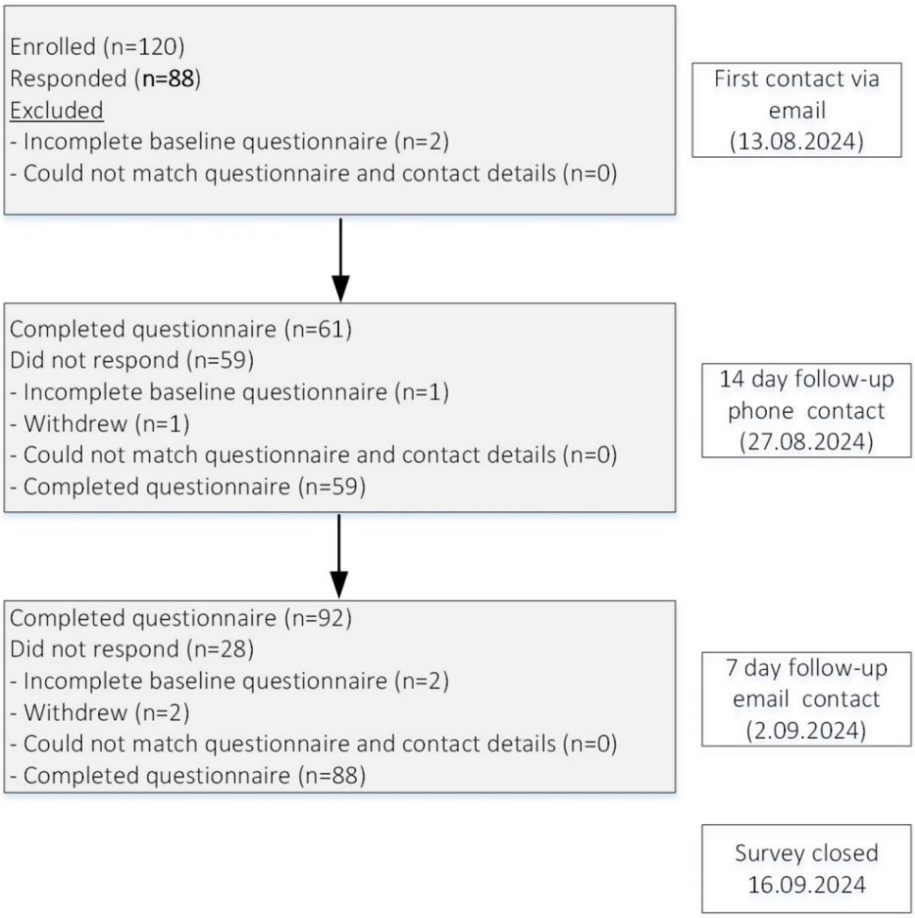


Figure 5-2. Workflow of the second directors' survey, including timescale and contact methods

In the following section, the answers to the second directors' survey are summarised. This is followed by a comparative analysis of the answers in relation to the first director's survey. All of the supporting plots, corresponding to the individual survey questions, can be found in Appendix C.2.1.2.

The first question (Question 2-A) assessed how important ventilation is considered to be in the classroom, and 50% of directors found this to be '*very important*' and 46% '*extremely important*'.

In question 2-B, *"How much do you think indoor air quality influences student academic performance?"*, 16.7% answered '*extremely*', 61.9% responded '*very*', 17.9% said '*quite*'. In Question 2-C, *"How important do you consider indoor air quality in terms of health and transmission of airborne diseases?"*, 39.3% responded '*extremely*', 41.7% said '*very*', and 14.3% answered '*quite*'.

In terms of Question 3, *"Why do you think ventilation is important?"*, most directors (96.4%) responded '*to maintain fresh air*'. The second highest response was '*for the removal of* CO_2 *and stale air*' (91.7%), whilst 75% answered '*removal of bad odour and provision of freshness*', as well as '*dilution and removal of airborne bacteria and viruses*'. Only 57.1% said that '*ventilation is important to reduce the risk of overheating and high temperatures*'. 35.7% selected '*control of humidity*', 19% '*removal of toxic chemicals from materials*' and 26.2% '*dispersal and dilution of contaminants*'. The deliberately incorrect responses, such as '*improved digestion*', '*improving building sustainability*', and '*changing melatonin levels*' were selected by only 3.6%, 11.9%, and 3.6%, respectively.

In response to Question 4, *"Thinking about your own classrooms, which approach best describes your approach to ventilation?"*, almost half (47.6%) responded '*intermittently during every lesson*', 26.2%

said '*every hour*' (i.e. before or after a lesson), 8.3% responded '*continuously*' and 13.1% said '*occasionally*' (i.e. at least once a day).

Question 5 asked, *"Which of the following sentences can you identify with?"*, the majority (83.3%) answered that '*they would ventilate even if others think it is pointless*'. However, 56% also said that '*it's their personal decision not to waste energy*', or that '*the school owner instructed them not to waste energy*' (34.5%). 25% complained about '*the feeling of a draught*'. In terms of mechanical systems, 8.3% '*found it difficult to operate mechanical ventilation, air purifiers or hybrid systems*' and 50% responded that '*they don't like the noise of ventilation units*'. 39.3% said that '*they use a CO_2 sensor to tell them when to ventilate*'. Only 8.3% said that '*they are unsure sometimes whether to ventilate*'. 15.5% '*do not like opening windows because it is noisy outside*', while 4.8% reported being '*too hot or too cold when they ventilate*'; 2.4% '*find it difficult to open windows*'; 2.4% '*find ventilation disturbing and impractical*' and 11.9% stated that '*their class is quiet when they do not ventilate*'. Only a small percentage, i.e. 2.4% stated that '*they always look at what others are doing*'.

Question 6 tested the understanding of CO_2 thresholds, by asking "*What do you think the maximum CO_2 level should be if you want to ensure a healthy working environment in a classroom?".* Directors were asked to choose the maximum permissible CO_2 concentration (ppm) on a sliding scale ranging from 0 ppm up to 5000 ppm. 60 out of 84 directors in total, i.e. 71% stated that maximum CO_2 value in a classroom should be '*1000 ppm or less*'. 11 provided values from '*1200 up to 1500 ppm*'. Only three directors (3.5%) gave values '*above 2500 ppm*'.

Question 7 asked *"Which factors influence air quality in a classroom?"*, most (90.5%) selected '*the number of people in the room*'. This was followed by '*the type of activity in the room*' (86.9%) and '*the number and size of windows*' (72.6%). Other responses were as follows: '*volume of air*' (*65.5%); 'quality of the outside air*' (60.7%); '*flow rate of the mechanical ventilator*' (53.6%); '*air humidity*' (51.2%); '*construction materials*' (48.8%); '*materials used in the class*' (17.9%). The incorrect answers '*indoor and outdoor temperature*' and '*artificial lighting*' were selected by 44% and 8.3%, respectively. Whilst 21.4% answered that '*they are not sure*'.

In response to Question 8 *"Do you think students should be informed about the impact of ventilation practices and air quality in classrooms?"*, 78.6% agreed that '*all students should be informed about ventilation practices and indoor air quality*'. 17.9% answered that '*it depends on their age*' (wherein, 13.3% responded that the '*children should be 5 years or older*', 13.3% said '*5 years or older*', 20% chose '*8 years or older*', 13.3% answered '*10 years or older*', 26.7% selected '*12 or older*', and 26.7% *'15 years or older*', whilst 3.6% responded that '*it is not their responsibility*').

In terms of Question 9 *"Do you think students should play a role in maintaining ventilation quality?"*, the vast majority (84.5%) responded '*yes, they should appoint a student who is responsible for monitoring the CO_2 concentration and ventilating the classroom*', 10.7% responded '*no*', and 4.8% answered '*maybe*'. Of those who said maybe, 77.8% said that '*it depends on their age*'. Of those who said *'no'*, the majority (75%) said that '*it is the teaching staffs' responsibility*', while 25% said '*it is the school's responsibility*'.

In response to Question 10 *"Do you think a CO_2 sensor with a traffic light display and instructions would help to improve indoor air quality in classrooms?"*, there were four '*no*', two '*maybe*', and two '*yes*' options. No one selected '*no, because my school prevents me from opening the windows*', but one person responded '*no, because I have no interest in air quality*' (1.2%) and one selected '*no, because I can't easily open the windows in my classroom*' (1.2%). Three said '*no, because my room is mechanically ventilated, and I have no control over it*' (3.6%). '*Maybe, it depends on how complicated* *it is*' was selected by 14.6% and '*maybe, if it doesn't distract me from teaching*' by 4.8%. The majority however responded positively to this question, with 72.6% saying '*yes, it would be very helpful*' and 41.7% said '*yes, if a student is appointed who is responsible for monitoring the CO_2 concentration and ventilating the classroom*'.

5.1.4 Differences in responses between first and second directors' survey results

In response to question 2-A *"How important is ventilation?"*, in the second survey more directors answered that it is '*very important*' (2023: 39.7%; 2024: 50%) but fewer responded, '*extremely important*' (2023: 57.4%; 2024: 46.6%). So overall, the directors' perception of the importance of ventilation decreased slightly over time.

In response to the question 2-B *"How much do you think indoor air quality influences student academic performance?"*, also here, fewer people responded '*extremely*' in 2024 (2023: 20.6%; 2024: 16.7%) and more responded '*quite*' (2023: 13.2%: 2024: 17.9%).

In relation to Question 2-C *"How important do you consider indoor air quality is in terms of health and the transmission of airborne diseases?"*, less people responded '*extremely*' (2023: 42.6%; 2024: 39.3%) and more said '*very*' (2023: 48.5%; 2024: 41.7%) and '*quite*' (2023: 7.4%; 2024: 14.3%). This shift in attitudes might reflect a change in perspectives with the passing of time since the height of the COVID-19 pandemic.

Overall, in relation to Questions 2 A–C, no one responded with '*I don't know*' during either survey. However, one person responded with '*not at all*' during the second survey (in 2024), whilst no one had responded with this answer previously (i.e. during the 2023 survey).

In relation to Question 3, *"Why do you think ventilation is important?"*, there were only slight differences between the years 2023 and 2024, in the following answers: '*maintaining fresh air*' (in 2023: 97.1%, 2024 96.4%); '*removal of CO_2 and stale air*' (2023: 88.2%, 2024 91.7%); '*reducing the risk of overheating and high temperatures*' (2023: 50%, 2024: 57.1%); '*dispersal and dilution of contaminants*' (2023: 33.8%, 2024: 26.2%); '*dilution and removal of airborne bacteria and viruses*' (2023: 79.4%, 2024: 75%); '*removal of odour and provision of freshness*' (2023: 73.5%, 2024: 75%), and '*removal toxic chemicals from materials*' (in 2023: 20.6%, in 2024: 19%). '*Control of humidity*' was selected by considerably fewer directors in 2024 (2023: 47.1% , 2024: 35.7%), however this may be due to the second survey taking place during the summer period. It was encouraging to see that fewer directors wrongly selected the deliberately incorrect answers, '*improved digestion*' (2023: 4.4%, 2024: 3.6%), '*improving the sustainability of the building*' (2023: 22.1%, 2024: 11.9%), '*changing melatonin*' (2023: 13.2%, 2024: 3.6%).

In response to Question 4, *"Thinking about your own classrooms, which approach describes best your approach to ventilation?"*, the difference between answers from 2023 to 2024 was very small (typically around 5% or less). In particular those responding, '*intermittently during every lesson*' (2023: 41.2%, 2024: 47.6%), '*every hour (either before or after)*' (2023: 22.1%, 2024: 26.2%) and '*occasionally (at least once a day)*' (2023: 13.2%, 2024: 13.1%). In contrast, the number of those responding '*continuously*' halved from 2023 to 2024 (2023: 16.2%, 2024: 8.3%). This change might be explained by the reduced focus on SARS-CoV-2 prophylaxis with the passing of time, particularly as the second study was carried out under warmer summer conditions where continuous ventilation is more likely.

Question 5 asked, *"Which of the following sentences can you identify with?"* and the responses showed a significant change in 2024 compared to 2023. In seven statements the percentage of affirmative (i.e. '*yes'* responses) increased, e.g. '*I use a CO_2 sensor to tell me when to ventilate*' (in 2023: 16.7% , 2024: 39.3%); '*I don't like the noise of ventilation units inside*' (2023: 1.5%, 2024: 50%), '*Feeling of draught*' (2023: 0%, 2024: 25%), '*Unsure sometimes whether to ventilate*' (2023: 3%, 2024: 8.3%), '*Personal decision not to waste energy*' (in 2023: 3%, in 2024: 56%), '*My class is quiet when I don't ventilate*' (in 2023: 1.5%, 2024: 11.9%), '*I would ventilate even if others think it's pointless*' (2023: 38.8%, 2024: 83.3%).

In the following statements the percentage of affirmative responses went down from the previous year: '*I don't like opening windows because its noisy outside*' (2023: 45.5%, 2024: 15.5%), '*I get too hot or too cold when I ventilate*' (2023: 19.7%, 2024: 4.8%), '*I find it difficult to open windows*' (2023: 10.6%, 2024: 2.4%), '*I find it difficult to operate mechanical ventilation, air purifier or hybrid system*' (2023: 50%, 2024: 8.3%), '*the school owner instructed us not to waste energy*' (2023: 60.6%, 2024: 34.5%), '*I find ventilation disturbing and impractical*' (2023: 6.1%, 2024: 2.4%), '*I always look at what others are doing*' (2023: 77.6%, 2024: 2.4%). In part, these changes may be a response to a change in awareness resulting from the presence of CO_2 sensors and ventilation guidance in the classrooms.

It is positive to note that 23% more directors now use a CO_2 sensor to ventilate (since the first survey was conducted), indicating that in total almost 40% of school directors now use a CO_2 sensor as part of their ventilation strategy. In addition, it is interesting to note that the negative perception of the operation of mechanical systems went down. Similarly, the issue of the negative perception of noise when opening windows went down by over 30%. Strikingly, 45% more directors (i.e. 83.3% in total) confirmed that they would ventilate even if others thought it was pointless, reflecting that significantly (75.2%) fewer directors are influenced by what others are doing. Collectively these findings suggest that after a year of being exposed to the use of CO_2 sensors (and clear information about relevant CO_2 thresholds and ventilation methods) school directors generally feel more confident in their ability to ventilate rooms appropriately.

In terms of the maximum threshold CO_2 value for a classroom, more than 20% responded (in 2023) that values above 1500 ppm were acceptable, with almost 10% suggesting values above 2500 ppm, and three providing values above the 3000 ppm. In 2024, at the end of the study, 14% responded that values above 1500 ppm were acceptable (hence less compared to 2023), and only one person suggested that a value above 3000 ppm was appropriate. Considering that at the same time the total number of respondents increased (from n=64 to n=84) this demonstrates that a clear improvement in the knowledge of appropriate CO_2 values occurred: wherein, 67% gave target values of 1200 ppm or less in 2023; in 2024 this increased to 76%. The percentage of those giving 1000 ppm as a threshold limiting value did not change, however. In 2023, n=13 provided this value opposed to n=17 in 2024. Considering the higher number of respondents; both values equate to approximately 20% of the total number of participants.

Question 7 asked, *"Which factors influence air quality in a classroom?"*, and similar answers were provided regarding the volume of air, number and size of windows, indoor and outdoor temperature, and mechanical ventilation airflow rate. Differences could be detected in the following answers: air humidity (2023: 41.8%, 2024: 51.2%), quality of outside air (2023: 52.2%, 2024: 60.7%), number of people in room (2023: 85.1%, 2024: 90.5%) type of activity in the room (2023: 74.6%, 2024: 86.9%).

In response to Question 8, *"Do you think students should be informed about the impact of ventilation practices and air quality in classrooms?"*, most directors agreed that all students should be informed about ventilation practices and indoor air quality, and that opinion did not change much over the project duration (in 2023: 80.6%, 2024: 78.6%). However, in both 2023 and 2024 18% responded that it depends on their age. Differing age ranges were indicated as appropriate, with a slight variation between the two surveys: 5 years or older (2023: 16.7%, 2024: 13.3%), 8 years or older (2023: 16.7%, 2024: 20%), 10 years (2023: 25%, 2024: 13.3%), 12 or older (2023: 16.7%, 2024: 26.7%), and 15 years or older (2023: 25%, 2024: 26.7%). While in 2023, 50% believed that students should be either 10 or even 15 years old, in 2024, 53.4% believed that students should be 12 or 15 years old, shifting the age threshold slightly upwards. In contrast one director in 2023 and 3 directors in 2024 responded with '*that it is not their responsibility*' (in 2023: 1.5%, in 2024: 3.6%).

Question 9 asked, *"Do you think students should play a role in maintaining ventilation quality?"*, in both surveys a similar number of directors responded '*yes, we should appoint a student who is responsible for monitoring the CO_2 concentration and ventilating the classroom*' (2023: 88.1%, 2024: 84.5%). Of those who said '*no*' (2023: 4.5%, 2024: 4.8%) opinions about who should take responsibility for maintaining ventilation quality changed from one year to the next. Whilst in 2023, two thirds thought it was the school's responsibility (2023: 66.7%, 2024: 25%), in 2024 three quarters of the director were of the opinion that the teaching staff were obliged to take care of this (2023: 33.3%, 2024: 75%).

In response to Question 10, *"Do you think a CO_2 sensor with a visible traffic light and instructions would help improve indoor air quality in classrooms?"* The overall numbers are very similar, and the number of people choosing '*no*' did not change much from one year to the next. '*No, because I have no interest in air quality*' (2023: 0%, 2024: 1.2%); '*no, because my room is mechanically ventilated and I have no control over it*' (2023: 4.5%, 2024: 3.6%); '*no, because I can't easily open the windows in my classroom*' (2023: 0%, 2024: 1.2%); '*no, because my school prevents me from opening the windows*' (2023: 0%, 2024: 0%). In terms of the '*maybe*' and '*yes*' answers, the percentages did not change much. A few people seemed to worry about the use of sensors being too complicated ('*maybe, it depends on how complicated it is*' (2023: 10.4%, 2024: 14.6%), fewer directors were worried about distraction ('*maybe, if it doesn't distract me from teaching*' (2023: 6%, 2024: 4.8%). Slightly less, compared to the previous year, felt it would be very helpful (2023: 76.1%, 2024: 72.6%) and slightly more felt that it is the student's responsibility ('*yes, if a student is appointed who is responsible for monitoring the CO_2 concentration and ventilating the classroom*' (2023: 38.8%, 2024: 41.7%). Overall these findings highlight that most directors find CO_2 sensors and ventilation instructions to be very helpful.

5.2 Teachers' surveys

5.2.1 First survey (winter) – results

The first online survey was sent out to the 1200 ImpAQS classroom teachers four months into the CO_2 monitoring campaign. This survey was timed to coincide with the middle of the winter period (24.01.2024). This was done in order to understand teachers' attitudes and knowledge with respect to ventilation and to uncover any specific issues related to the winter season. Reminders were sent out in February, and the survey was closed in early March 2024 (Fig. 5-3).

There were 771 valid respondents to the winter survey, 554 (72%) from classrooms with the visible sensor displays (T) and 217 (28%) without visible displays (C). All of the plots, documenting the responses to this survey, can be found in Appendix C.2.2.1.

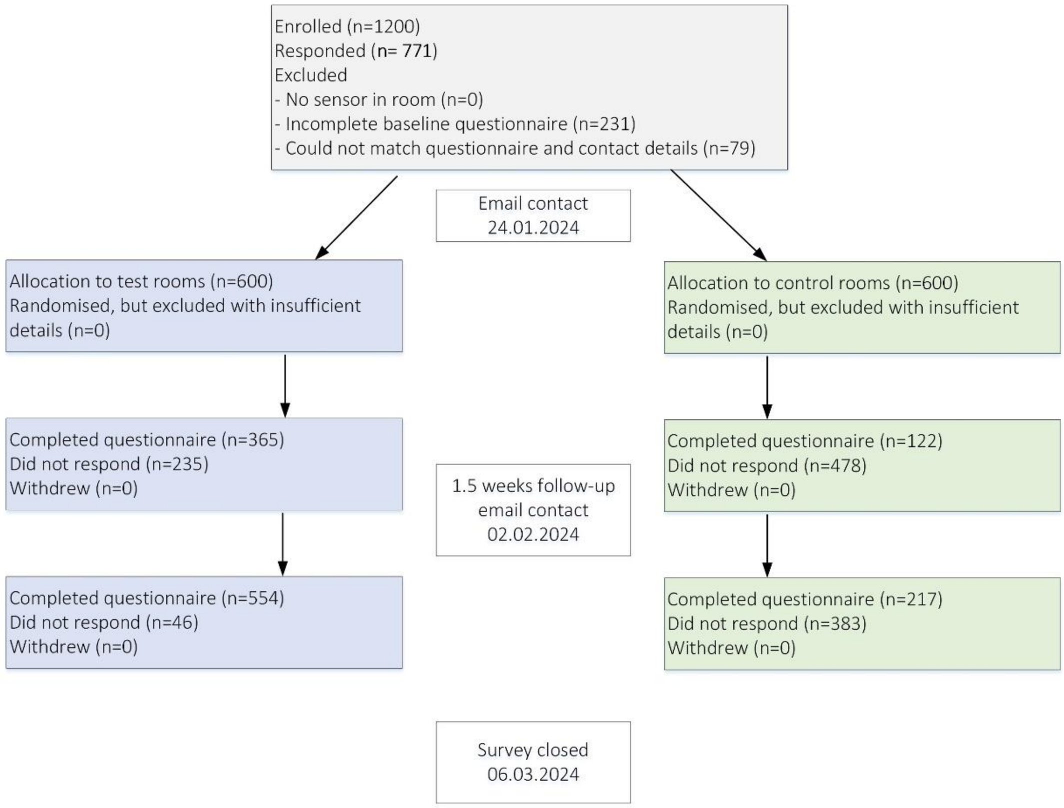


Figure 5-3. Workflow of first teachers' survey, including timescale and method of contact.

In relation to the room temperature when ventilating, 26.2% responded that they '*never or seldom found the room temperature too warm or too cold when ventilating*'. 39% replied that temperatures were '*sometimes too low*', whilst 31.5% reported they were '*often too low'*, with an additional 3.4% saying they were '*always too low*'. This corresponds to the response that 35.1% would like temperatures to be '*often or always to be warmer*', with 42.5% desiring this '*only sometimes*', whilst 22.5% stated '*seldom or never*'. This gives an indication that classrooms are perceived by a significant proportion of teachers as being too cold in winter, with only half the teachers being content with the conditions. This fact is likely to influence the willingness of those teachers to ventilate in wintertime.

In terms of draughts, the answers were more positive, with 70% responding that they '*do not feel any draught or find it pleasant, or even very pleasant*'. This is in contrast to 30% who responded that they consider the draughts in their classroom as '*unpleasant or even very unpleasant*'. 33.6% would prefer at least '*a bit more air movement*' whilst 34.5% '*do not want any change*' and the remainder (31.9%) would prefer '*less air movement*'.

In relation to noise outside, 42.8% considered it to be '*disturbing*' or even '*very disturbing*', whilst 14.7% were '*neutral*' and 42.5% did *'not consider it as disturbing*'.

In relation to the effect of ventilation on concentration opinions were divided with 30.1% saying that '*student concentration was improved via ventilation*' whilst 28% responded that '*ventilation worsened concentration*'.

18% reported facing '*practical issues in opening windows*' (such as locked windows or conflict with shading devices), whilst 28.8% were '*unsure whether to ventilate*'. Interestingly, in the winter survey, just as many teachers reported that it was '*too warm*' (36.9%) as those who reported that it was '*too cold*' (38%).

It is interesting that, 47.1% responded that '*school regulations prevented them from opening windows in order to save energy*'. Whilst 57.4% said it was '*their personal decision to not waste energy*'. 29% remarked that '*their class is restless when they ventilate*' and 20.4% responded that '*ventilation distracts and is unpleasant*'. 46.8% considered noise to be a problem during ventilation, whilst 30.6% considered draughts to be a problem. In contrast, only 6.9% considered '*outside air pollution to be a problem*'.

Question 9 attempted to establish *"What item or information (from the ImpAQS study) has helped you to better ventilate?".* Most teachers stated that it was the CO_2 sensor with numerical display (28.4%), followed by the CO_2 sensor with numerical display <u>and</u> traffic light indicator (24.1%), followed by the wall-mounted CO_2 guidelines with their explanation of threshold limiting values (17.1%), followed by the CO_2 sensor traffic light (on its own) (9.2%), and lastly the wall-mounted ventilation guidelines (7.6%). Remarkably, less than one quarter (21.3%) responded that fully automatic mechanical ventilation would be their preferred ventilation option, whilst more than one third (34.2%) responded that none of the above items has helped them to ventilate better[26].

Question 10 asked, *"What would or could help you to ventilate better in future?"*. The answers are presented from the highest to the lowest percentage of agreement: a stopwatch or timer (to measure the duration of window opening) (36.3%), specific recommendations about the energy and CO_2 costs for the ventilation of their classroom (19.3%), a personal visit by a ventilation expert (19.2%), and specific guidance on avoiding draughts when using window ventilation (17.9%).

In relation to complying with the target thresholds, 26.2% responded that they '*never or seldom manage to stick to the recommended CO_2 threshold*'. 50.2% answered that they '*sometimes or always manage to be within the recommended CO_2 threshold*'. Whilst 13.5% replied that it is '*difficult*' or even '*very difficult*' to ventilate correctly with a CO_2 sensor. Conversely, 63.1% responded that it is '*very easy*' or '*easy*' to ventilate correctly with the help of a sensor.

Next, teachers were asked about the difficulties they experience when using a CO_2 sensor. The answers are presented from the highest to the lowest percentage of agreement: 63.5% '*have no difficulties*', 5.8% stated that '*the sensor behaves in unexpected ways*', 3.7% '*found the sensor display confusing*', 3.1% '*have to look at the manual before using the sensor*', 2.1% '*found the sensor instructions unclear*', 1.6% '*found the ventilation guidance unclear*'. Overall, this is seen as a very positive response, since the majority did not report any difficulties when using the CO_2 sensor[23].

Confirming which of the given statements is correct, 51.1% stated that '*they have no problems with the sensor*', and 21.2% responded that '*with the new CO_2 sensor and the ventilation instructions, it is easier to keep the CO_2 values in a good range'*.

In relation to their ventilation behaviour in the future, the answers are presented from the highest to the lowest percentage of agreement: 42.4% stated that '*they are planning to ventilate better*', 18.6% responded that '*they are still practising how to ventilate correctly*'. 17% said '*they have to cope with*

[26] It should be noted that responses to the teachers' surveys were provided by teachers occupying both T (72%) and C (28%) classrooms, therefore the responses to questions related to the benefit of (or interactions with) visible interventions (such as CO_2 sensors and wall display posters) will be influenced by this fact.

resistance by students and staff. 13.5% said '*they are unsure how to keep up ventilation*', 8.8% responded that '*they are still practising how to understand the sensor*'.

In terms of the impact of the CO_2 sensor and ventilation guidance on ventilation behaviour, the answers are presented from the highest to the lowest percentage of agreement: 63.4% stated that '*they think that more frequent ventilation is a good idea*'. 48.1% thought that '*the new CO_2 sensor and ventilation guidance is a good idea*'. 27.8 % '*made an effort now, with the help of the CO_2 sensor and learnt ventilation techniques to keep up good air quality in a classroom*'. 12.5% '*have now the knowledge and the means to ventilate correctly*'. Only 8.9% '*thought that the CO_2 sensor and ventilation instructions are pointless*'. Whilst a similar percentage (8.8%) '*were unsure if the CO_2 measuring and ventilation is a good idea*'. Only a very small percentage (3.7%) stated that they '*did not understand the purpose of measuring CO_2 and ventilation*'.

In terms of the importance of measuring CO_2 as a means of regulating ventilation habits, the answers are presented from the highest to the lowest percentage of agreement: 54.5% stated that '*they are opening the windows several times a day*'; 33.6% '*only looked seldomly at the CO_2 sensor*'; 22.9% '*looked often (or several times) at the CO_2 sensor*'; 21,4% '*have the tendency to use the new CO_2 sensor as a guidance for their ventilation behaviours instead of keeping the windows closed*'; 16.9% '*never looked at the CO_2 sensor*'; 16.6 % '*observed the CO_2 with great attention and then ventilate several times a day, in order to obtain the best indoor air quality*'.

In terms of their general perception of the CO_2 sensor, the answers are presented from the highest to the lowest percentage of agreement: 43% stated that '*they like to look at the CO_2 sensor*'; 16.2% said that '*the CO_2 is of no interest to them*'. 14.4% said '*they have no time to use the CO_2 sensor*'; 7.2% even said that '*the sensor is depressing them*'. 6.1% responded that '*they are opening and closing the window so often that it distracts them*'. 2.1% said that '*they are not interested in indoor air quality*'[23].

5.2.2 Open-ended answers – winter survey

5.2.2.1 Ventilation problems and individual strategies

For a number of questions it was possible to add additional comments in a section entitled '*other*'. For example, subsequent to question 7, an open-ended question was asked: "*If you have encountered one or more of the above problems and have found a way around the problem, please describe the problem in more detail and how you solved it?"*.

Many of the problems encountered were related to how and when ventilation should happen, as mixed messages have circulated regarding whether purge ventilation or tilted window ventilation is better. Despite some claims of it being energy inefficient, **many used tilted windows** and '*often just tilted the window permanently when there were few people there and it wasn't too cold*', or '*only opened the window completely when the construction noise was bearable*'. Energy efficient thinking is clearly present as some '*don't want to waste energy by tilting the windows*' – so, in case all the windows are opened, '*they switch off the radiators*'.

In terms of **purge ventilation**, many said it is '*no problem, short and intensive!*' stating that shock ventilation is their preferred option (i.e. they ventilated briefly, but several times per day). Some '*only ventilate for a maximum duration of 2 minutes so that the disturbance period remains short*'. Or '*only when the room is too warm*'. Some continue to ventilate when it is cold, e.g. '*the air quality was just too bad, we opened all the windows and left the classroom for 3 minutes*'. Instead of opening windows fully, some left their small fanlights open. Some aired their rooms more often but for shorter periods, to lower the room temperature and to minimise noise pollution from outside.

The **timing of ventilation** was considered to be an important issue in terms of not disrupting teaching. Teachers figured out differing times to ventilate. Some wrote '*it is often good to air the room when entering the class to start, as this increases alertness...*', some arrive at class a minute or two early and then air during the beginning or show a preference for ventilation at the beginning and end of the lesson. Some do '*several short ventilation breaks*' during the lesson, others however, report this as being '*disruptive*'. Ventilation during a lesson rarely happened for many. Some ventilated during the breaks or both, '*came in beforehand and ventilated during the break or ventilated after each learning phase, not during it*' and a few only '*ventilate during breaks and after lessons*'. Some adapt to the seasons and use '*shock ventilation in winter; with continuous window opening in the warm season*'.

Issues with **window design, safety and risk when opening windows** were mentioned, e.g. '*due to the structural measures (no more sliding sash windows), one or two pupils are sitting in the middle of the window casement or have the window casement directly in front of their eyes?*'. Some wrote that '*the new windows with fire protection cannot be opened, also the position of windows can be a problem*', or '*windows are very large and right next to a row of desks, which means that pupil's heads are in the way when airing or their view is obstructed and in winter it quickly gets too cold for those sitting next to them. It cannot be changed*'. Another teacher wrote that '*the window shape (2-light bottom-opening) is completely unsuitable for ventilation, and that windows hit the tables when they are opened and are in the way of the students. They have to clear the tables. There is no solution*'.

Several teachers reported **maintenance and safety issues** with windows that could not be opened (e.g. due to repair or safety reasons). In some cases alternative windows in the classroom could be opened. One teacher hoped that windows that were mechanically locked would be openable in the future.

Some schools have **sky lights** installed that can improve ventilation effectiveness. However, some reported issues and that the electric actuators controlling the skylights was broken. '*The problem with ventilation in our school is that the skylights and windows are not in the best condition, to put it politely. Due to the fact that the building is managed by the city of Graz, it is unlikely that these will be replaced soon (budget situation of the city, note)*'. In one school, a solution was found by installing an extra handle on an elevated window so that it could be opened manually, with the remark that: '*This has notably replaced some of the stale air in the ceiling area*'.

Those schools without skylights tried to make use **of cross ventilation** and noticed that: '*the air flow improved significantly*' if they also opened '*windows on the other side of the building*' or the classroom door. With the observation that, '*This will help the air to circulate more quickly*'. One teacher wrote that to '*achieve better indoor air quality*' they '*opened the door in addition to the three windows*'. This created more draughts, which brought more CO_2 out of the room. At the same time, it got unpleasantly cold in the room. One teacher however noticed that '*If the classroom doors are also open during ventilation, stale air from the corridors enters the classroom. This increased the CO_2 concentration.*'

Draughts were considered pleasant as well as unpleasant dependent on the outdoor temperatures. Some complained that draughts interfered with documents and that '*the notes are blown away when you open the door – hence the door is kept closed*'.

Temperature was considered a big issue during the winter. '*Many children get cold quickly, especially if they are sitting by the window.*' In some schools, the temperature control for heating was noted as being very poor. As the windows are not airtight in many schools it is sometimes very cold even without opening them, and room temperatures are reported to be an issue. In this regard it should be noted that down-draughts, from poor quality glazing, can occur even without air leakage, simply as a result of the cold internal surface temperatures of the glass in wintertime.

Teachers wrote that some children '*suffer from the cold air, especially those by the windows. If the value is above 1000, it is hardly possible to achieve lower values in the long term; you would have to open [windows] every 10 minutes.*' Even though temperature was an issue here, one teacher admitted that the room temperature was only briefly too low (especially noticed by female students) –'*and after airing, it soon rose again to a comfortable temperature*'.

Temperatures are even considered a problem during breaks, if students want to stay in class. '*Then they sit in class with their winter jackets on*'. Some reported students to be more sensitive to temperatures than teachers. '*Students were cold when the windows were opened, but teachers were not*', and that there are '*complaints from students that it is too cold when the windows are opened*'. One teacher wrote: '*Students are very upset when I air the rooms when it is very cold. But I only air the rooms briefly, and sometimes I also open the door and then close everything again quickly so that they don't freeze to death*'. One teacher complained that he could not reach the recommended CO_2 target in winter: '*It was very cold (winter) and you would have to ventilate almost constantly to get the desired unit of measure. This is not reasonable for the seated children.*' Some reported issues with the heating system in their classroom: '*The room is constantly cold because the radiators are cold.*' There were a few comments regarding external distractions, and about discussions between teachers and pupils. In terms of distractions, e.g. '*The children are only distracted at the beginning of the airing. If the windows are open longer, the kids get used to the ambient noise. The windows are opened, even though it is briefly unpleasant. But we have better air for the rest of the hour. It's worth it.*' In terms of discussions between teachers and pupils: '*In winter, airing always leads to the discussion 'it's too cold' - this disturbs the lessons. Or in winter, the children complain of the cold when the windows are opened. Since the windows have to be opened almost twice an hour, this is a disruptive factor (and it is noisy outside). We have not found a solution.*' Some reported that there is a dispute between the students because some want a lot of fresh air, and others (often the girls) are cold. Some of the pupils find it unpleasant (primarily because it is too cold), and some want to keep the windows open - even in winter.

These disputes are considered a great distraction and disruption in class. One teacher wrote: '*Therefore, only I decide how long and how often the windows are opened. They don't argue with me.*' One teacher wrote: '*From the class in which the measuring device was installed, I cannot report any unrest, but there are many classes where a burst of ventilation triggers discussions. The students sitting furthest away from the window complain about the room temperature being too warm and ask for fresh air, while the students sitting next to the window complain about the cold after about 1 second with the window open. As a result, they are asked by their classmates to put more clothes on, since some of them are sitting in class wearing short T-shirts, and the discussion continues.*' The seating position of the pupils in relation to opening windows was mentioned many times: '*Due to the cold season, ventilation is a problem because it is simply too cold for the row next to the windows to let the icy air in during lessons.*' Or similarly, '*Often it is so cold outside that you don't want to open the window if students are sitting too close. The students sitting by the windows put on jackets after complaining about the very cold draughts from outside.*'

Some state that they ventilate '*Even if some pupils are cold at the window in winter, I still ventilate consistently*'. In winter, the '*main problem is pupils sitting in front of the open windows are cold (understandably). Jackets could help in some cases*'. **Dress code** is mentioned as a solution to ventilation in winter with students being restless '*because some got cold faster than others and then complained - they were then told to put on jackets or similar*'. Many teachers report actively approaching students to put on more clothes or their jackets, '*to dress warmer*'. Teachers also write that students are wearing winter jackets in class and that '*as a student, this is unbearable and annoying'* or that *'students are allowed to use blankets/jackets in class (when sitting, you quickly feel the cold)*'. The problem of cold temperatures is often solved by simply accepting lower air quality, e.g. '*On some cold days, it would have been necessary to air the entire lesson in order to achieve a good value again. I didn't keep that up – so I solved it by airing less and we accepted the poorer air quality.*'

There is a widespread misconception that exposure to cold air can directly cause an illness, however this is scientifically unsubstantiated[27]. E.g. '*Ventilation in winter is a problem because it is simply too cold for the row of windows to let in the icy air during class. The children freeze and then they get sick.*' A few others wrote that '*Everyone is sick from the cold air. The problem is pupils quickly get too cold. Those sitting next to the window run the risk of catching a cold.*' One teacher put it as follows: '*The biggest problem associated with ventilation is that students believe they can catch a cold when the windows are opened! Unfortunately, some colleagues also believe this, which leads to collective whining during every ventilation process, which in turn disrupts the lesson!*'

Another problem encountered in class is related to **external noise**: '*city noise'*, *'street noise is a problem when working on learning content'* and *'outside noise is considered very annoying*'. In addition, there are building sites where '*the noise is often unbearably loud at short notice or when the lawnmower has to be outside in autumn or winter*'. This leads to teachers closing windows and reporting that '*It is almost impossible to hear what pupils are saying when the window is open*'. Teachers also said that they adapted '*When there was disturbing noise from outside (e.g. rubbish collection outside the window), the windows were closed temporarily and then opened again*'. The timing of ventilation is considered a solution here as well with respect to the assignment of learning/ teaching phases for either ventilation or keeping windows closed: '*Ventilation during quiet work phases works well. Opening the windows and explaining something at the same time is not possible due to the street noise.*'

Also, **internal noise** is reported from adjacent corridors due to teachers trying to cross ventilate whilst keeping internal doors open. '*Air circulates poorly in the classroom during shock ventilation, the classroom door must also be opened wide. This causes noise from outside and from the corridor. If there is a lot of noise from outside, I open the door from time to time and ventilate from the corridor. There is far too much noise on the street to ventilate without noise! In addition, it is sometimes too noisy in the corridor to ventilate without problems. And verifiable ventilation only works if the door is opened as well. Ventilation only through the window has far too little effect on the result according to the measuring device.*' Or '*Opening windows and doors into the corridor to create draughts when it is very hot outside, which heats up the room (towards the end of the lesson, however, concentration is reduced due to noise from the corridor).*'

Using the concept of **sensor-based ventilation** was mentioned positively by many: '*Ventilating when the air quality was demonstrably poor is good and sensible and was only enforceable in this way because of the red warning light.*' One teacher commented that '*for the past three years they even had their own self-made CO_2 measuring device that works very well and is easy to read from a*

[27] Whilst evidence suggests that indoor temperatures < 18 °C are associated with negative health effects, the evidence is insufficient to allow clear conclusions regarding the direct impacts of specific temperature thresholds for different population groups (i.e. independently of the effects of higher respiratory pathogen numbers circulating in wintertime) (Janssen et al., 2023).

distance of 10 metres', and '*The students at our HTL have become accustomed to this system and use it to ventilate automatically!*' '*Students just check to see if it is lit up red.*' Equally, using a **CO_2 champion** in class was mentioned as a solution and setting up a student roster so that '*a different child is responsible for airing the room every week*'.

In this light, educating students and teachers, **raising awareness** as to the importance of ventilation and **generating acceptance** are noted as critical factors by some teachers. '*Explaining the ventilation process and CO_2 values to a class*' is mentioned as a solution to some of the above issues. '*The measuring stations that display the value are very helpful and the students are more likely to accept airing in this way.*' Or similarly, '*the display helps as a justification for opening the windows*'. Finally, one well-informed teacher wrote: '*I believe that students and teachers should be regularly, but at least once a year, informed (by external experts!) that you "catch a cold" in poorly ventilated, warm classrooms and not in well-ventilated, briefly cool, classrooms!*'.

5.2.2.2 Common solutions and knowledge diffusion

When it comes to documenting what has helped teachers to ventilate many quite subjective responses are listed that have very little to do with the sensor itself. Noise and common sense were mentioned many times, as well as subjective perceptions of '*bad air*', *'first-hand knowledge'*, *'smell'*, and other personal perceptions of air quality (e.g. '*because breathing becomes more difficult'*).

People responded that they '*air when necessary*' (e.g. because of stale air, or being too warm), that they follow their own intuition, their own sense of poor air quality, and the smell when entering the class. For example, one teacher wrote: '*My nose, which notices when it stinks in the class, and my head, which starts to hurt when the air is bad – of course this is much too late. Or the CO_2 saturation in the room increases over time, depending on the number of people. You don't need an app or a sensor for this. The sensitivities of the students must be taken into account (too hot/too cold/draughty).*'

Someone who considered the sensor a disruption wrote '*We have always ventilated when necessary. The system's traffic lights were a major disruption to teaching and always caused unrest and heated discussions among the students, as some who sit right next to the radiators find ventilation pleasant and those who are far away from them are constantly freezing and have to wear their winter jackets. I can ventilate with common sense in my class. Nevertheless, we have had and still have many corona patients and various flu cases.*'

A large number of teachers also mentioned the sensor and CO_2 related ventilation e.g. '*With the sensor display, it is easier to explain to students that ventilation is now necessary.*' Some even reported that '*students ventilated even independently*' and teachers did not really have to do anything. Some schools commented that they have additional sensors installed, even some with an acoustic signal at 1400 ppm.

Raising awareness, improved communication-and starting conversations about the CO_2 sensors (even if some were not visibly displaying data) were considered important, so that the students ventilated more often. Some shared their '*positive experience*' as students reminded them or alerted teachers that the limit has been exceeded. Some highlighted the importance of the children in general as their behaviour had quite an influence and that some '*were sensitised to the situation and always informed teachers about worrying values*'.

Some added '*markings on the class clock to remind them of regular ventilation intervals or used a trigger via the school bell*'. The '*knowledge that you have to ventilate at least every 20 minutes*' helped to adhere to purge ventilation or keep the windows tilted '*if the temperature allowed it*'.

Some ventilate routinely, i.e. '*they air every time they enter the class!*' A couple wished for a fully automatic ventilation system, which they called '*the ultimate*'. Some wished for more instructions or complained that '*unfortunately, they had no instructions at all about the devices*'. Some teachers (in the control classrooms) without a visible display however also commented that they received instructions and support from colleagues.

One person seemed rather annoyed and wrote that he/she '*ventilates the classroom at their own discretion and does not need an additional measuring device for this!!!*'. The point of '*own discretion*' is made by another teacher, he/she also '*does not need a device to tell when the air is bad*'. Some refused to engage, whilst they knew there was a sensor present in their classroom they simply did not want any instructions and wrote that they *'will ventilate when it suits'*. Thinking about ventilation while teaching is considered by some to be '*an additional challenge*'.

An interesting and positive remark was made by one person (which is likely to be applicable to other teachers who occasionally teach in rooms with a sensor): since he/she '*teaches in a class with CO_2 sensors with and without display*' he/she has learnt '*to ventilate the other classes as well while the air still feels good*' because he/she noticed that the target value was usually exceeded by the time the air felt stale. Likewise, a teacher from a control room stated that despite the fact that there is no visible display in the room, '*awareness has increased as a result of the campaign*'.

5.2.2.3 Additional ideas to support ventilation

Although some teachers stated that everything was clear to them many offered simple solutions that would not cost much time or money, for example: '*Provide easier opening of windows or skylights*', or (rather than an automatic ventilation system) '*free up window areas (i.e. no school desks right next to the windows)*'. Someone desired the option to '*ventilate during breaks*' (apparently some in-house rules prohibit ventilation during breaks) and few wished for '*fewer students per class/larger classrooms so that then the air is not used up so quickly'*. In terms of the room layout, some wished for fewer desks in the room and better access to windows. Consequently, this would mean fewer students sitting right next to open windows. Notably, automatic window and shading devices were considered to be a '*catastrophe*' and '*a hindrance to natural ventilation*'.

'*A larger room or fewer students*' is something that many pointed out makes it easier to achieve a good CO_2 level in winter, as they have realised that '*a quick airing once before the lesson is not enough*'. Apart from the sensor many wished for a reminder at the teachers' table to air the rooms. Some pointed out that the school is using a quarter-hourly airing gong. One teacher wrote: '*If the values are too bad, it gets too warm*', then an alarm should go off to remind teachers to air the rooms and also to close the windows again. Some even report excessively warm temperatures in classrooms in winter, which is why the windows are open for a long time, even in winter.

One teacher wished for '*an acoustic (single, unobtrusive) signal when the CO_2 limit is exceeded or the option to start a timer directly on the device at the push of a button, which emits an acoustic signal to close the window after some minutes*' or '*a visual signal that children can see and act upon such as an enlarged traffic light*'.

Some wished for educational support in advance so that ventilation does not distract from teaching or '*simple tips on an A4 page, nothing too complicated*' that could help '*make regular ventilation a habit in all lessons*'. General information about why the sensors were installed, and that '*the installed sensors are actually relevant*' and '*not just for research purposes*' was requested. Practical issues were reported to over-ride air quality, e.g. '*the problem is that there are many more students who quickly find it much too cold and, if the air is not bad at the beginning, I do not pay attention to the air quality during the lesson (I am otherwise occupied).*'

Intermediate and more expensive solutions suggested by teachers were '*larger windows that can be opened*', '*more windows*' and '*proper windows*', '*air purifiers*', '*CO_2 sensors with display and possibly an acoustic warning signal in all classes*'.

More complex and expensive options (but still within the power of the school owner) would be '*a permanent mechanical ventilation system*', '*ventilators in summer and/or the provision of air conditioning as the temperatures in the classes are often unbearable even in the first lesson*'. In one case, a teacher claimed that '*ventilation is pointless anyway, as only warm air would get inside*. *This has a negative impact on CO_2 levels and therefore also on the performance of the pupils*'.

Mitigating street and outside noise in order to help teachers to ventilate better is, however, very difficult to realise. Most teachers simply stopped ventilating when outside noise levels became disruptive.

A small number of teachers where either completely resistant to, or dismissive of, the need for ventilation. One person wrote that he/she '*ventilates the way he/she wants, regardless of when the ppm value is high, when it stinks and when there is not a single molecule of O_2 left in the room.*' Another one wrote that he/she '*does not pay attention to regular ventilation and is not sensitised to the CO_2 issue*'.

Conversely, several teachers commented very positively that, '*Information from the sensor is great*' and that they '*don't have any wishes – it works*'. '*The students have become sensitised to the topic.*'

5.2.3 Second survey (summer) – results

Towards the end of the monitoring period (after the summer break) the teachers were surveyed again in order to uncover any seasonal or project related changes in their responses. The teachers were first contacted in early June with reminders being sent in July and September (Fig. 5-4). The survey remained open until the 20.09.2024.

In the summer survey, there were 598 valid respondents, 427 (71.5%) with visible displays (T) and 171 (28.5%) without visible screens (C). Although the total number of responses dropped from 771 to 598, in the summer survey, the distribution between the control and test groups remained almost identical. All plots relating to the second teachers' survey can be found in Appendix C.2.2.2.

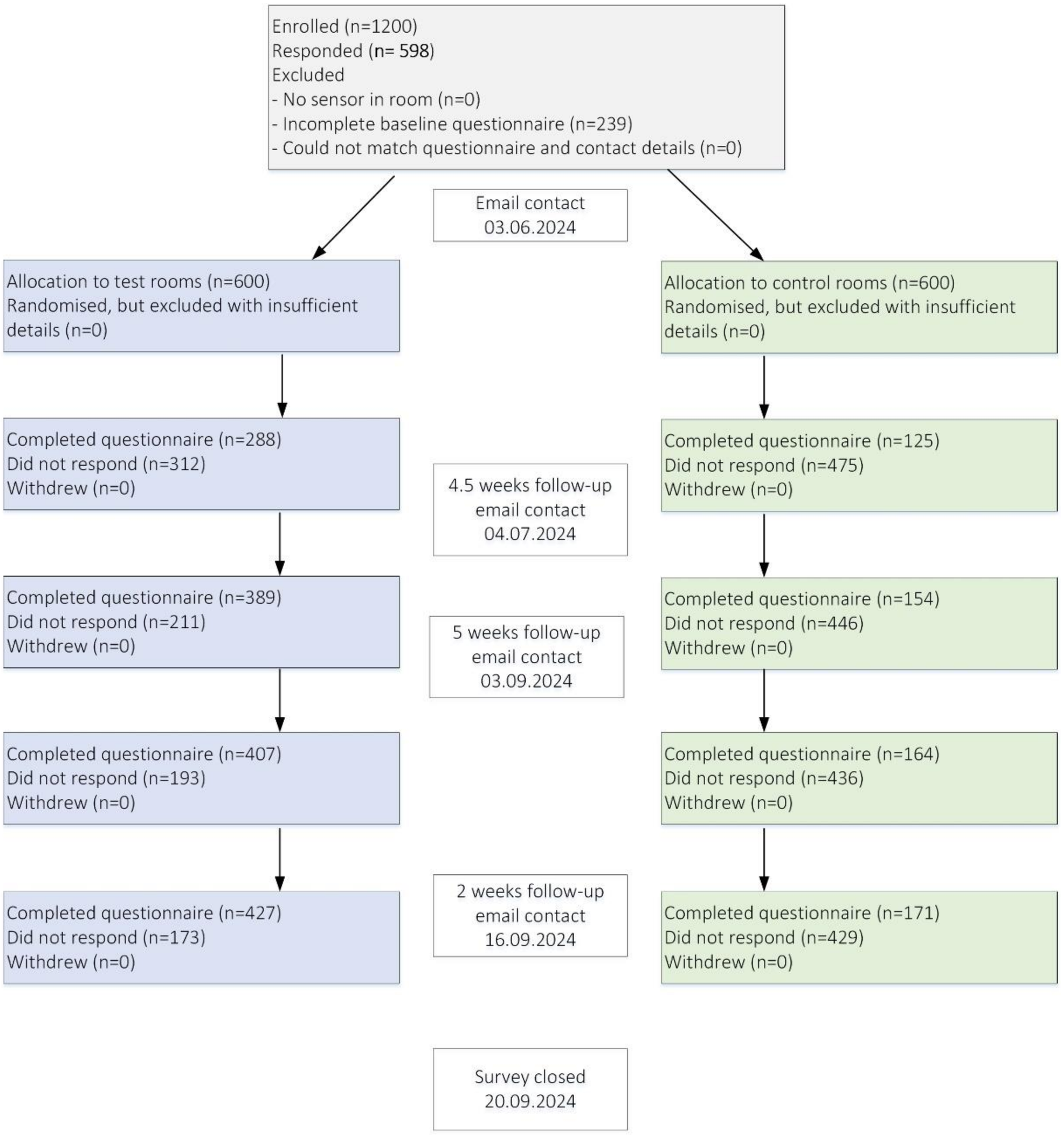


Figure 5-4. Workflow of the second teachers' survey, including timescale and method of contact.

Only 27.7% responded that temperatures were acceptable during the past year when ventilating. 29.1% replied that temperatures were often too warm, with an additional 2.7% saying they were always too warm. This corresponds to the response that 36.2% would like temperatures '*often or always to be cooler*', and 42.5% '*only sometimes*', while 21.3% stated '*seldom or never*'. This gives an indication that many classrooms are potentially too warm during the summer.

In terms of draughts in summer, 87.6% responded that '*they do not feel a draught or find it pleasant, or even very pleasant*'. This is in contrast to 12.4% who responded that '*they consider it as unpleasant or even very unpleasant*'. 61.2% would prefer at least '*a bit more air movement*', whilst 27.9% '*did not want any change*', whilst the remaining 10.9% would '*prefer less air movement*'.

In relation to external noise, 52.7% considered outside noise as '*disturbing or even very disturbing*', whilst 32.6% '*do not consider it as disturbing*', with another 14.7% being '*neutral*'.

Whilst 36.6% responded that '*student concentration is improved via ventilation*', 20.9% responded that '*ventilation worsened concentration*'.

In the summer survey, 59.5% responded that '*temperatures had been too warm*' whilst 8.9% of all teachers said '*they were too cold*'. 59.5% considered noise an issue during ventilation, and 14.7% considered draught an issue. Only 6.2% considered outside air pollution to be a problem.

In terms of barriers to opening windows, 17.9% faced problems such as permanently closed windows or conflicting shading devices, whilst 25.1% were unsure whether to ventilate. Interestingly, 50.2% responded that '*school regulations prevented them from opening windows in order to save energy*'. Whilst 63.5% said '*it was a personal decision to not waste energy*'. 15.6% stated that '*their class is restless when they ventilate*' and 11.7% responded that '*ventilation distracts and is unpleasant*'.

Question 9 tried to establish what has helped teachers to better ventilate their classrooms. Most teachers stated that it was a CO_2 sensor with numerical display (29.3%), followed by a CO_2 sensor with a numerical display <u>and</u> RAG visual alerts (19.9%), followed by CO_2 guidelines with an explanation of limiting values (14.9%), followed by a CO_2 sensor with RAG visual alerts (7.7%), and lastly the ventilation guidelines (7.7%). 37.8% responded that '*none of the above has helped them to ventilate better*'. Whilst 18.6% responded that '*full automatic mechanical ventilation would be their preferred option*'.

Question 10 asked, *"What would or could help them to ventilate better in future?"*. The answers are presented from the highest to the lowest percentage of agreement: '*a stopwatch or timer (to measure the duration of window opening)*' (28.6%), '*a personal visit by a ventilation expert*' (20.4%), '*specific recommendations about the energy and CO_2 costs for the ventilation of their classroom*' (18.1%), and '*specific guidance on avoiding draughts when using window ventilation*' (13.4%).

In the summer survey, four additional questions were included as the survey was also conducted at the end of the project. The first additional question was designed to gauge teachers' knowledge of permissible CO_2 values in classrooms, the same question was already included in the directors' surveys. 66% of all teachers provided values of 1200 ppm or less, with only 7% providing values over 2000 ppm. The impact of introducing sensors and guidance documents is particularly evident when comparing the control group with the test group. Test classroom teachers (with sensor displays on) were over 10% more likely to know the correct threshold CO_2 value of 1000 ppm (38% of all respondents). Moreover, 70% of teachers with a visible CO_2 display provided values of 1200 ppm or less compared to 59% in classrooms without displays.

Question 12 asked, *"Do you think students should be informed about the impact of ventilation practices and air quality in classrooms?"*. Most teachers agreed that '*all students should be informed about ventilation practices and indoor air quality*' (65.4%). 22.7% said that '*it depends on their age*' wherein the following ages were indicated as appropriate: '*5 years or older*' (2.9%), '*8 years or older*' (15.4%), '*10 years*' (27.2%), '*12 or older*' (30.1%), and '*15 years or older*' (22.8%).

In relation to Question 13, *"Do you think students should play a role in maintaining ventilation quality?"*, 73.2% responded '*yes, we should appoint a student who is responsible for monitoring the CO_2 concentration and ventilating the classroom*'. Of those who said *'no'*, the majority thought '*it is the teacher's responsibility*' (58.3%). This opinion contrasts with the directors' opinions, where the majority believed that it's the role of the school to maintain the ventilation quality.

Question 14 asked, *"Do you have a CO_2 champion in class who monitors the CO_2, and then ventilates?"*, 96.3% said '*yes*'. 15.4% responded that '*they never or seldom manage to stick to the recommended CO_2 threshold*'. 71.9% answered that '*they sometimes or always manage to be within the recommended CO_2 threshold*'. 17.8% replied that '*it is difficult or even very difficult to ventilate* *correctly with a CO_2 sensor*'. In contrast, 70.9% responded that '*it is very easy or easy to ventilate correctly with the help of a sensor*'.

Next, teachers were asked about the difficulties they encountered when using a CO_2 sensor. The answers are presented from the highest to the lowest percentage of agreement: 73.8% have '*no difficulties*', 5.6% '*have to look at the manual before using the sensor*', 4.4% stated that '*the sensor behaves in unexpected ways*', 3.5% '*find the sensor display confusing*', 2.3% '*find the ventilation guidance unclear'*, 2.1% '*find the sensor instructions unclear*'. Overall, this finding is positive, as the majority of teachers did not report any difficulties when using the CO_2 sensor.

These findings were reconfirmed by asking which of the following statements is correct, 60.2% stated that '*they have no problems with the sensor*', and 25.1% responded that '*with the new CO_2 sensor and the ventilation instructions it is easier to keep the CO_2 values in a good range*'[28].

In terms of their future ventilation behaviour, the answers are presented from the highest to the lowest percentage of agreement: 43.1% stated that '*they are planning to ventilate better*', 15.2% responded that '*they are still practising how to ventilate correctly*'. 14.5% said '*they are unsure how to keep up ventilation*'. 9.1% said '*they have to cope with resistance by students and staff'*, while 8.4% responded that '*they are still learning to understand the sensor*'.

In terms of the impact of the CO_2 sensor and guidance on ventilation behaviour, the answers are presented from the highest to the lowest percentage of agreement: 63.9% stated that '*they think that more frequent ventilation is a good idea*'. 47.5% thought that '*the new CO_2 sensor and ventilation guidance is a good idea*'. 32.6% reported '*making an effort now, with the help of the CO_2 sensor and the learnt ventilation techniques to keep up good air quality in a classroom*'. 16.2% '*now have the knowledge and the means to ventilate correctly*'. Only 6.1% thought that '*the CO_2 sensor and ventilation instructions are pointless*'. 8.9% were '*unsure if the CO_2 measuring and ventilation is a good idea'*. Whilst 3.7% expressed that they '*did not understand the purpose of measuring CO_2 and ventilation*'.

In terms of the importance of the CO_2 concentration and regulating the amount of ventilation required, the answers are presented from the highest to the lowest percentage of agreement: 55.7% stated that '*they are opening the windows several times a day*'; 32.9% '*only looked seldomly at the CO_2 sensor*'; 19.7% '*never looked at the CO_2 sensor*'; 18.7% '*have the tendency to use the new CO_2 sensor as a guidance for their ventilation behaviours instead of keeping the windows closed*'; 17.7% '*looked often (or several times) at the CO_2 sensor*'; 12.5% '*observed the CO_2 with great attention and then ventilate several times a day, in order to obtain the best indoor air quality*'.

In terms of their personal perceptions of the CO_2 sensor, the answers are presented from the highest to the lowest percentage of agreement: 40.6% stated that '*they like to look at the CO_2 sensor*'; 20.4% said that '*the CO_2 level is of no interest to them'*. 17.7% said '*they have no time to use the CO_2 sensor*'. 5.4% responded that '*they are opening and closing the window so often that it distracts them*'. While 4.2% remarked that '*the sensor depresses them*', whilst an even smaller percentage (1.5%) commented that '*they are not interested in indoor air quality*' [25].

[28] It should be noted that the responses to the second teachers' surveys were provided by teachers occupying both T (71%) and C (29%) classrooms. The responses to questions related to the benefit of (or interactions with) visible interventions (such as CO_2 sensors and wall display posters) will be influenced by this fact and should be interpreted accordingly.

5.2.4 Open-ended answers – summer survey

5.2.4.1 Common problems and solutions

For a number of questions, it was possible to add additional comments in a section entitled ‘*other*’. For example, for the question ‘*If you have encountered one or more of the above problems and have found a way around the problem, please describe the problem in more detail and how you solved it.*’

In the summer survey, most of the comments concerned the topic of noise. For example, ‘*Unfortunately, the street noise outside is very loud here*’ or ‘*When the window is open, it is no longer possible to have a classroom discussion as the noise from the street means that we can't hear each other.*’ In some cases, teachers wrote that ‘*there is no solution*’. Noise could also be related to children playing outside in the courtyard, which resulted in teachers opening the internal doors to corridors instead. Others were quite pragmatic and wrote ‘*If the street noise is loud, then as a teacher I have to speak loudly too*’ or they answered that ‘*the children were able to deal with it quickly (1–2 reminders)*’. The majority however, simply closed the windows to minimise external noise intrusion or opened windows only at one end of the classroom, or ventilated intermittently, or ‘*mostly when pupils didn't need to be so focussed*’ and ‘*during the breaks*’. One teacher wrote that ‘*they were not sure whether to ventilate based on noise*’ and simply asked the class for their opinion. Reviewing internal school regulations to minimise noise on the school premises, also in relation to maintaining indoor air quality, was considered to be an important issue by some.

Some teachers raised the problem of thermal discomfort. In summer, some considered it less of a problem as ‘*temperatures are pleasant (10–20 degrees in summer...)*’ however another responded that due to the high outdoor temperatures, ‘*good ventilation is and was almost impossible*’ and that at times they ‘*already had almost 30 °C at 10.00 am*’ which then increased to the mid and high 30’s. As a solution to ‘*the hot air coming from outside*’, the classroom was ventilated before the start of lessons. Notably, experience in conducting sensor-based ventilation has helped some teachers to find the right rhythm in ventilating in relation to specific classroom activities, e.g. when students do practical work and not during phases where they have to listen or explain something. In the summer, teachers did not look at the sensor that often, ‘*the window was often open when I entered the classroom*’. They also reported ‘*no ventilation discussion*’ (i.e. nobody froze and demanded that the windows be closed). However, at the height of summer, some felt that many ‘*people don't know how to ventilate properly*’ in terms of keeping temperatures at a minimum and that they ‘*leave the window open for hours when it's almost 30 °C*’ so that the room temperature heats up unnecessarily. In cooler periods (e.g. during spring), the situation was different, and teachers wrote that the class then ‘*didn't appreciate it when they aired the room*’. Some opened the windows anyway (in particular the window nearest to the teacher's desk) to avoid students becoming cold. In particular, girls were mentioned to have issues with the cold and subsequently closing windows. Similarly to temperature, wind was reported as an obstacle to ventilation, causing teachers to close the windows.

Issues with keeping within the recommended CO_2 thresholds **using a sensor** were noted: ‘*Ventilation would have to be virtually continuous in order to maintain the air quality, which leads to extreme temperature fluctuations and noise issues.*’ As in the winter survey, this led some to adapt ventilation behaviour based on classroom activities, e.g. if students were working independently, ventilation was considered less of an issue compared to during didactic teaching. Thermal discomfort led to some teachers being more relaxed about the CO_2 thresholds, as they concluded that ‘*it was unpleasant to bring extremely high CO_2 levels back down to a safe level*’. Or ‘*sometimes it takes 15–20 minutes to bring the level down to < 1000 ppm*’. This occurred when teachers did not ventilate for 2 hours in order to have '*more peace and quiet in the room*'. The latter comment suggests that some teachers may be consciously avoiding ventilating their rooms to benefit from the sedating effect induced by elevated CO_2 levels and warmer temperatures.

Even in summer, **energy consumption and heating control** contributed to the problems reported. One teacher said that '*in general, the classroom is heated centrally - when it is warm in the transitional months, the classroom is overheated because it is centrally controlled, and the heating cannot be turned off*'. Another teacher reported a similar problem adding that it is '*complete madness, because the unnecessary energy consumption is also insanely harmful to health (dry mucous membranes) and you end up with unbearable room temperatures that drastically reduce performance!!!!*'.

Construction related issues were often mentioned. One school went through a renovation process with scaffolding of the '*entire school building including plastic covers on windows*'. Here, teachers took remedial action by cutting some of the covers open to allow ventilation. The issue of fire protected doors and windows were reported as barriers to cross ventilation. Also, the location of the windows (sometimes too high up) did not allow some to physically reach and open the windows, so that tables had to be moved, and pupils had to climb up to open the window. One improvised solution, to the issue of windows closing by themselves (even without a draught), included using a broom propped in the window frame to keep it open. To allow more airflow into the rooms, teachers reported having '*opened all possible windows and our classroom door to get enough draught*' during breaks but then having to close them again during lessons.

A number of teachers said that they did not try **time-based purge ventilation** as they did not want to '*just ventilate every 20 minutes*' or that '*only every 20 minutes is too infrequent*'. Side effects such as headaches were reported which is why they kept '*at least one*' window open all the time. Pupils also took part in actively ventilating. Also here, female students were mentioned to be '*generally more sensitive to temperatures, which limited ventilation somewhat*'. Contrary to some teachers stating that ventilation makes students restless, one reported that '*The class is not restless when I ventilate. The class is breathing halfway normally again.*' Only one **negative** answer was included in the open-ended responses, wherein one teacher declared that '*the sensors are completely rubbish! Common sense guides a responsible citizen to ventilate!!!*'.

5.2.4.2 The timing of natural ventilation

In response to the question of how teachers dealt with the timing of natural ventilation a few standard answers were offered including '*using a sensor with a numerical display*', '*RAG visual alert indicators*', '*guidance documents*' etc. In addition to these set responses, the teachers could also add their own comments, which were mostly positive. One teacher responded that they '*carried out a project on CO_2 levels using a mobile device*'. Some teachers also mentioned using their own personal CO_2 measuring device with an acoustic signal at certain CO_2 threshold to help them ventilate better.

The role of the students was highlighted in the sense that '*pupils wishes*' often played a role, and that '*pupils sometimes had their eyes on the sensor and occasionally reminded me to ventilate*'. Also raising awareness that fresh air is important and healthy has helped, and that a '*class roster*' was introduced to delegate responsibility to ventilate. Some said they don't need an additional reminder as they '*are used to ventilating*', or they '*ventilate all day*', or '*all year round*', or even '*almost constantly, even without a measuring device, as long as the pupils can stand it*'. Only one teacher (0.17%) wrote that '*these sensors are unnecessary*' and that he/she wants them to be removed.

An important note that was raised was that every new teacher who teaches in the school is '*not necessarily familiar with the CO_2 limits, etc.*', hence highlighting a clear need to have regular briefing sessions or provide material to inform new staff about sensor-based ventilation and the impacts of indoor air quality on occupant health and wellbeing.

5.2.4.3 Additional ideas to support ventilation

A number of suggestions were provided by the survey respondents to support better ventilation practices: including, video seminars, a stop-watch timer, additional advice, or a visit from an expert. Some responded that they '*found the CO_2 sensor with display helpful enough*', but some also remarked that '*as a classroom occupant, you only notice the bad air late, which is why some additional measures would help*'. The ideas suggested can be categorised in terms of those that can be easily implemented and those which are more difficult to apply.

Aspects that could be changed **more easily,** which were mentioned by teachers, are as follows: '*repaired windows*'; '*introducing an automatic announcement or a regular reminder when to ventilate during lessons, possibly an alarm clock or similar*'; '*installing CO_2 sensors in all classrooms*'. Those teachers with sensors without a visible display (i.e. 'C' classrooms) reported that they would like a fully functioning sensor in their rooms[29]. In relation to facility management some reported that '*there are ventilation systems in some of the classes that nobody knows whether they work at all*' and that are '*completely ineffective*'. Some wished for the '*possibility of letting cool air into the rooms at night*'. Finally, yet importantly, teachers wished for reminders by pupils during class and requested their '*active involvement*' in ventilating the classroom.

More difficult and expensive to implement are requests involving structural changes, such as: '*more and larger windows*', '*windows that can be opened*', and the possibility to achieve cross ventilation. Even more expensive (and/or logistically complex) would be the installation of '*mechanical ventilation systems*' (requested by two teachers), or the provision of a '*fundamentally better indoor climate (e.g. through thermal refurbishment or more efficient insulation to avoid 35 °C or more in the classroom*'). Some teachers also wished for '*lower numbers of children per classroom*' as a means of improving the air quality.

Some just wished for '*ventilation without pupils freezing to death*', '*ventilation without street noise or noise from outside*', but also realised that it is '*very difficult to change aspects related to noise*' and that it is sometimes even impossible to open windows in the summer due to the noise outside. Some teachers responded very positively, that 'it works very well with the sensor', that they have now '*introduced the role of a ventilation officer*' in class, and that '*it would be great if such a device (with a visual display) was in all classes*'. Nevertheless, for some ventilation seemed to be an emotive topic, which could also be seen in a couple of the answers in this section. One person wrote that '*the suggested answers are an affront*' and that they are '*grown up enough to ventilate appropriately with the help of the sensor display*'. Another person wrote that they would rather '*need to be paid overtime*' and that they do not need '*technical solutions for ventilation!*'.

5.2.4.4 CO_2 champion in the classroom

In the final (summer) survey, over 90% of all teachers who responded stated that they have a CO_2 champion in their class. This was explained by some in more detail. The number of students helping

[29] Note that after the project finished (September 2024) all the 'C' sensors with blank displays were switched on.

differed from a single person to two or three people, or even the entire class. In some classes this person is appointed at the beginning of the year and is responsible for monitoring the CO_2 concentration and either informing the teacher or ventilating the classroom accordingly. Some also referred to '*energy officers in each class*', who take over the role of monitoring the ventilation as well. In one example, where two pupils per class were authorised representatives (according to the class constitution) training was also provided. The use of weekly '*classroom presidents*' (that are also responsible for blackboard service, handout distribution etc.) was considered a good way of keeping an eye on the CO_2 value.

In terms of the selection of students, in some classes it was simply '*the pair sitting closest to the measuring device that had the task of watching the screen and, if necessary, alerting the teacher when they need to ventilate*'. Similarly, pupils in the first row were sometimes designated as responsible for ventilation '*and drew the teacher's attention when the value rose above 1000 ppm*' or '*when the device was flashing*' as teachers often could not see this straight away because they had their backs to the device.

5.2.4.5 Common difficulties using a sensor

In terms of the difficulties encountered when trying to ventilate adequately during the summer months, most answers mentioned noise, outside and inside temperatures. Whilst some would like to ventilate more often, it was '*not always possible due to the noise*' on the street, in the schoolyard, etc. so they only sometimes reached the correct value.

Despite regular ventilation procedures some respondents appeared frustrated as they did not seem to be in a position to prevent high values of CO_2 from occurring, reporting that '*values are constantly too high in our building*' and '*despite regular and proper ventilation, it is not possible to comply with the recommended values*'. Despite sensors and open windows, they could not reach the required value '*because i) cross-ventilation is not possible and ii) the window openings are too small*'.

Some stated that, *'the sensors were not functioning'* (for those in Control rooms the displays were turned off during the study)[25], and because of that they did not notice them and did not pay attention to them. Teachers also noticed that students liked to play with the sensors (by breathing or burping into them). Some referred to the size of the sensor display and commented that it was '*too small to stand out*' and that '*it needs to be bigger to see the value*'. One person expressed their irritation by stating that the '*sensor is annoying*' and that he or she has '*no time to always think about the sensor*'. The importance of appropriate ventilation training was highlighted, where some complained that they '*did not receive instruction*' and that *'training was desired or missing'*[30].

5.2.4.6 Additional comments – summer survey

A large number (>50) of very positive comments were mentioned in this section. First of all, the sensor is reported to be '*a good indicator of when it's time to air the room properly*'. In addition to this, responses were as follows: '*The sensor is easy to understand*', '*helpful*', '*a good idea*', '*great support*', it helps to '*ventilate properly*', '*it's great*', it is '*connected to a feeling of well-being*', and it makes users '*feel good when airing the room*'.

[30] In designing the ImpAQS project the idea of ventilation and sensor training was discussed with the BMBWF (as a means of maximising teacher engagement) however this was considered to be too demanding on teachers' time and was therefore omitted.

Overall, many stated that '*everything works well*' and that it is '*a great device*' and that they will adhere to the established system of checking the sensor and ventilating in the future. Also, many said that '*pupils keep checking it and alerting me*' when the sensor lights up red, for example. In some cases, teachers claimed, that just one usage helped them to immediately adapt their approach and conduct ventilation properly.

The ImpAQS project team did not try to intervene with ventilation behaviour or to educate school staff (apart from the two wall-mounted posters[27]) and so it is not surprising that some teachers reported that they '*wonder what the number means*' and that they are missing out on '*any instructions*' and that '*the purpose of the CO_2 sensor was never explained*' to them at school.

Many commented (as noted in the preceding section) about their disappointment at not reaching the target values. The CO_2 sensor works, '*but there is no improvement in the values despite ventilation*'; and that '*values stagnate at a poor level*' despite ventilating. Or that the room layout and window configuration is not helping as '*the sensor is only helpful if you can ventilate sufficiently*'. Some say that they like to ventilate because they think fresh air is important, but one person wrote that the '*big problem at school is the construction of the "new building"*', which was described as being *'unbearably hot in summer (despite open windows and doors)*'. This problem was exacerbated by the noise from the '*sports field',* which prevented them from ventilating. Others wrote '*there must always be at least one window open*' in the classroom, since only then will '*the figures on the sensor fit*'.

It is no wonder that for some teachers '*it's stressful*' to see that they are '*always above the recommended range*', even if they ventilate a lot. Some say '*the 'values always shock them*' and that they feel that the sensor shows them that '*they have no chance*' because e.g. '*the room is too small*'. To highlight one response: '*The air gets bad extremely quickly. Even when it's just ME (sic) in the classroom, the sensor often rises to over 500, although I usually start with 430 - 450. As soon as the first children enter the classroom, the sensor reading rises rapidly, so I start ventilating straight away.*'

Some felt like they had missed out and that they '*would like to have good air quality in the classroom*' and use a visible CO_2 sensor for this but that they had the '*model that did not show anything*'[26]. In the absence of a visible display, a few write that they rely on their instincts. Still, a strong commitment to ventilation can be seen as (despite not having visible displays) they report that in summer, '*at least one window is always fully open during lessons and sometimes even with the door open to let in a draught*'. In winter, it can happen that they only ventilate when the air is already very stale, or that they put rules in place such as e.g. to '*ventilate every hour if it's cold outside'*.

Some were very pragmatic and stated that they look at the sensor '*almost every hour at random*' and '*if the reading is high*' they ventilate and that '*the CO_2 sensor helps me to recognise the latest time to ventilate*'. A few teachers have their own additional measuring device that they bring with them.

There is a strong consensus that ventilation is important and should '*therefore be a matter of course*', which leads many to '*ventilate very often*' and only close windows during the break for safety reasons, or if it is cold or noisy outside.

Teachers also agreed that a significant wider argument in favour of having a CO_2 sensor is to help in '*achieving acceptance for more ventilation*' and '*raising awareness*' but that it also '*clashes with the temperature*' or *'energy problem'*. Students are sometimes unwilling to ventilate when it is cool outside but paradoxically still point out that the CO_2 concentration is too high.

Two teachers wished for bigger sensor displays and felt that the current sensor is too inconspicuous, so they do not notice it enough. Also, some complained that the sensor often gives '*very delayed readings*'[31].

On the negative side, one teacher said that he/she is '*of the opinion that this study is a waste of time! There is no way around automatic ventilation of the rooms and that is what this study will produce!*' Another wrote that, '*Unfortunately, it will fail because of the funding and all schools, but mainly the privately run ones, will "muddle on" as before regarding this topic.*'

Overall, the ventilation of classrooms is a polarising topic, and some teachers are clearly sceptical as to whether the study will contribute to meaningful change. However, the vast majority of responses were very positive, with teachers appreciating the installation of the devices and asking for functioning sensors (in those rooms without a visible display). In general, CO_2 sensors were desired in all classrooms, along with further training and expert support.

[31] The CO_2 sensors were set to provide new readings every two minutes, however the sensor's location (away from the windows) on an internal wall means that it can sometimes take a few minutes for the room air to mix with fresh air and for this to be recorded by the sensor.

5.3 Summary and consolidation of the qualitative findings

Looking at the differences between the winter and summer teachers' surveys, approximately the same number of teachers stated that the temperatures, whilst ventilating, were often too low or too warm (in 2023: 31.5%; in 2024: 29.1%).

In terms of draught, during the teachers' summer survey more people (32.9%) responded that they do not feel a draught, compared to the winter survey (23.2%. A significantly larger percentage would prefer some, or more, air movement in summer (61.2%) compared to winter (33.6%). Noise is perceived as a bigger issue during the summer period, with 52.7% being disturbed by outside noise in summer compared to 42.8% in winter. Issues with student concentration whilst ventilating seemed to be reduced during the summer months, with 20.9% of teachers responding that students had difficulties concentrating, compared to 28.0% in winter.

In winter, classroom temperatures had been reported as being both too warm (36.8%) and too cold (38%), whilst in summer, almost 60% reported temperatures as being too warm. More teachers considered noise to be an issue in summer (winter: 46.8%, summer: 59.5%), however, fewer draught related problems were mentioned (winter: 30.6%; summer: 14.7%). Outside air pollution was not considered a hindrance to ventilation in either summer or winter (in both cases around 6% of teachers identified it as an issue). During the summer survey, around half as many teachers reported that their students were disturbed by ventilation practices in summer (15.6%) compared to in winter (29%). Conversely, (during the winter survey), almost double the number of teachers reported that ventilation '*distracts and is unpleasant'* in winter (20.4%) compared to summer (11.7%).

There is no difference in the order of items that could help teachers to better ventilate, between the two surveys. Most (around one third) selected a CO_2 sensor with a numerical display in the winter and summer surveys. Around a quarter selected a CO_2 sensor with a numerical display <u>and</u> a RAG visual indicator.

In terms of what would or could help them to ventilate better in the future, there is no qualitative difference to be noted between the seasonal surveys. Many teachers would like an alarm or timer to remind them when to ventilate. More teachers managed to comply ('*always*' or '*often'*) with the recommended CO_2 values in summer (71.9%) (question 15) compared to in winter (50.2%) (question 11). In terms of how difficult it is to ventilate with the help of a CO_2 sensor (question 12 in winter and question 16 in summer), less people found it difficult to ventilate in winter (13.5% compared to 17.8% in summer). But also less people found it easier in winter to ventilate overall (63.1% compared to 70.9% in summer). This apparent contradiction highlights the conundrum that on one hand, it is easier to achieve lower CO_2 values in winter due to the temperature dependent air-pressure difference; but, at the same time it is more challenging to maintain thermal comfort. In terms of the technological adaptation questions, less people seemed to have difficulties with using the CO_2 sensor in the second survey (in winter: 63.5% and in summer: 73.8% reported no difficulties), providing evidence of having improved their familiarity with the CO_2 sensor and ventilation guidance. Equally, fewer teachers seemed to have problems with the sensor per se (in winter: 51.1% and in summer: 60.2%), hence almost 10% more of all participating teachers had become accustomed to the sensor with the passing of time.

In terms of the differences in the additional comments (i.e. open text-based answers), in the winter survey, many teachers reported ventilating based on common sense and their own feelings (rather than using the sensor). In the second (summer) survey, the desire for a signal, timer etc. to ventilate was more evident. Also, a large percentage of classes appear to have voluntarily appointed a CO_2

champion since the first survey, reminding the class when to ventilate. In the first (winter) survey, the misconception of catching a cold (from cold air) was mentioned multiple times. That it was not mentioned in the second survey could have to do with the increased ambient temperatures in summertime or an improved awareness of health-related and air quality related matters. Issues related to education and awareness in class, with respect to (a lack of) ventilation and its implications for health, were aspects that were mentioned multiple times by teachers in the additional comment section.

5.3.1 Answer to the research question 5

This section is primarily aimed at answering **research question 5** *but also provides further qualitative evidence in support of* **research question 2.** In terms of **research question 5**, the results showed that 99% of all school directors see either a potential or a very positive effect from introducing CO_2 sensors and ventilation guidance in classrooms. Directors from elementary and middle schools were amongst the most positive in relation to the introduction of CO_2 sensors and instructions on how to use them to improve indoor the air quality in classrooms. The main motivations for ventilation were identified as: reducing the risk of transmission of viral aerosols and other airborne contaminants in classrooms, improved indoor air quality, and the improved performance of students. The overwhelming majority (96.3%) of all teachers answered at the end of the monitoring period that they have now appointed a CO_2 champion in class who monitors the CO_2 level and then informs the teacher or ventilates accordingly. This is an incredible voluntary response to the ImpAQS study. Half of all participating teachers think that a CO_2 sensor and the provision of ventilation guidance is a good idea, with around 25% agreeing that a CO_2 sensor helps them to improve their ventilation behaviour. Only a very small minority (2.1%) of all respondents answered that indoor air quality is of no interest to them. Equally in the text answers, only two respondents supplied negative comments (whilst the majority were very positive). These two respondents reported feeling powerless to maintain appropriate CO_2 values and to comply with the required targets due to practical and environmental constraints.

In terms of barriers, around half of the respondents (50.2%) reported that school regulations prevented them from opening windows, in order to save energy. 18% reported having physical problems opening the windows, whilst 73.8% had no difficulty using a sensor. Temperature and noise were reported as the biggest barriers to ventilating sufficiently in winter. Similarly, wind was reported as an obstacle to ventilation. In relation to thermal comfort (**research question 2**), localised thermal comfort differences within classrooms were mentioned multiple times with students closer to the windows suffering from the cold more than others. Girls were also identified as suffering more from the cold than boys.

Noise was the biggest barrier to ventilation in summer (**research question 2**). In addition, teachers often mentioned issues with the construction or maintenance of the building that prevented them from opening windows fully. Temperature also played a role in summer but mostly in the shoulder seasons or during the warmer months in the context of overheating. Some teachers and directors saw a hindrance in using CO_2 sensors in practice, particularly where they may not have understood the *importance* of ventilation. This barrier can be overcome by raising awareness and providing instructions and training to both, students and teachers. Some teachers initiated this process in class by raising awareness and including students in the ventilation procedure (via the CO_2 champion) or by initiating class projects related to air quality. Clearly there is no sense in installing sensors, if people do not know what CO_2 targets are required, or how ventilation can be achieved in a healthy, comfortable and efficient way.

The expression that ventilation is a 'cultural technique' was mentioned, meaning it is or needs to become part of who they are (i.e. culturally accepted). This means an entire shift in awareness, which could be instigated by providing an informative briefing session at a regular interval (e.g. once a year and/or for all new staff members). Continuous training and independent monitoring will be needed to ensure widespread compliance with existing and emerging ventilation standards. Such procedures are already being implemented in schools in France and other European countries (Section 2.5.3). Training of facility managers in mechanically ventilated buildings should incorporate aspects such as filter cleaning, filter specification, appropriate ventilation flow rates, and control strategies (also during pandemics). The training of teachers working in naturally ventilated buildings would answer questions on why and how to ventilate (e.g. tilt versus purge ventilation), what are appropriate CO_2 threshold values, dealing with draughts, the pros and cons of using cross-ventilation from corridors, amongst others.

6 Discussion

The discussion section aims to derive meaning from the most important findings of the ImpAQS study and contextualise them in relation to previous studies and existing practices and standards. This synthesis serves to provide the basis for actionable outcomes where the findings are clear, and when there is uncertainty to highlight areas where additional research may be needed. This section is divided into the following sub-sections: Section 6.1 – Contextualising the quantitative findings in relation to previous studies and European standards; Section 6.2 – Contextualising the findings in relation to emerging 'health-based' ventilation guidance; Section 6.3 – Cost–benefit analysis of improving ventilation standards in schools; Section 6.4 – Evaluating the benefit of CO_2 sensors; Section 6.5 – Consideration of the findings in relation to outdoor pollutants; Section 6.6 – Contextualising of the quantitative findings in relation to the qualitative (survey) findings.

6.1 Contextualising the quantitative findings in relation to previous studies and European standards

Historic data on the ventilation and air pollutant characteristics of Austrian schools is sparse. In relation to the few studies that were carried out prior to the current millennium Brandl (2001) observed that the fresh air ventilation rate was often more than an order of magnitude below the required level. More recently, the European SINPHONIE study, which included Austria, reported mean and median CO_2 levels higher than 1,000 ppm in most European primary schools and kindergartens, with schools located in Central, Eastern and Southern Europe having mean levels above 1,500 ppm (Csobod, 2014). The majority (86%) of classroom ventilation rates in the SINPHONIE study were found to be lower than the recommended target value (at that time) of 4 l/(s·person). A more recent study of 244 Bavarian classrooms (Schwarzbauer, 2022) reported substantially lower median CO_2 concentrations of 706 and 776 ppm, for rooms with decentralised AHUs and centralised AHUs respectively, whilst for naturally ventilated rooms the median value was 750 ppm. The timing of Schwarzbauer's study may have influenced the relatively low median CO_2 levels reported however, since the study was conducted during the early phase of the COVID-19 pandemic, at a time when there was heightened vigilance of the importance of ventilation in schools.

The findings of the ImpAQS study show lower median CO_2 values than those reported in the historical Austrian literature, with a daily median CO_2 concentration of 1,058 ppm and an arithmetic daily mean of 1,145 ppm. However, average values, such as these, across an entire year can give a misleading impression of the overall air quality in classrooms. At the school level only a quarter (25%) of schools maintain an annual daily mean CO_2 concentration below 1,000 ppm. In wintertime the situation is much worse with fewer than 5% of naturally ventilated schools maintaining a daily mean CO_2 concentration below 1,000 ppm. Furthermore, in winter nearly one third (32.1%) of naturally ventilated classrooms have a daily mean CO_2 concentration above 1500 ppm.

In relation to ventilation airflow rates, the ImpAQS study recorded a daily median ventilation rate of 5.9 l/(s·person), which is more than 41% below the threshold for compliance with Category I of EN 16798-1:2019 (CEN, 2019) and 36% lower than the age related airflow rate (for 11–18 year olds) specified in ÖNORM H 6039:2023 (ASI, 2023) (Tbl. 2-3). Of perhaps greater concern is the fact that for a quarter (25%) of the time, classrooms recorded airflow rates lower than 4 l/(s·person), which (for health reasons) is less than the minimum ventilation rate of 4 l/(s·person) set out in EN 16798-1:2019

(CEN, 2019, p52) (Tbl.4-9). Similar values were reported in a study of 322 UK schools, during the Autumn term of 2023, where it was found that the overall mean ventilation rate was 5.3 l/(s·person), rising to 6.8 l/(s·person) during warmer weather and falling to 3.8 l/(s·person) during colder weather (Wood, 2024). Similar to the UK, Austria is a country with a high percentage of naturally ventilated schools, and collectively these findings highlight the challenges of complying with established ventilation standards in naturally ventilated schools during the colder periods of the year.

The results highlight another dimension to the challenges of providing adequate ventilation in naturally ventilated schools, and that pertains to the occupant density of the classroom. In summer the daily mean compliance threshold (of 1000 ppm) is comfortably met (for 91% or more of the time) by schools in every school category (Appendix, Tbl. A-9). That situation changes noticeably in the autumn when the daily mean threshold is exceeded by the majority of school types, with the exception of special needs schools (SS). In winter the naturally ventilated SS[32] schools are still able to comply with the 1000 ppm threshold the majority (82%) of the time, whilst all other naturally ventilated school types consistently exceeded this compliance threshold. A reason why CO_2 concentrations were found to be lower in the SS schools may pertain to the fact that their average spatial density (5.26 m^2/student) is significantly higher than all other school types (combined mean 2.89 m^2/student). Overall the mean spatial density per student in the ImpAQS study is 20% greater than the European average value (of 2.44 m^2/student) reported in the SINPHONIE project (Csobod et al., 2014). Similar findings on the influence of classroom occupant density on the resultant CO_2 concentrations and ventilation rates in naturally ventilated classrooms have been reported in other studies (Laiman, 2014).

Mechanically ventilated schools performed better than naturally ventilated schools overall, and this finding is consistent with other similar studies (Gao et al., 2014; Schwarzbauer, 2021; Buonanno, 2022). The year-round median ventilation rate for rate for naturally ventilated schools of 5.6 l/(s·person) is 44% less than for mechanically ventilated schools (10.0 l/(s·person)) (Tbl. 4-14) . This difference is even more pronounced during the wintertime, when the median airflow rate provided by naturally ventilated schools (4.4 l/(s·person)) is less than half the median airflow rate provided in mechanically ventilated schools (9.3 l/(s·person). Based on a daily mean airflow rate (10.5 l/(s·person) the mechanical systems comply on average with Category 1 of EN 16798-1:2019 (10 l/(s·person)) (CEN, 2019), and the legal minimum set out in the Austrian Workplace Regulations (AStV) (of 9.7 l/(s·person)) (RIS, 2024a). Whilst the mean, mechanical ventilation, airflow rate is also above the requirements set out in ÖNORM H 6039:2023 (9.2 l/(s·person)) for 11-18 year olds (ASI, 2023), this evaluation does not imply that the standard is consistently met in all mechanically ventilated schools.

When viewed at the school level 82% of the mechanically ventilated schools maintain a daily mean CO_2 concentration below 1000 ppm across the year, whilst only 18% of the naturally ventilated schools manage to stay below that level. In combination only a quarter (25%) of all schools manage to maintain a daily mean CO_2 level below 1000 ppm year-round. In wintertime the situation is even worse, with only 12% of schools reporting a daily mean CO_2 level below 1000 ppm, whilst more than a quarter (29%) of schools have a daily mean CO_2 level above 1500 ppm (Tables 4-10 and 4-11).

[32] Note that caution is needed in interpreting this finding since only 2 schools of the SS category were included in the study.

6.2 Contextualising the findings in relation to emerging 'health-based' ventilation guidance

Airborne transmission is accepted to be one of the dominant routes by which SARS-CoV-2 (Jiminez, 2020; Nazaroff, 2022; Greenhalgh et al., 2022) and many other common viruses, including influenza (Hanna et al., 2023), tuberculosis, measles and chickenpox (Tellier et al., 2019) are transmitted. Moreover, the probability of further airborne pandemics occurring in the coming decades is projected to increase (Everard et al., 2020; Mishra et al., 2021; Williams et al., 2023), which suggests that there is a clear benefit in considering the prophylactic role which ventilation can play in reducing airborne pathogenic transmission in schools (Section 4.5) and other public spaces. In response to this awareness European and international organisations (including REHVA, The Lancet, and ASHRAE) have proposed 'health-based' ventilation methodologies to help mitigate the airborne spread of disease indoors. These strategies typically involve maintaining target CO_2 thresholds in the region of 800 ppm or lower (REHVA, 2022), or ventilation rates equivalent to 14 l/(s·person) (The Lancet COVID-19 Commission, 2022) and up to 20 l/(s·person) (ASHRAE, 2023) for classrooms. These strategies may be applied either reactively in an infectious risk management mode (IRMM) (i.e. in response to a pandemic wave or disease outbreak) such as ASHRAE Standard 241 advocates ASHRAE (2023), or proactively (i.e. at all times) such as REHVA (2022) and The Lancet COVID-19 Commission (2022) propose.

The airborne infection risk analysis shown in this study (Section 4.5) highlight the importance of ventilation in relation to reducing the long range transmission of SARS-Cov-2. Wherein for the classroom example provided (Section 4.5.1), an airflow rate of 4 l/(s·person), corresponding to IEQ Category 3 of EN 16798.1:2019 (CEN, 2019), would result in a theoretical group infection risk of around 74 % after 6 hours of exposure. Whilst with an airflow rate of 7 l/(s·person), corresponding to IEQ Category 2, the risk is reduced to 60%. At 10 l/(s·person), corresponding to IEQ Category 1, the risk is further reduced to 50%. In comparison, the Lancet Commission's Non-infectious Air Delivery Rates (NADR) recommendation of 14 l/(s·person) (The Lancet COVID-19 Commission, 2022) lowers the group infection risk to 43%, whilst the ASHRAE Standard 241:2023 recommendation for the control of infectious aerosols of 20 l/(s·person) (ASHRAE, 2023) reduces the long-range transmission risk to 32%.

The annual median ventilation rate recorded in the ImpAQS study, of 5.9 l/(s·person), is 58% less than The Lancet COVID-19 Commission (2022) non-infectious air delivery rate (NADR) target recommends, and is less than one third of the ventilation rate advised by ASHRAE Standard 241:2023 (ASHRAE, 2023) for mitigating the spread of airborne disease in classrooms. During wintertime, when viral loads are typically higher in the indoor air, the situation is even worse, with a median ventilation rate of 4.7 l/(s·person) recorded in this study, which is approximately one third of the airflow rate recommended by REHVA (2022) and The Lancet COVID-19 Commission (2022) and less than one quarter of the rate recommended by ASHRAE (2023). At this critical time of the year, for a quarter of the core operational time, classrooms were found to have a ventilation rate of 3.4 l/(s·person) or less (Tbl. 4-13). This implies that the risk of airborne SARS-CoV-2 infection is almost double what it would be in an identical classroom operating in line with the Lancet Commission's Non-infectious Air Delivery Rates (NADR) recommendation of 14 l/(s·person) or the REHVA (2022) guidelines.

In relation to meeting contemporary 'health based' ventilation thresholds over 90% of Austrian schools would fail to comply with the relevant guidelines (including the BMK Class A+ target (BMK, 2024b) or the REHVA health-based target of 800 ppm (REHVA, 2022), or the Lancet Commission's Non-infectious Air Delivery Rates (NADR) recommended ventilation airflow rate of 14 l/(s·person) (The Lancet COVID-19 Commission, 2022)) (Tbl. 4-10). In wintertime this figure increases to over 96%, indicating that less than 4% of Austrian schools are able to comply with contemporary 'health-based' ventilation targets year-round (Tbl. 4-11).

Although the situation in mechanically ventilated classrooms is better than in naturally ventilated rooms, only 30% of the mechanically ventilated schools achieved a mean CO_2 level below 800 ppm in wintertime. While there is currently no legal imperative to do so, 'health-based' guidance from REHVA (2022) and The Lancet COVID-19 Commission (2022) recommend that such levels should be maintained as a prophylaxis measure to help mitigate the transmission of seasonal illnesses and recurrent viruses such as SARS-CoV-2. This finding suggests that either not all mechanically ventilated school facility staff are aware of the importance of maintaining 'health-based' ventilation targets or that other reasons (e.g. undersized systems, energy saving policies etc.) are preventing them from implementing these standards. Clear ventilation system design and operational guidance, issued at the national (or regional) level, accompanied by the regular inspection of mechanical systems would help to avoid the performance discrepancies evident in some mechanically ventilated schools.

Whether a room is mechanically ventilated or not, and to what standard, plays an indirect role in the resultant probability of airborne infection. Based on the ventilation rates observed in this study mechanically ventilated classrooms had a 12% lower mean airborne transmission risk (of SARS-CoV-2) than the naturally ventilated classrooms (Tbl. 4-23). However the precise benefit of using a mechanical ventilation system to mitigate viral aerosol transmission depends not only on the airflow rate, but also the specific design of the ventilation system in relation to its efficiency in removing suspended aerosols from the air (Pollozhani, 2024; Zabihi, 2024). For example, vertical displacement ventilation and/or hood extract systems, can have significantly higher aerosol removal efficiencies for a given volumetric airflow rate. This is an area where there is considerable room for improvement in future school ventilation system design and this should be a policy priority in relation to improving public health and the management of future pandemics.

Occupant density and overcrowding is known to play a key role in the spread of infectious disease (von Seidlein et al., 2020; Herath et al., 2024). In this regard it is notable that the special needs schools (SS) in this study have a much lower occupant density than the other school types (Section 4.2.1.7). As a result, despite these schools being naturally ventilated, they achieved some of the lowest median CO_2 concentrations (Section 4.2.2) and highest median ventilation rates (Section 4.2.3) recorded in the study. This finding suggests that *occupant density plays a critical role in the maintenance of target ventilation rates in naturally ventilated schools*, and therein the long-range (far-field) airborne infection risk level.

Higher occupant densities inevitably mean that students are sitting in closer proximity to one another for prolonged periods of time, and this will also influence the short-range (near-field) transmission of disease as well (Public Health Ontario, 2022). When the room occupants are not wearing facemasks evidence shows that the near-field aerosol cloud produced by an infectious person can travel several metres (Bourouiba, 2020), and up to 7–8m when sneezing (Beggs et al., 2024). Moreover, research on exhaled aerosol jets has shown that the viral concentration at the end of an exhaled jet is a function of both the viral concentration exhaled by the infectious person and the viral concentration in the surrounding room air (Li et al., 2022). This emphasises that *the risk of short-range transmission indoors is directly influenced by the viral load in the room air, and therein by the ventilation rate*, thus forming a positive feedback loop (Beggs, 2024).

From these findings it can be inferred that there may be a health-based limiting threshold for the occupant density of naturally ventilated classrooms, beyond which it is increasingly difficult to comply with current ventilation guidelines in the Austrian climatic context. Therefore, in relation to policies advocating higher occupant densities in classrooms, greater consideration needs to be given to the health-related implications of this, including the adequacy of ventilation strategies.

6.3 Cost–benefit analysis of improving ventilation standards in schools

To date there have been relatively few attempts to evaluate the wider economic cost implications of poor ventilation in school classrooms. In part this might be because public schooling is free (at the point of use) in most European countries, whilst the association between indoor air quality and the net societal costs (of ill health, under-performance and absenteeism) are understudied and vulnerable to compounding factors.

Bruns (2023) calculated that for US school classrooms (based on a default occupancy of 30 people and a mean infectious duration of 5-days) the annual number of SARS-CoV-2 infections prevented by adopting the ASHRAE 241 standard (during a 112 day respiratory virus season) is estimated at 3.8 per classroom. The societal costs of this were estimated to have an economic value of $7,000 (USD) (this figure ignores the monetized values of other co-benefits, such as increased productivity and reductions in other seasonal airborne infections). These benefits are set against an estimated preventative implementation cost of $820 (USD) per classroom. Whilst for a lecture hall (with an occupancy of 150) the economic value is estimated as $25,000 (USD) and the preventative cost $7,500 (USD). Based on these assumptions there appears to be a clear financial and human benefit to implementing the ASHRAE Standard 241 during the respiratory virus season, and possibly year-round.

A similar cost-benefit analysis carried out, in a US school context, prior to the COVID-19 pandemic, by Mendell et al. (2013) found that *increasing classroom ventilation rates above the Californian state standard would substantially decrease illness absence rates whilst providing substantial economic benefits*. In part this finding was based on Californian schools' eligibility for state funding, which is linked to attendance numbers, but the societal cost of missed school days was also influential in this finding.

In a central European context Pollozhani et al., (2024) showed that in the heating dominated context of Graz (Austria) the choice of ventilation strategy (tilted windows, purge-ventilation, hybrid and heat recovery ventilation) can strongly influence the final energy performance of a classroom, as well as long-range viral transmission rates. Controlling the air exchange rate, using hybrid or purely mechanical means, to maintain an appropriate IAQ target, improved energy efficiency (compared to natural ventilation methods). Due to the high air exchange rates in the winter months, long-term ventilation with permanently tilted windows or regular purge-ventilation proved to be energetically inefficient in comparison to hybrid or full-mechanical ventilation. This study provides evidence for the use of hybrid and full mechanical ventilation systems, in a central European climate, as a means of reducing operational energy costs and reducing absenteeism caused by airborne disease transmission.

In considering the full cost-benefits of elevated health-based ventilation rates it should be noted that pandemic waves (including SARS-CoV-2) have not always coincided with the winter respiratory season (Fig. 1-1). There are also numerous other health, attendance, and attainment benefits associated with good ventilation (Sections 1.2, 2.2–2.4). Therefore, there may be significant additional benefit to mandating 'health-based' ventilation targets, year-round. To the authors' knowledge, a full cost/benefit analysis of such a proposition has not been undertaken, to date, in an Austrian or European context.

6.4 Evaluating the benefit of CO_2 sensors

Relatively few studies have directly investigated the benefit of using visible CO_2 sensors (or air quality monitors) as a means of improving ventilation practices in schools. In a study of ventilation behaviour in Dutch primary schools Geelen et al. (2008) found that the use of a CO_2 warning device and an accompanying information package appeared to be effective tools in improving ventilation behaviour and IAQ in classrooms. Conversely, they noted that giving class-specific ventilation advice without any supporting means was ineffective. However, the authors of this study point out that whilst ventilation was significantly improved (through behavioural change and the use of a CO_2 sensor) classroom CO_2 concentrations still exceeded 1000 ppm for more than 40% of the school day. As a consequence, the study concluded that whilst a CO_2 warning device and teaching information package are useful interim tools for improving ventilation behaviour and IAQ in classrooms, ultimately the ventilation facilities needed to be upgraded (Geelen, 2008).

Wargocki and Da Silva (2015) conducted a similar short term study, in Denmark, using two pairs of matched paired classrooms. Their findings demonstrated that providing visual CO_2 feedback affected the window opening behaviour of the occupants and reduced the resultant CO_2 concentration in classrooms (by approximately 100–200 ppm on average). The results also showed that in winter windows were more frequently opened when visual CO_2 feedback was installed, and that this resulted in lower CO_2 levels in these classrooms compared to classrooms without visual feedback. In late spring/early summer however, the frequency of window opening was found to be similar, irrespective of the visual feedback. Whilst in classrooms with mechanical ventilation, there were no measurable differences between the CO_2 levels whether visual CO_2 feedback was present or not (Wargocki and Da Silva, 2015).

In November and December the median difference between the C and T sensors was 227 and 215 ppm respectively, showing a clear advantage to using CO_2 sensors during the colder months (Tbl. 4-17). In contrast the difference between the C and T sensors was significantly lower in June and July where the median difference was only 57 and 28 ppm respectively. Over the whole year the median difference between rooms using a C sensor and those using a T sensor was 142 ppm. These finding reflects the seasonal pattern and mean values observed by Wargocki and Da Silva (2015).

Whilst the ImpAQS study confirms the overall findings of previous short-term studies of CO_2 sensors in European classrooms, it also highlights that the most significant benefit of using visible CO_2 sensors is found in the upper quartile (i.e. worst performing) of the naturally ventilated classrooms. It can be seen (Tbl. 4-17) that in December and January for 25% of the occupied time T-classrooms (with a visible CO_2 sensor) reported approximately 500 ppm lower CO_2 concentrations (496 and 506 ppm respectively) compared to the corresponding C-classrooms (Section 4.4.1 and 4.4.2). This finding highlights the importance of examining the matched-pair data at different levels of the interquartile range, since the median and mean values do not reveal the full potential of using visible sensors. In practical terms this finding shows that in naturally ventilated classrooms there is a substantial benefit to using visible CO_2 sensors, particularly during the colder months and in the worst performing classrooms.

Avella et al., (2021) conducted a short duration (3 week-long) monitoring study in two paired classrooms in four schools, in an historic school building, in the South Tyrol. Their aim was to investigate the impact of using a CO_2 based (RAG) visual alerting system on improving the IAQ in school classrooms. The comparison between the paired-classrooms showed that the effectiveness of the CO_2 device is highly dependent on occupant behaviour. The results show that classrooms using a visible CO_2 alerting system have lower CO_2 concentrations (by 28–42%) relative to the control classroom. However, the authors note that short-term behavioural changes, induced by the COVID-19 pandemic, and the cold weather conditions at the time of the study may have influenced their findings (Avella, 2021).

Collectively, the existing evidence suggest that most naturally ventilated classrooms will achieve a noticeable reduction in CO_2 concentrations through the use of a visible CO_2 sensor (or RAG visual alerting system). Moreover, the benefit of CO_2 sensors is most pronounced during the colder months when ventilation is generally poorer, and the probability of seasonal illnesses is greater. In interpreting the findings of the ImpAQS study, it is important to bear in mind that no formal training was provided to the T- or C-classroom teachers in relation to the correct usage of a CO_2 sensor or appropriate ventilation strategies (other than two small wall-mounted display posters in the T-classrooms) (Appendix B.6). This suggests that an even greater benefit might be foreseen from the widespread roll-out of CO_2 sensors in classrooms if their deployment was accompanied by a supported training process for staff and students.

6.5 Consideration of the findings in relation of outdoor pollutants

Outdoor pollutants measured at official UBA monitoring stations were used to evaluate the presence of four key air pollutants ($PM_{2.5}$, PM_{10}, NO_2, O_3) in proximity to the ImpAQS schools (Fig. 3-12 and Section 4.3.2). The distance of each measuring station to the respective school, along with other local environmental factors (such as the wind direction and urban canyon effects) will influence the precise interpretation of these results. The proximity of each school to the nearest UBA measurement station (for each pollutant) can be found in Tbl. A-3 in Appendix B.9.

In relation to particulate matter of 2.5 micron diameter or smaller ($PM_{2.5}$) almost all (98%) of the UBA stations exceeded the annual mean WHO $PM_{2.5}$ air quality guideline (AQG) limit of 5 µg/m^3. In one case the annual mean value was exceeded by a factor of more than 3 times the respect of WHO AQG limit. In relation to the daily limit almost all (98%) of the UBA stations show 3 or more exceedances (per year) of the WHO AQG $PM_{2.5}$ limit value of 15 µg/m^3 (when assessed at the 99th percentile) (Fig. 4-33). These results suggest that almost every school in the ImpAQS study (with the exception of one school in Lower Austria) is likely to be exceeding both WHO $PM_{2.5}$ exposure limits. Further measurements at the site of the individual schools would be needed to confirm this finding.

In relation to particulate matter of 10 micron diameter or smaller (PM_{10}) nearly half (49%) of the stations exceed the annual mean WHO AQG threshold of 15 µg/m^3. Whilst the daily WHO AQG threshold (of 45 µg/m^3) is exceeded on more than 3 occasions (per year) by more than half (59%) of the stations. Although this represents fewer exceedances than for $PM_{2.5}$, it suggests that the majority of schools currently exceed the WHO PM_{10} exposure limits. Further measurements at the site of the individual schools would be needed to confirm this finding.

In relation to nitrogen dioxide (NO_2) the annual WHO AQG limit of 10 µg/m^3, is exceeded by the majority (82%) of the UBA stations in proximity to the schools. Whilst the daily AQG limit of 25 µg/m^3 is exceeded at the 99th percentile (i.e. on more than 3 occasions per year) by 94% of the stations. This suggests that almost every school in the study (with the exception of three schools) is likely to be exposed to NO_2 levels which are above the WHO limits. Assessments were not made against the AQG one-hour limit of 200 µg/m^3 however, since measurements at this resolution would need to be made at the school's precise location to ensure that highly localised short-term influences are captured (Greenpeace, 2018).

In relation to ozone (O_3) all (100%) of the UBA stations significantly exceed the WHO AQG daily 8-hour mean threshold of 100 µg/m³ at the 99th percentile. This suggests that all schools in the proximity to these stations are likely to fail to comply with the WHO daily exposure limit for ozone. A second WHO limit applies in relation to the peak season O_3 value which is set at 60 µg/m³ (where the peak season value is defined as the average of the daily maximum 8-hour mean concentration in the six consecutive months with the highest six-month running average O_3 concentration). This value peaked in the month of September, and the peak value test for O_3 was failed in all cases.

Collectively these results paint a concerning picture of the outdoor air quality in proximity to the ImpAQS schools. These findings are congruent with earlier findings reported in the European SINPHONIE study which found that 85% of schoolchildren were exposed to $PM_{2.5}$ at concentrations above 10 µg/m^3 (the WHO guideline annual mean AQG value at that time, now reduced to 5 µg/m^3). The levels of traffic related pollutants ($PM_{2.5}$, NO_2 and O_3) were also found to be elevated in the vicinity of many schools (Csobod, 2014).

In interpreting these findings, consideration should be given to the fact that the total pollutant exposure received by a student over the entire day (and year) needs to be considered when assessing the long-term impact of air pollution on their health. The 'burden of disease' is typically accounted for by different mortality and morbidity indicators and is often quantified in terms of disability-adjusted life years (DALYs) attributable to an individual's environment (Troeger et al., 2017; WHO, 2024). Since school attendance comprises about 15% of a student's annual pollutant exposure time (Csobod, 2014) it constitutes a relatively small fraction of their total 'burden of disease'. At the same time schools owe a duty of care to their students and staff; since all the outdoor pollutants evaluated here are associated with serious short and long-term health implications, attention should be given to mitigating their impacts in so far as is possible. This is particularly important from the perspective of reducing health inequalities, since not all children and staff have the benefit of living in a location with good air quality and some individuals are at an elevated risk of health issues due to pre-existing medical conditions and/or their individual living circumstances.

Particulate matter, including $PM_{2.5}$ and PM_{10} can be largely filtered from the incoming air supply using appropriate filtration in conjunction with mechanical ventilation (Eurovent, 2018). In naturally ventilated schools, indoor particulate concentrations can be reduced, albeit to a lesser extent, through portable room based HEPA filtration. Given that particulate pollution is associated with serious short and long-term health implications (Section 3.7.2) priority should be given to the installation of monitoring equipment and particulate filtration in the worst affected schools.

Gaseous pollutants require special filters, which typically use an activated carbon chemical mixture that acts upon the gaseous pollutants common in urban air (including NO_x, NO_2, SO_2, O_3 and VOCs). In-line pollution filters are available for use with both decentralised and centralised air handling units. (AHUs). Tests carried out under typical operational circumstances have shown that Type 1 Gas Filters will filter NO_2 concentrations to below the EU Directive limits of 40µg/m^3 when challenged with gas concentrations up to 200µg/m^3 (Airclean, 2024). In most cases inline filters can be retrofitted to existing AHUs.

The maintenance and running costs of operating air handling units and filtration systems can be prohibitive, particularly in the context of constrained school budgets. This raises the question of whether regional or federal funding should be made available to ensure that every child in the Austrian education system has an equal right to breath clean air? Without additional support, both in terms of technical guidance and financial subsidies, it seems unlikely that such complex issues can be satisfactorily resolved at the school level.

6.6 Contextualising the quantitative findings in relation to the qualitative (survey) findings

Section 5.3 summarizes the results of two surveys targeted at school directors of the 120 schools participating in the ImpAQS project; as well as two additional surveys directed at classroom teachers of the 10 monitored classrooms in each school. In support of the monitored data, the qualitative survey results provide valuable insights into the social implications of using CO_2 monitors, as well as the impact of environmental conditions (and other issues) on ventilation practices in schools.

A study by Sanguinetti et al. (2022) emphasizes that classroom CO_2 monitoring, coupled with teacher education, is essential for empowering educators to protect their health and that of their students. This sentiment is echoed by a high proportion of teachers surveyed during the ImpAQS project who feel more secure when they have access to real-time data regarding air quality, allowing them to make informed decisions about when and for how long to open the windows. The differences between the classrooms with (T) and without monitors (C) demonstrate that most classroom teachers value the presence of CO_2 sensors, and report that the information provided by them influences their ventilation strategies and enhances the overall classroom conditions. Overall, the mean CO_2 rate in the T-classrooms is lower than in the C-classrooms (Section 4.4) and this indicates improved ventilation rates.

Moreover, the educational benefits of CO_2 sensors extend beyond the immediate health and well-being aspects. The ability to visualize CO_2 levels in real-time can help to embed a deeper understanding of environmental science concepts in the classroom. Some schools reported that they built their own sensors and that students had become more alert to indoor CO_2 values. The willingness to leave windows fully open during summertime, appreciating the effect on the CO_2, without any detriment to thermal comfort, is also demonstrated by the lower CO_2 readings over the warmer time of the year. Window opening behaviour is often determined by environmental factors, such as temperature, solar radiation, noise, and wind. Research confirms that indoor and outdoor temperatures significantly influence window-opening behaviour. For example, higher outdoor temperatures often lead to increased window opening to cool down indoor spaces (Pan et al., 2018). Additionally, during colder months, teachers may be hesitant to open windows due to concerns about lowering indoor temperatures too much (Jian et al., 2011). Whilst external factors play a crucial role in influencing teachers' individual window opening behaviours so do personal factors, including their knowledge of the consequences of poor ventilation. These observations are reflected in the ImpAQS survey responses (Chapter 5) as well as the significant variations seen in the monitored classroom data at similar times of the year (Section 4.3.3).

Generally, air pollution and outdoor air quality are considered less of a problem, in relation to window opening behaviour, according to the survey responses (Section 5.3). Although the recorded outdoor air pollution levels often exceed WHO air quality guidelines (Section 4.3.2), it was not identified as an issue in the survey responses, nor does the monitored data show a strong association between ventilation rates and worsened outdoor pollutant levels. This may be in part because some pollutants, such as ozone, are invisible and odourless; whilst NO_2 has a pungent odour, people can become habituated to such smells over time, associating them with the urban environment (Wojnarowska et al., 2020).

Aspects related to thermal comfort (e.g. temperatures being too cold or too warm) and acoustic comfort (construction noise, street noise or even the noise from their own students playing outside) attracted considerable concern in relation to window opening behaviours (Chapter 5). This is also observed in the literature, Torresin et al., (2021) report that noise from outside can deter teachers from keeping windows open, especially in urban environments where external sounds may disrupt the learning process and are reported as a hindrance. This finding may partially explain the improved CO_2 levels found in suburban schools compared to those in more centralised urban settings (Fig. 4-21) although this hypothesis has not been explicitly tested.

Through a deeper statistical analysis of the directors' survey results it was found that the use of CO_2 sensors and wall mounted instructions, to improve indoor air quality, are perceived as more helpful in urban schools than rural ones. Similarly, this outcome is reflected in the recorded data, where there is a clear difference in monitored CO_2 values between rural and urban areas (Fig. 4-21).

Overall the results showed that 99% of all school directors see either a potential or a very positive effect of introducing CO_2 sensors and ventilation guidance in classrooms. Directors from primary and middle schools were amongst the most receptive to the introduction of CO_2 sensors and instructions on how to use them to improve indoor air quality in classrooms. Primary schools have an inherent advantage in terms of maintaining lower CO_2 values in absolute terms (due to the lower exhaled CO_2 emission rates of younger children), but this biological characteristic is compensated for in the calculation of the ventilation rates according to age (Section 3.4.1). This fact explains why the ranking of schools according to their mean CO_2 concentration (Fig. 4-25) does not precisely reflect the ranking according to their mean ventilation rate (Fig. 4-26) and why primary schools, which rank highly based on CO_2 concentration rank poorly on ventilation (Section 4.2.3.4).

Regional differences could also be noted in the surveys, for example, school directors in Vienna and Tyrol recognized the importance of maintaining optimal indoor air quality in educational environments in relation to health, well-being, and academic performance to a higher level than school directors in Carinthia and Vorarlberg. In this regard Carinthia (Figs. 4-23 and 4-24) also shows one of the highest exceedances of the CO_2 target threshold levels of all federal regions.

Whilst the data shows that mechanically ventilated schools generally perform better than naturally ventilated schools (since typically no intervention is needed from students and teachers to regulate CO_2), the data also shows that some mechanically ventilated schools perform worse than many naturally ventilated schools. In fact, two naturally ventilated schools are ranked in the top 6 schools in the study. Interestingly, many teachers voiced concerns about mechanical ventilation. Whilst some referred to it as "the ultimate solution", others spoke out against it (Chapter 5). Research indicates that some favour opening windows as a means to enhance ventilation and improve the indoor environment.

Costs (not just capital expenditure but specifically running costs) will continue to play an influential role in which type of ventilation system is favoured in schools. Some teachers in classrooms equipped with mechanical systems complained that the systems, in their school, were never running. Follow-up enquiries revealed that in at least one school the system was not switched on, due to estimated annual running costs of 7000 Euro. Consequently this school was reclassified as a naturally ventilated school to allow an unbiased assessment of its performance. This situation is also reflected in some of the results of poorly functioning mechanically ventilated classrooms, which may be under-ventilated at times due to intermittent operation or poor maintenance (Fig 4-28, Fig 4-37).

Thus, having a mechanical ventilation or filtration system installed does not automatically guarantee better indoor air quality. This issue was highlighted in the example of the city of Münster, Germany, who with the support of the state of North Rhine-Westphalia installed a total of 1,188 mobile air filtration systems in its schools to protect children, young people and teachers from infection at the beginning of the COVID-19 pandemic. This intervention cost almost 2 million euros whilst, according to official figures, replacing the filters in every device would cost approximately 700,000 euros per year. As a result many schools in the region now want to dispose of the units (having been left to absorb these additional costs without regional or federal support) (Olbrisch, 2024). Therefore the decision to invest in running mechanical air-handling units, air purifiers, or even just CO_2 sensors requires that routine maintenance costs are foreseen and budgeted for. The pros and cons of such financial decisions – possibly including a full cost-benefit analysis (Section 6.3) need to be assessed and the findings clearly communicated in order to avoid short-term decisions. Whilst mechanical systems can provide higher ventilation flow rates, with improved thermal comfort in wintertime, without proper planning and consideration of the wider issues they are not necessarily the solution to better indoor air quality.

7 Conclusions and recommendations

The ImpAQS project (Improving Air Quality in Schools) investigated CO_2 concentrations, ventilation rates and indoor environmental data in 1200 Austrian classrooms covering 7 different school types spread over the 9 federal regions of Austria, across the entire 2023–24 school year. Supplementary data from the Austrian Environment Agency (UBA) air pollution monitoring stations, located in proximity to the schools was analysed to assess the background air quality in the vicinity of the schools. Anonymised absenteeism data was provided by most of the participating schools, and this was used to investigate associations between indoor air quality and attendance. Further analysis, involving the Austrian federal wastewater monitoring system, was carried out to investigate associations between school absenteeism and waste-water SARS-CoV-2 RNA levels. In total over 1 billion data-points were collected and analysed, making this one of the largest studies of ventilation and air quality carried out in Austrian schools to date.

This section begins by summarising the main conclusions that can be drawn from the ImpAQS study (Section 7.1). Based on these conclusions, and the previous discussion of the research findings (Section 6), recommendations are made to improve the current situation (Section 7.2). These recommendations are divided into recommendations for praxis (Section 7.2.1) and recommendations for policy (Section 7.2.2). This chapter concludes with a brief description of the main limitations of the study (Section 7.3.1) and recommendations for further work (Section 7.3.2).

7.1 Overall conclusions

7.1.1 Compliance with existing European and Austrian standards

The CO_2 data recorded by the ImpAQS project indicates a widespread failure to comply with existing European and national ventilation guidelines in Austrian schools. Only a quarter (25%) of all schools manage to maintain a daily mean CO_2 level below the 1000 ppm threshold set out in ÖNORM H 6039 (ASI, 2023), EN 16798-1 Category I (CEN, 2019) and BMK Class A (BMK, 2024d). The majority (89%) of Austrian classrooms are naturally ventilated, and whilst most schools maintain good ventilation levels in the summer months, regardless of the ventilation type, the situation changes rapidly as the outside temperatures fall. Whilst 90% of mechanically ventilated schools maintain a daily mean CO_2 concentration below 1000 ppm across over the year, fewer than 18% of the naturally ventilated schools manage to stay below that level. In wintertime the situation is even worse, with less than 12% of schools reporting a daily mean CO_2 level below 1000 ppm, whilst more than a quarter (29%) of all schools have a daily mean CO_2 level exceeding 1500 ppm (Table 4-10).

The yearly median ventilation rate across all schools is 5.9 l/(s·person), however the distribution is skewed to the right (because of a small number of better performing schools) which gives a higher mean ventilation rate of 7.4 l/(s·person). Therefore the median is 41% lower, and the mean is 26% lower, than the threshold for compliance with Category I of EN 16798-1:2019 (CEN, 2019). The yearly median is 36% lower, and the mean 20% lower, than the age related airflow rate specified (for 11-18 year olds) in ÖNORM H 6039:2023 (ASI, 2023). Moreover, for a quarter of the year Austrian classrooms are providing ventilation rates below the minimum value (of 4 l/(s·person)) advised by EN 16798-1:2019 (CEN, 2019, p52). On average, 77% of the daily mean ventilation rates across all 1200 classrooms fall below 10 l/(s·person) and therefore do not meet either the Category 1 standard of EN 16798-1 (CEN, 2019) or the Class A standard (of 1000 ppm) described in the current Austrian guidelines “Richtlinie zur Bewertung der Innenraumluft – Kohlenstoffdioxid als Lüftungsparameter” (BMK, 2024d) (Section 4.2.3). Moreover, the large disparities between the CO_2 concentrations and ventilation rates recorded in individual classrooms, schools, and regions underscores a significant potential risk of health and academic attainment inequalities occurring across the Austrian school system.

7.1.2 Compliance with ‘health-based’ guidance targets

In relation to more recent ‘health-based’ guidance targets, which are designed to minimise the transmission of airborne pathogens in schools, the results look even worse. More than two years ago clear recommendations were made by the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA, 2022) to maintain a ‘health-based’ CO_2 threshold value of 800 ppm in European classrooms in response to the ongoing COVID-19 pandemic. An equivalent ventilation target of 14 l/(s·person) was recommended by The Lancet COVID-19 Commission (2022) in response to current scientific and medical evidence. The ‘health-based’ target value of 800 ppm is described as Class A+ in the current Austrian guidelines “Richtlinie zur Bewertung der Innenraumluft – Kohlenstoffdioxid als Lüftungsparameter” (BMK, 2024d). During the winter months, when seasonal viruses peak, only 30% of mechanically ventilated schools comply with the 800 ppm target. In contrast less than 1% of naturally ventilated schools are able to maintain this target threshold during the winter months. Since naturally ventilated schools make up 89% of the sample, this means that in total only 3.3% of schools comply with the BMK (2024d) Class A+ target in wintertime (Sections 2.5.6 and 4.2.2).

7.1.3 Benefits of using CO_2 sensors

Overall there is a clear benefit to using visible CO_2 sensors, however the results are nuanced and depend on a number of factors including the outside air temperature and the type of ventilation system used. On average across the school-year classrooms with a visible CO_2 sensor reported a daily mean CO_2 level that was 156 ppm lower than their matching control classroom. The benefits of using a CO_2 sensor are even more pronounced in wintertime. In the month of January the daily mean difference increases to 208 ppm, whilst for a quarter of the days in that month a daily mean difference of 495 ppm was recorded (Section 4.4.1).

In the warmer months the benefit of using a visible CO_2 sensor diminishes, for example in the summer of 2023 the median benefit was only 15 ppm whilst during the summer of 2024 that benefit increased slightly to 33 ppm. The main reason why CO_2 sensors show relatively little benefit during the summer months is because most classrooms are well ventilated at this time, with daily mean CO_2 levels during school days in June, July and September remaining predominantly below the 800 ppm threshold (Section 4.2.2). Since the visible CO_2 sensor’s RAG visual indicator was set to turn from green to amber at concentrations above 800 ppm (Section 3.5.5), there would be no visual impetus for rooms with a visible CO_2 sensor to provide additional ventilation at these levels.

From the end-user perspective most teachers reported that they found CO_2 sensors extremely helpful in regulating the air quality in their classrooms; albeit at times they found it frustrating not to be able to maintain the target threshold values. Whilst CO_2 sensors can provide useful real-time information, they don't provide solutions to all of the challenges teachers face in trying to ventilate their classrooms adequately throughout the year.

7.1.4 Outdoor air pollution

Outdoor air pollution plays a critical role in determining how healthy the air inside a school building is. Whilst there are numerous sources of indoor air pollutants, in addition to CO_2 and human bio-effluents, the air quality inside a classroom is rarely better than the outside air. This is because the entire room air in a classroom is typically renewed about 3 to 6 times per hour and during that renewal process (unless the air is pre-filtered) outdoor air pollutants enter the room. For this reason the study examined the outdoor air quality in proximity to the schools using official UBA measurement station data for four key pollutants ($PM_{2.5}$, PM_{10}, NO_2, O_3). These contaminants were assessed in relation to the most recent World Health Organisation (WHO) air quality guideline (AQG) threshold limits (WHO, 2021b).

In relation to $PM_{2.5}$, the results show that almost every measurement station in the ImpAQS study (except one) exceeded the WHO annual and daily exposure limits. In relation to PM_{10} approximately half of the stations exceed the annual WHO limit, whilst 59% of stations exceed the daily threshold. In relation to NO_2, 82% of the stations exceed the WHO annual limit whilst 94% of stations exceed the daily limit. In relation to O_3 the situation is worse, with 100% of the stations in proximity to the ImpAQS schools failing to comply with both the maximum daily 8-hour mean value and the peak season value (which is based on the 6-month running mean).

Collectively these findings indicate that the outdoor air quality in the proximity to the schools in the ImpAQS study is likely to be harmful to student and staff health. Detailed onsite measurements, both inside and outside the schools, would be needed to confirm these finding at the individual school level. It is also clear from the results (Section 4.3.2) that some schools suffer from much higher outdoor air pollutant concentrations than others. In a small number of cases the daily mean pollutant concentrations are higher than WHO thresholds which should not be breached more than 3 times per year (Figs. 4-33, 4-35). In such cases priority should be given to investigating pollutant levels at the site of the worst affected schools. If confirmed by on-site testing implementation of appropriate air filtration techniques, in combination with mechanical ventilation, is recommended to reduce the levels of the most harmful contaminants.

7.1.5 Airborne transmission of disease

It is well known that many harmful pathogens, including: SARS-CoV-2, influenza, tuberculosis, measles, and chickenpox are transmitted by airborne routes. Viral and bacterial particles may be encased in droplets and transmitted directly over relatively short distances by speaking, coughing or sneezing or advection (i.e. via an air current). In addition smaller particles may become aerosolised, where they can remain suspended in the room air for many hours. Through the use of an analytical model the influence of the ventilation rate on the theoretical risk of SARS-CoV-2 transmission in the ImpAQS classrooms was studied.

The analysis was carried out in comparison to a theoretical reference classroom which was ventilated at 10 l/(s·person) in compliance with Category 1 standard of ÖNORM EN 16798-1 (CEN, 2024) (Section 4.5). The results of this analysis demonstrate that the risk of airborne infection rises with increased occupancy and the duration of exposure. The ventilation rate also plays a very influential role in the resultant risk level. Wherein an airflow rate of 4 l/(s per person) results in a group infection risk of around 74% after 6 hours of exposure. In comparison, compliance with the Lancet Commission's Non-infectious Air Delivery Rates (NADR) recommendation of 14 l/(s·person) would lower the group infection risk to 43% (The Lancet COVID-19 Commission, 2022).

It must be acknowledged however, that whilst ventilation can play a significant role in reducing the risk of long-range airborne transmission, viruses (and other pathogens) are also transmitted by other modalities. Short-range transmission, whilst influenced by the ventilation rate (Beggs, 2024), is likely to be worse in densely occupied spaces. In this regard other prophylaxis strategies (such as masking) may be needed, to augment good ventilation, in mitigating the spread of disease.

7.2 Recommendations

7.2.1 Recommendations for praxis

The following practical recommendations are intended to provide solutions to address the main physical problems highlighted in this report, they are categorised as follows:

(i) Short-term solutions – these are recommendations than can be implemented immediately without substantial infrastructure costs and complex planning.

(ii) Long-term solutions – these are recommendations that apply to medium and longer term strategies including the design and construction of new schools and major refurbishment.

7.2.1.1 Short-term solutions

Given that the majority of classrooms in Austria are significantly under-ventilated, according to existing norms and standards, urgent measures need to be taken to improve this situation. The worst affected schools should be prioritised first; however, almost all schools require support to improve their current situation. Therefore 'core measures' should be provided to all schools and a priority list of 'additional measures' should be provided to the worst affected schools. In this way school directors and school owners can be offered a package of support measures commensurate with the assistance required by individual schools.

<u>Core measures</u>:

(i) **Basic CO_2 monitoring and ventilation training for all school staff** – this should include training in how to ventilate, using different ventilation strategies appropriate to the season. Such training can be provided online or in-person via regional group training seminars.

(ii) **CO_2 monitors and room display posters** – the role out of calibrated CO_2 sensors which include both numerical CO_2 and room temperature displays and visible (RAG) alerts (corresponding to the BMK recommended thresholds at 800 ppm (amber) and 1000 ppm (red) are recommended for all naturally ventilated classrooms. Room-display posters to remind teachers of the appropriate CO_2 threshold values and seasonal ventilation strategies should be fixed to an internal classroom wall near to the sensor.

(iii) **Classroom CO_2 champions** – in classes with age groups of 10 years and above (possibly younger in some cases) it is appropriate to appoint a student as the classroom CO_2 champion. This student is then responsible for keeping an eye on the CO_2 monitor and informing the teacher when the light turns red and additional ventilation is needed.

(iv) **Room ventilation audits** – school facility managers should be tasked with carrying out an annual ventilation audit of each occupied classroom. This audit should ensure that sufficient windows are openable to provide adequate ventilation when the classroom is occupied and that open windows do not interfere with the seating layout. Where windows are locked, difficult to open, or cannot be latched in a secure position remedial work should be undertaken to rectify the situation. Similar audits should be undertaken with respect to mechanical ventilation systems, following the guidance published by REHVA and/or other professional ventilation bodies (e.g. VDI, CIBSE, ASHRAE).

Additional considerations:

(i) **HEPA filters** – could be considered as a temporary solution in the worst effect schools, as a means of augmenting intermittent ventilation strategies during the colder months. The decision to deploy HEPA filters needs to be carefully planned to ensure the quietest possible systems are installed, and that any air purification device does not emit harmful byproducts. Since each classroom will require multiple HEPA filters, to achieve demonstrable benefit, careful consideration needs to be given to the room layout and the location of power points. The implementation of HEPA filters should be undertaken with independent expert advice as there are a number of critical issues to consider, including noise, positioning, and filter cleaning requirements. The cost of regular filter changes and maintenance needs to be factored into this decision.

(ii) **Mechanical ventilation system control** – it is notable that schools with mechanical ventilation are sometimes 'over-ventilated' in the warmer months, presumably because windows are opened for additional fresh air or cooling whilst mechanical systems are running. This process is wasteful of energy, and outside of pandemic waves unnecessary. In the warmer months mechanical ventilation can often be turned off (in cases where the outside air is not too polluted to do so and external noise is tolerable). However ventilation systems (or zones) should only be turned off where there are sufficient window openings to ventilate naturally (and classroom CO_2 levels can be kept below 800 ppm). Conversely, in a small number of cases mechanical ventilation systems are operational but classrooms appear to be receiving insufficient ventilation; in such cases airflow rate and CO_2 measurements should be carried out in individual classrooms to identify the source of the problem.

7.2.1.2 Long-term solutions

(i) **Mechanical ventilation** – if properly designed and maintained, mechanical ventilation can provide demonstrably better indoor air quality, than natural ventilation, in Austrian classrooms. Decentralised mechanical ventilation with heat recovery is a probably the most energetically efficient and cost effective solution for most new classrooms. However detailed consideration should be given to the choice of ventilation system wherein maintenance and noise considerations are paramount. For this reason the highest efficiency systems (i.e. those with heat-recovery efficiencies greater than 90%) might not be the best choice for classrooms since they typically require high fan pressures to operate, and hence power consumption and noise increase. In addition high efficiency filters are needed to protect the functioning of the very narrow channels in high efficiency heat exchangers. A better suited option for classrooms, might be to use lower efficiency units (e.g. 70-80% efficiency) which can operate at lower pressures and are less sensitive to maintenance issues. Such systems should be sufficiently sized to meet the 'health-based' ventilation rates described in this report, at the system's nominal flow rate. In some cases this may require two ventilation units per classroom. It is important to consider the whole life operational, maintenance, and carbon implications (including annual filter changes and servicing costs) when installing mechanical ventilation systems.

(ii) **Outdoor air quality assessments** – Similarly to the approach set out in the North American standard ASHRAE 62.1 the outdoor air quality must be thoroughly investigated prior to specifying a new or retrofit ventilation system design. This investigation requires comprehensive measurement and documentation of the outdoor air quality at both the regional and local (i.e. school location) level. Such an assessment can help to inform the optimal design and siting of ventilation systems, including appropriate filtration for both particulate and gaseous compounds where required.

(iii) **Real-time data visualisation and alerting** – compared to standalone air quality sensors networked monitoring systems have the advantage of continuous data logging and visualisation from multiple devices. Around the world schools are increasingly using real-time, networked indoor air quality monitoring systems to improve student and staff health and the environmental quality of learning environments. These systems use sensors to measure pollutants like CO_2 and particulate matter, as well as temperature, and humidity, and are able to provide real-time data (as well as recording historical data trends). Sensors can also be used to automatically regulate mechanical ventilation systems. Currently ventilation systems are unable to directly 'sense' when pathogens are present in the room air, however such technology is under development. The availability of other sources of real-time pathogen data (based for example on regional waste-water RNA) offers valuable information regarding times when the risk of airborne disease transmission is elevated. This information could easily be made available to facility managers and school staff to ensure heightened vigilance in relation to ventilation protocols as such times. Equally, at times when outdoor air pollutants are elevated, advice to use room HEPA filters and reduce window ventilation could help buffer the worst effects. The involvement of students in citizen science projects and as class air quality champions could also be linked to real-time data monitoring in this way.

(iv) **Upper room UV-C disinfection** – can be a useful adjunct to ventilation in reducing the risk of airborne disease transmission in densely occupied spaces. Although not directly addressed in this report, the use of UV-C lighting to sterilise airborne pathogens is an established air cleaning method. Unlike conventional 254 nm UVC, far-UVC at 222 nm is considered non-harmful to human health and is considered safe to use in occupied spaces, whilst still being effective for disinfection purposes (Pereira et al., 2023). Either by natural buoyancy or mechanical ventilation, stale air flows to the top layer in the room where it comes into contact with the UV-C light and pathogens are rapidly deactivated. After which the sterilised air descends and mixes naturally with the air in the occupied lower parts of the room. If correctly designed and installed, upper-room UV-C disinfection units can provide a safe and effective means of providing additional airborne pathogen protection to students and staff in classrooms. Expert advice should be sought in conjunction with the design and specification of far-UVC systems in classrooms.

7.2.2 Policy recommendations

There are currently too many different ventilation policy documents and standards often with conflicting and/or overlapping guidance regarding CO_2 thresholds and ventilation metrics. This guidance needs to be harmonised such that clear and consistent targets are provided to schools from a single reputable source. Moreover, the threshold targets set out in any guidance document or standard require routine monitoring and enforcement if they are to be consistently met. Without appropriate enforcement measures most air quality targets are likely to remain aspirational, or subject to the voluntary engagement of individual school staff. The current unregulated policy landscape has resulted in significant discrepancies in the ventilation and indoor air quality standards found in individual classrooms and schools, as evidenced in this report. This situation will inevitably contribute to and exacerbate existing health-inequalities and performance related outcomes amongst school students and staff across Austria.

Existing European and Austrian indoor air quality standards and protocols do not adequately reflect the ‘health based’ ventilation and CO_2 targets advocated my REHVA (2022), The Lancet COVID-19 Commission (2022) and ASHRAE (2023), nor the implications of recent revisions to outdoor air quality guidelines from the WHO (2021b). Existing guidelines and standards need to be revisited and updated to ensure that current best-practice is implemented in the context of indoor air quality and ventilation in schools. Clear guidance must be accompanied by a comprehensive air quality monitoring campaign in school classrooms and robust enforcement measures, without which the current situation will only continue. A detailed cost/benefit analysis of implementing higher ventilation rates and/or supplementary air cleaning measures (such as ASHRAE Standard 241) has not been undertaken in an Austrian or European context (to the authors’ knowledge), and this would be an important pre-requisite for developing the economic rationale in support of such revisionist policies.

In relation to the planning of new school buildings consideration needs to be given to a number of interconnected issues which can have a profound effect on indoor air quality, health and wellbeing. These include:

(i) Classroom sizes – naturally ventilated classrooms with lower occupant densities perform better in terms of maintaining acceptable indoor air quality and allowing adequate free space between desks and openable windows. Guidelines should be established for maximum occupant densities and minimum window opening areas in classrooms, as a function of the intended occupancy.

(ii) Ventilation system type and design – mechanical ventilation with heat recovery (if properly designed) can provide an energy efficient and thermally comfortable environment that complies with modern ventilation guidelines year-round. The nominal and maximum capacity of the system(s) as well as the system configuration (location of supply and extract grilles) should be designed such that it provides the highest possible ventilation effectiveness and complies with modern 'health-based' ventilation design standards.

(iii) Window design and positioning –openable windows remain an important aspect of good ventilation design even in mechanically ventilated rooms. The location of openable window lights is critical to their utility as a means of ventilation. Having both low and high level opening lights enables maximum use of the 'buoyancy effect' which can greatly enhance the efficacy of single sided ventilation. High level openings are particularly useful in wintertime to reduce draughts and remove stale air and in summer to remove heat from the room. Window gearing and furniture (i.e handles, locks etc) need to be easily accessible (particularly on high level opening lights) also for those with mobility impairments. Internal and external shading devices should function without obstructing the ventilation air flow.

7.3 Study limitations and further work

7.3.1 Limitations

This study was mobilised rapidly, in order to help inform decisions regarding the future of ventilation practices in Austrian schools, at a time when the COVID-19 pandemic was still causing major disruption to the operation of schools. The preparation and planning time was therefore comparatively short, given the scale of the project. In the space of less than 6 months more than 1320 sensors, 120 gateways, and ancillary equipment were procured, calibrated and installed in 120 schools across the 9 federal regions of Austria. In hindsight, and with the benefit of more time, there are aspects of the research design, planning and roll-out which might have been improved. For example, more time and resources would have allowed for further refinement of the sensor calibration processes and a better understanding of the limitations of the sensors and LoRaWAN technology, prior to the installation phase.

There are also a number of gaps in the existing knowledge that once filled will help to reduce the uncertainty associated with some of the findings. For example, in relation to the overall infection risk of many airborne viruses (including SARS-CoV-2) the precise ratio of short-range (droplet and advected aerosol transfer) to long-range (diffusion) risk, in any given setting, remains uncertain. Better information is also needed to understand the precise prophylaxis benefits achievable from ventilation systems in real-world contexts (both in terms of ventilation rates, ventilation effectiveness and system design). Despite a wealth of theoretical evidence and modelling studies there is a scarcity of high-quality empirical studies in this regard.

New knowledge regarding the role of CO_2 as a direct causal factor in prolonging the aerosol stability of airborne viruses (Haddrell, 2024) has emerged during the course of this study. That knowledge has not yet been incorporated into the infection risk models and 'health-based' thresholds used to evaluate the risk of airborne disease transmission in classrooms. In time this emerging knowledge may add additional weight to the importance of maintaining low CO_2 values in classrooms.

Similarly, the benefit of ventilation in relation to academic performance and absenteeism have sometimes led to inconsistent findings. Whilst general associations between poor indoor air quality and reduced academic performance (Shendell, 2004; Petersen, 2016) and increased illness related absenteeism (Mendell, 2013; Csobod, 2014) are well documented (Fisk, 2017; Wargocki, 2020), further work is needed to clarify the precise nature of the associations. This is important in developing targeted solutions, since associations between improved ventilation rates, academic performance and absenteeism could be mediated (or partially mediated) via a third variable, such as volatile organic compound (VOC) concentrations.

In relation to the derivation of ventilation airflow rates based on mass-balance conversion from steady-state CO_2 concentrations, ASTM D6245 cautions that mass-balance calculations are sometimes presented with little or no discussion of their limitations or the assumptions on which they are based. As a result the ASTM (2018) claim that the mass-balance technique has often been misused in the past and indoor CO_2 concentrations may have been misinterpreted as a result. This suggests that the misapplication of this method in previous studies might affect the reliability of the ventilation rates so derived, rendering direct comparisons with this study unreliable in some cases. It should be noted however, that the ASTM D6245 standard itself offers potential for misinterpretation in this respect, since it states that indoor CO_2 concentrations can be monitored in a building after the occupants have left to determine the outdoor air change rate of the building. Whilst such an approach may be suitable to estimate background air leakage rates in certain contexts, there are clear limitations to this approach in relation to typical school buildings where large volumes of stale air (at well above ambient CO_2 concentrations) remain trapped in adjacent corridors and connected rooms, often for prolonged periods of time.

Finally, a key limitation of this study is that no training was provided to teachers or school students in relation to the use of CO_2 monitors, or on how to correctly ventilate a classroom according to the time of year and outside temperatures. This fact means that the full benefit of using CO_2 monitors in classrooms, as part of a fully supported ventilation training programme is largely unknown. However, it is reasonable to assume that with appropriate training the results achieved are likely to be even better than those recorded by this study.

7.3.2 Recommendations for further work

A number of recommendations can be made for further work to consolidate the findings of this study in relation to improving ventilation and air quality in schools. These include (in no particular order):

- Carrying out a detailed audit of the ventilation characteristics of all schools (like Germany has recently undertaken). Then creating a detailed construction and ventilation database for all schools, including their EPCs, ventilation systems (natural or mechanical) and system characteristics (flow rates, ventilation effectiveness, noise etc).
- Carrying out a detailed end-user performance study (including operational and cost issues) associated with the use of mechanical ventilation systems in schools.
- Monitoring of air quality and ventilation on school buses and other public transport networks.
- Comprehensive monitoring of outdoor and indoor pollutants (including particulates, gases and airborne pathogens) inside and outside of school buildings, targeting high risk schools.
- Experimental and field studies investigating the efficacy of HEPA filters in naturally ventilated classrooms as a means of reducing airborne pathogens and air pollutants.
- Interventional double blind cross-over studies assessing mechanical ventilation and/or HEPA filters and upper room UV-C in relation to occupant health and reduced absenteeism.

8 Acknowledgements

We would like to extend a special thank you to the directors of the 120 schools which participated in the ImpAQS project, for providing us with access to their schools and for contributing their thoughts and time in responding to our surveys. We are also very grateful for the support provided by the school facility managers during the installation phase and ongoing monitoring of our sensor equipment. Finally, we would like to thank the participating classroom teachers for responding whole heartedly to our surveys, and for their daily work in maintaining classroom air quality whilst educating the younger generation.

A large number of researchers, organisations and individuals have contributed their time and effort in support of this project. We are grateful for the advice, discussions, information, time and practical support they have shared with us, which has contributed to strengthening the quality of this study. Amongst the dozens of people who have contributed in some way, we would like to express our particular gratitude to the following individuals for the support they have provided to the project.

Ao. Univ.-Prof. Dr. Martin Polaschek, former Federal Minister for Education, Science and Research, Austria

Mag. MBA Martin Netzer, Secretary General, Federal Ministry of Education, Science and Research, Austria

Dr.in Hemma Bauer, RLin, Federal Ministry of Education, Science, and Research, Austria

Mag. Markus Pasterk, Gastprof. MinR, Federal Ministry of Education, Science, and Research, Austria

Isabell Duscher, ADirin, Federal Ministry of Education, Science, and Research, Austria

Mag. Dr. Robert Klinglmair, Federal Institute for Quality Assurance of the Austrian School System

Michael Bruneforth, MA, Federal Institute for Quality Assurance of the Austrian School System

Dr. Roman Freunberger, Federal Institute for Quality Assurance of the Austrian School System

Moritz Friedrich, MSc, Federal Institute for Quality Assurance of the Austrian School System

Dr.techn. Dr.h.c.mult.Univ.-Prof. Dr. Harald Kainz, former Rector TU Graz

Univ.-Prof. Dipl.-Ing. Dr.techn. Horst Bischof, Rector of TU Graz

Univ.-Prof. Dipl.-Ing. Dr.techn. Michael Monsberger, Vice Rector of TU Graz

Assoc. Prof. Dipl.-Chem. Dr.rer.nat. Torsten Mayr, TU Graz Chemistry Dept.

Dominik Rabl, MA, TU Graz Chemistry Dept.

Mag.iur. Mag.rer.soc.oec. Roman Moser, TU Graz, and the entire Human Resources team

Univ.-Prof. Dipl.-Ing. Dr.techn. Andrea Berghold, Medical University Graz

Prof. Priv.-Doz. Mag. Dr. Alexander Avian, Medical University Graz

Prof. Dr. Ulrich Pöschl, Max Planck Institute for Chemistry

Dr. Thomas Klimach, Max Planck Institute for Chemistry

Dr. Frank Helleis, Max Planck Institute for Chemistry

Dipl.-Ing. Clara Pogner, Austrian Institute of Technology

Dr. Ivan Lunati, EMPA

Dr. Gorji Hossein, EMPA

Roger Vonbank, EMPA

Mag. Dipl.-Ing. Wolfgang Spangl, Environment Agency, Austria

Dr. Bradley Matthews, MSc, Environment Agency, Austria/BOKU

Ph.D. M.Sc. Kathiravan Mohamed Meeran, BOKU

Priv.-Doz. Mag.rer.nat. Dr.rer.nat. Andrea Watzinger, BOKU

Prof. Dr. Christian Schwarzbauer, Hochschule München

Mag.rer.soc.oec. Thomas Trink, MSc, TU Graz F&T Haus

Mag. (FH) Susanne Filzwieser, Media Service TU Graz

Andreas Gössler, Amtsdirektor, Purchasing Service TU Graz

Hofrat Mag.iur. Robert Schröcker, TU Graz

Assoc.Prof. Dipl.-Ing. Dr.techn. Stefan Radl, TU Graz

Prof. Mag. Dipl.-Ing. MA Hannes Grunbichler, HTL Weiz

Mr. Reinhard Novak, CEO LineMetrics GmbH.

Mr. Michael Tempelmayr, LineMetrics GmbH.

Mr. Rainer Resel, LineMetrics GmbH.

Mr. Alexander Gruber, LineMetrics GmbH.

Finally, we would like to express a special thankyou to the ImpAQS project technicians and support staff, without whom the equipment installation phase and room surveys would not have been completed on time.

Ines Abram; Dr. Jayaprithika Anandan; Maria Illinca-Badulescu; Dipl.-Ing Nina Bruckner; Dipl.-Ing Lukas Edl; Georg Eidenhammer; Gregor Fries; Lisa Hierzenberger; Johannes Huboi; Max Jost; Lena Maier; Andreas Miklau; Verena Neuhold; Dipl.-Ing. Mario Oboril; Sofia Pastori, PhD; Christoph Paulegger, Dipl.-Ing. ; Dipl.-Ing Muhammad Sanli; Michael Schmidberger; Jakob Traxler; Elizabeth Würzinger.

References

Afshari, A., Aganovic, A., Cao, G., Ekberg, L., et al. (2023). *Health-based target ventilation rates and design method for reducing exposure to airborne respiratory infectious diseases*. Available at: http://www.scanvac.eu [Accessed: 18 September 2024].

Airclean (2024). Indoor Air Quality Filtration System - Nitrogen Dioxide, PM10, PM2.5, NOx Filter for MVHR. Available at: https://www.airclean.co.uk/indoor-air-quality-filtration/indoor-air-quality-filter-system/ [Accessed: 24 October 2024].

Allen, J.G., MacNaughton, P., Satish, U., Santanam, S., et al. (2016). Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments. *Environmental Health Perspectives* 124(6), pp. 805–812. doi: 10.1289/EHP.1510037.

Allen, J.G. (2024). Recommitting to Ventilation Standards for Healthy Indoor Air Quality. *American journal of public health* 114(10), pp. 991–993. Available at: http://www.ncbi.nlm.nih.gov/pubmed/39231402 [Accessed: 25 September 2024].

Alsved, M., Nyström, K., Thuresson, S., Nygren, D., et al. (2023). Infectivity of exhaled SARS-CoV-2 aerosols is sufficient to transmit covid-19 within minutes. *Nature Scientific Reports* 13(1), pp. 1–9. Available at: https://www.nature.com/articles/s41598-023-47829-8 [Accessed: 21 March 2025].

Altrichter, H. and Helm, C. (2022). Austrians schools in the COVID-19 pandemic era. *Tertium Comparationis Journal für International und Interkulturell Vergleichende Erziehungswissenschaft* 28(3), pp. 300–331.

Andamon, M.M., Rajagopalan, P. and Woo, J. (2023). Evaluation of ventilation in Australian school classrooms using long-term indoor CO2 concentration measurements. *Building and Environment* 237, p. 110313. doi: 10.1016/J.BUILDENV.2023.110313.

Antoniou, F., Alghamdi, M.H. and Kawai, K. (2024). The effect of school size and class size on school preparedness. *Frontiers in Psychology* 15, p. 1354072. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC11002959/ [Accessed: 18 October 2024].

Arbeitsinspektion (2020). Occupational safety and health provisions. Available at: https://www.arbeitsinspektion.gv.at/Information_in_English/OSH_provisions/Occupational_safety_and_health_provisons.html [Accessed: 30 August 2024].

ASHRAE (2019). *ANSI/ASHRAE Standard 62.1-2019. Ventilation for Acceptable Indoor Air Quality*. Atlanta. Available at: https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2 [Accessed: 19 April 2022].

ASHRAE (2021). *ANSI/ASHRAE Addendum aa to ANSI/ASHRAE Standard 62.1-2019 Ventilation for Acceptable Indoor Air Quality*. Available at: www.ashrae.org [Accessed: 6 February 2025].

ASHRAE (2022). *ANSI/ ASHRAE Standard 62.1 - 2022, Ventilation and Acceptable Indoor Air Quality*. Available at: https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2 [Accessed: 24 September 2024].

ASHRAE (2023). *ASHRAE Standard 241-2023, Control of Infectious Aerosols*. Available at: https://www.ashrae.org/technical-resources/bookstore/ashrae-standard-241-control-of-infectious-aerosols [Accessed: 27 July 2023].

ASI (2023). *ÖNORM H 6039:2023 - Lüftungstechnische Anlagen - Kontrollierte mechanische Be- und*

Entlüftung von Schul-, Unterrichts- oder Gruppenräumen sowie Räumen mit ähnlicher Zweckbestimmung - Anforderungen, Dimensionierung, Ausführung, Betrieb und Wartung. Available at: https://www.austrian-standards.at/de/shop/onorm-h-6039-2023-02-01~p2880050 [Accessed: 18 September 2024].

ASTM (2018). *ASTM D6245-18 Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation*. Available at: https://www.astm.org/d6245-18.html [Accessed: 23 September 2024].

ASTM (2024). *ASTM D6245-24. Standard Guide on the Relationship of Indoor Carbon Dioxide Concentrations to Indoor Air Quality and Ventilation*. Available at: https://www.astm.org/d6245-24.html [Accessed: 11 October 2024].

Avella, F., Gupta, A., Peretti, C., Fulici, G., et al. (2021). Low-Invasive CO2-Based Visual Alerting Systems to Manage Natural Ventilation and Improve IAQ in Historic School Buildings. *Heritage 2021, Vol. 4, Pages 3442-3468* 4(4), pp. 3442–3468. Available at: https://www.mdpi.com/2571-9408/4/4/191/htm [Accessed: 20 August 2024].

Bakó-Biró, Z., Clements-Croome, D.J., Kochhar, N., Awbi, H.B., et al. (2012). Ventilation rates in schools and pupils' performance. *Building and Environment* 48(1), pp. 215–223. doi: 10.1016/j.buildenv.2011.08.018.

Barcellini, L., Forlanini, F., Sangiorgio, A., Gambacorta, G., et al. (2021). Does school reopening affect SARS-CoV-2 seroprevalence among school-age children in Milan? *PLOS ONE* 16(9): e0257046. Available at: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0257046 [Accessed: 8 August 2024].

Batterman, S. (2017). Review and Extension of CO_2-Based Methods to Determine Ventilation Rates with Application to School Classrooms. *International journal of environmental research and public health* 14(2). Available at: https://pubmed.ncbi.nlm.nih.gov/28165398/ [Accessed: 18 October 2024].

Baukulturpolitik (2024). Städte und Dörfer. Available at: https://www.baukulturpolitik.at/staedte-und-doerfer.html [Accessed: 18 October 2024].

Beggs, C.B., Abid, R., Motallebi, F., Samad, A., et al. (2024). Airborne Transmission of SARS-CoV-2: The Contrast between Indoors and Outdoors. *Fluids* 9(3), p. 54. Available at: https://www.mdpi.com/2311-5521/9/3/54/htm [Accessed: 10 April 2025].

Beinfait, D., Fitzner, K., Lindvall, T., Seppanen, O., et al. (1992). *Guidelines for Ventilation Requirements in Buildings. Report No.11. European Collaborative Action (ECA) – Indoor air quality and its impact on man.*

Belgian statutes *Belgium Clean Air Law: A Law to Improve Indoor Air Quality in Enclosed Spaces Open to the Public* . Available at: https://whn.global/app/uploads/2023/05/06112022_-_loi_qai_wet_blk.pdf [Accessed: 23 September 2024].

Berg-Munch, B., Clausen, G. and Fanger, P.O. (1986). Ventilation requirements for the control of body odor in spaces occupied by women. *Environment International* 12(1–4), pp. 195–199. doi: 10.1016/0160-4120(86)90030-9.

Bergeron, O. and Strachan, I.B. (2011). CO2 sources and sinks in urban and suburban areas of a northern mid-latitude city. *Atmospheric Environment* 45(8), pp. 1564–1573. doi: 10.1016/J.ATMOSENV.2010.12.043.

Blocken, B., van Druenen, T., Ricci, A., Kang, L., et al. (2021). Ventilation and air cleaning to limit aerosol particle concentrations in a gym during the COVID-19 pandemic. *Building and Environment* 193, p. 107659. doi: 10.1016/J.BUILDENV.2021.107659.

BMBWF (2021). 4-Punkte-Plan für einen sicheren Schulstart im Herbst. Available at: https://www.bmbwf.gv.at/Ministerium/Presse/20210804.html [Accessed: 19 August 2024].

BMJ (2024). 11. Correlation and regression. Available at: https://www.bmj.com/about-bmj/resources-readers/publications/statistics-square-one/11-correlation-and-regression [Accessed: 12 October 2024].

BMK (2021). Positionspapier zur Bewertung von Innenräumen in Hinblick auf das Infektionsrisiko durch SARS-CoV-2. Available at: https://www.bmk.gv.at/themen/klima_umwelt/luft/innenraum/arbeitskreis.html [Accessed: 30 August 2024].

BMK (2022). Positionspapier zu lüftungsunterstützenden Maßnahmen zur Infektionsprophylaxe – Einsatz von Luftreinigern und Einbringung von Wirkstoffen in die Innenraumluft Positionspapier des Arbeitskreises Innenraumluft. Available at: https://www.bmk.gv.at/themen/klima_umwelt/luft/innenraum/arbeitskreis.html [Accessed: 30 August 2024].

BMK (2024a). Immissionsschutzgesetz-Luft (IG-L). Available at: https://www.bmk.gv.at/themen/klima_umwelt/luft/recht/ig_l.html [Accessed: 30 August 2024].

BMK (2024b). Positionspapier zu Lüftungs- erfordernissen in Bildungseinrichtungen. Wien. Available at: https://www.bmk.gv.at/themen/klima_umwelt/luft/innenraum/arbeitskreis.html [Accessed: 19 August 2024].

BMK (2024c). Positionspapiere des Arbeitskreises Innenraumluft. Available at: https://www.bmk.gv.at/themen/klima_umwelt/luft/innenraum/arbeitskreis.html [Accessed: 19 August 2024].

BMK (2024d). Richtlinie zur Bewertung der Innenraumluft – Kohlenstoffdioxid als Lüftungsparameter. Wien. Available at: https://www.bmk.gv.at/themen/klima_umwelt/luft/innenraum/rl_luftqualitaet.html [Accessed: 18 September 2024].

Bordass, B., Leaman, A. and Ruyssevelt, P. (2001). Assessing building performance in use 5: conclusions and implications. *Building Research & Information* 29(2). Available at: https://www.tandfonline.com/action/journalInformation?journalCode=rbri20 [Accessed: 16 October 2024].

Boslaugh, S.E. (2023). sick building syndrome. *Encyclopedia Britannica* . Available at: https://www.britannica.com/science/sick-building-syndrome.

Bourouiba, L. (2020). Turbulent Gas Clouds and Respiratory Pathogen Emissions: Potential Implications for Reducing Transmission of COVID-19. *JAMA* 323(18), pp. 1837–1838. Available at: https://jamanetwork.com/journals/jama/fullarticle/2763852 [Accessed: 10 April 2025].

Brandl, A., Tappler, P., Twrdik, F. and Damberger, B. (2001). Untersuchungen raumluft- hygienischer Parameter in oberösterreichischen Schulen. In: *AGÖF Tagungsband des 6. Fachkongresses 2001 – Umwelt, Gebäude und Gesundheit*. Nürnberg, pp. 355-366. Available at: https://www.innenraumanalytik.at/Newsletter/brandl.pdf.

Bruns, R. (2023). *Cost-Benefit Analysis of ASHRAE Standard 241*. ASHRAE Journal. Available at: https://shorturl.at/4cnZl [Accessed: 18 September 2024].

BSGPK (2024). Abwassermonitoring Österreich. Available at: https://abwassermonitoring.at/dashboard/ [Accessed: 23 August 2024].

Buonanno, G., Ricolfi, L., Morawska, L. and Stabile, L. (2022). Increasing ventilation reduces SARS-CoV-2 airborne transmission in schools: A retrospective cohort study in Italy's Marche region. *Frontiers in public health* 10. Available at: https://pubmed.ncbi.nlm.nih.gov/36568748/ [Accessed: 8 August 2024].

Burge, S., Moore, V., Huntley, C., Robertson, A., et al. (2021). Occupational asthma in school teachers. *European Respiratory Journal* 58(suppl 65), p. PA1899. Available at: https://erj.ersjournals.com/content/58/suppl_65/PA1899 [Accessed: 6 September 2024].

Burridge, H.C., Bontitsopoulos, S., Brown, C., Carter, H., et al. (2023). Variations in classroom ventilation during the COVID-19 pandemic: Insights from monitoring 36 naturally ventilated classrooms in theUK during 2021. *Journal of Building Engineering* 63, p. 105459. Available at: https://doi.org/10.1016/j.jobe.2022.105459 [Accessed: 21 August 2024].

BUWAL (1997). Luftqualität in Innenräumen. *Luft* 287

Cai, C., Sun, Z., Weschler, L.B., Li, T., et al. (2021). Indoor air quality in schools in Beijing: Field tests, problems and recommendations. *Building and Environment* 205, p. 108179. doi: 10.1016/J.BUILDENV.2021.108179.

California Energy Commission (2013). *2013 Building Energy Efficiency Standards For Residential and Nonresidential Buildings*. California Energy Commission. Available at: https://www.buildingincalifornia.com/wp-content/uploads/2014/02/2013-energy-standards.pdf

Canha, N., Mandin, C., Ramalho, O., Wyart, G., et al. (2016). Assessment of ventilation and indoor air pollutants in nursery and elementary schools in France. *Indoor Air* 26(3), pp. 350–365. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/ina.12222 [Accessed: 9 September 2024].

Carrer, P., de Oliveira Fernandes, E., Santos, H., Hänninen, O., et al. (2018). On the development of health-based ventilation guidelines: Principles and framework. *International Journal of Environmental Research and Public Health* 15(7). Available at: /pmc/articles/PMC6068630/?report=abstract [Accessed: 17 September 2020].

CDC (2024). Estimated US Flu Disease Burden . Available at: https://www.cdc.gov/flu-burden/php/data-vis/index.html [Accessed: 25 September 2024].

CEN (2019). *EN 16798-1:2019 Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. Available at: https://shorturl.at/DMNQ0.

CEN (2019a). *CEN/TR 16798-2:2019 - Energy performance of buildings - Ventilation for buildings - Part 2:* Brussels. Available at: https://shorturl.at/R9JcL [Accessed: 13 September 2024].

CEN (2022). *EN 16798-3:2022 Energy performance of buildings - Ventilation for buildings - Part 3: For non-residential buildings*. Available at: https://www.austrian-standards.at/de/shop/onorm-en-16798-3-2022-12-15~p2644384 [Accessed: 11 September 2024].

CEN (2024). *ÖNORM EN 16798-1:2024 03 01 Energy performance of buildings - Ventilation for buildings - Part 1.* Available at: https://www.intertekinform.com/en-gb/standards/-norm-en-16798-1-2024-03-01-1167997_saig_on_on_3377479/ [Accessed: 12 September 2024].

Chen, Z.Y., Petetin, H., Méndez Turrubiates, R.F., Achebak, H., et al. (2024). Population exposure to multiple air pollutants and its compound episodes in Europe. *Nature Communications 2024 15:1* 15(1), pp. 1–11. Available at: https://www.nature.com/articles/s41467-024-46103-3 [Accessed: 29 September 2024].

Csobod, E., Annesi-Maesano, I., Barrero-Moreno, J., Beregszászi, T., et al. (2014). *SINPHONIE : Schools Indoor Pollution & Health Observatory Network in Europe : final report*. Publications Office of the European Union. Available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC91160 [Accessed: 8 August 2024].

Daniels, R. (2016). Making School Spaces: BB101 – Ventilation in School Building. Available at: https://thespaces.org.uk/wp-content/uploads/2016/07/BB101-Ventilation-Richard-Daniels-.pdf [Accessed: 18 October 2024].

Dorer, V. and Breer, D. (1998). Residential mechanical ventilation systems: performance criteria and evaluations. *Energy and Buildings* 27(3), pp. 247–255. doi: 10.1016/S0378-7788(97)00049-2.

ECDC (2023). Factsheet for health professionals on COVID-19. Available at: https://www.ecdc.europa.eu/en/infectious-disease-topics/z-disease-list/covid-19/factsheet-covid-19 [Accessed: 17 September 2024].

ECDC (2024). Questions and answers on COVID-19: Children aged 1 – 18 years and the role of school settings. Available at: https://www.ecdc.europa.eu/en/covid-19/questions-answers/questions-answers-school-transmission [Accessed: 8 August 2024].

Education and Skills Funding Agency (2018). *BB 101: Guidelines on ventilation, thermal comfort and indoor air quality in schools*. Available at: https://www.gov.uk/government/publications/building-bulletin-101-ventilation-for-school-buildings#history [Accessed: 11 September 2020].

EEA (2024). *Europe's air quality status 2024*. Available at: https://www.eea.europa.eu/publications/europes-air-quality-status-2024 [Accessed: 29 September 2024].

EMPA (2021). More infections in poorly ventilated classrooms. Available at: https://www.empa.ch/web/s604/covid-and-co2 [Accessed: 22 March 2022].

EPA (2009). Risk Assessment Guidance for Superfund. Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment). *US Environmental Protection Agency* . Available at: https://semspub.epa.gov/work/HQ/140530.pdf [Accessed: 26 August 2024].

EPA (2024). Health Effects of Ozone Pollution. Available at: https://www.epa.gov/ground-level-ozone-pollution/health-effects-ozone-pollution [Accessed: 29 September 2024].

European Commission (2016). General Data Protection Regulation (GDPR) . Available at: https://gdpr-info.eu/ [Accessed: 12 March 2025].

European Commission (2019). Fitness Check of the Ambient Air Quality Directives concludes that they have been partially effective in improving air quality and achieving air quality standards - European Commission. Available at: https://commission.europa.eu/news/fitness-check-ambient-air-quality-directives-concludes-they-have-been-partially-effective-improving-2019-11-29_en [Accessed: 16 October 2024].

European Commission (2024). EU air quality standards. Available at: https://environment.ec.europa.eu/topics/air/air-quality/eu-air-quality-standards_en [Accessed: 30 September 2024].

European Parliament (2023). *REPORT on the proposal for a directive of the European Parliament and of the Council on ambient air quality and cleaner air for Europe (recast). A9-0233/2023*. Available at: https://www.europarl.europa.eu/doceo/document/A-9-2023-0233_EN.html [Accessed: 29 September 2024].

European Union *Directive 2004/107/EC of the European Parliament and of the Council of 15 December*

2004. European Union. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32004L0107 [Accessed: 16 October 2024].

European Union *Directive 2008/50/EC of the European Parliament and of the Council* . European Union. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0050 [Accessed: 16 October 2024].

Eurovent (2018). *Eurovent 4/23 - selection of EN ISO 16890 rated air filter classes for general filtration applications*. Brussels. Available at: www.eurovent.eu. [Accessed: 30 September 2024].

Evans, J.R. and Mathur, A. (2005). The value of online surveys. *Internet Research* 15(2), pp. 195–219. Available at: https://doi.org/10.1108/10662240510590360 [Accessed: 16 October 2024].

Everard, M., Johnston, P., Santillo, D. and Staddon, C. (2020). The role of ecosystems in mitigation and management of Covid-19 and other zoonoses. *Environmental Science and Policy* 111, pp. 7–17. Available at: /pmc/articles/PMC7247996/ [Accessed: 22 June 2021].

Fanger, P.. and Berg-Munch, B. (1983). Ventilation and body odor. AIVC. Available at: https://www.aivc.org/resource/ventilation-and-body-odor [Accessed: 17 September 2024].

Fears, A.C., Klimstra, W.B., Duprex, P., Hartman, A., et al. (2020). Persistence of Severe Acute Respiratory Syndrome Coronavirus 2 in Aerosol Suspensions. *Emerging infectious diseases* 26(9). doi: 10.3201/eid2609.201806.

Fisk, W.J., Black, D. and Brunner, G. (2011). Benefits and costs of improved IEQ in U.S. offices. *Indoor Air* 21(5), pp. 357–367. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/j.1600-0668.2011.00719.x [Accessed: 25 September 2024].

Fisk, W.J. (2017). The ventilation problem in schools: literature review. *Indoor Air* 27(6), pp. 1039–1051. Available at: http://doi.wiley.com/10.1111/ina.12403 [Accessed: 20 January 2021].

Gao, J., Wargocki, P. and Wang, Y. (2014). Ventilation system type, classroom environmental quality and pupils' perceptions and symptoms. *Building and Environment* 75, pp. 46–57. doi: 10.1016/J.BUILDENV.2014.01.015.

Gao, Y.Q., Seah, J.J., Wang, M.L., Tang, Q. ping, et al. (2024). An unusually high prevalence of allergic rhinitis at high altitudes in 6–7 year old children – An epidemiological study. *The World Allergy Organization Journal* 17(5), p. 100887. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC11089395/ [Accessed: 18 October 2024].

Geelen, L.M.J., Huijbregts, M.A.J., Ragas, A.M.J., Bretveld, R.W., et al. (2008). Comparing the effectiveness of interventions to improve ventilation behavior in primary schools. *Indoor Air* 18(5), pp. 416–424. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/j.1600-0668.2008.00542.x [Accessed: 7 May 2025].

Di Gilio, A., Palmisani, J., Pulimeno, M., Cerino, F., et al. (2021). CO2 concentration monitoring inside educational buildings as a strategic tool to reduce the risk of Sars-CoV-2 airborne transmission. *Environmental research* 202. Available at: https://pubmed.ncbi.nlm.nih.gov/34224708/ [Accessed: 20 August 2024].

Greenhalgh, T., Jimenez, J.L., Prather, K.A., Tufeki, Z., et al. (2022). Transmission of SARS-CoV-2: still up in the air – Authors' reply. *The Lancet* 399(10324), pp. 519–520. Available at: http://www.thelancet.com/article/S0140673621027951/fulltext [Accessed: 24 October 2024].

Greenpeace (2018). *Mon air, mon école - Greenpeace Belgique*. Brussles. Available at: https://www.greenpeace.org/belgium/fr/rapport/998/mon-air-mon-ecole/ [Accessed: 23 September 2024].

Greer, N., Bart, B., Billington, C.J., Diem, S.J., et al. (2022). Original research: COVID-19 postacute care major organ damage: a systematic review. *BMJ Open* 12(8), p. e061245. Available at: /pmc/articles/PMC9412042/ [Accessed: 17 September 2024].

Gunnarsen, L. and Ole Fanger, P. (1992). Adaptation to indoor air pollution. *Environment International* 18(1), pp. 43–54. doi: 10.1016/0160-4120(92)90209-M.

Haddrell, A., Oswin, H., Otero-Fernandez, M., Robinson, J.F., et al. (2024). Ambient carbon dioxide concentration correlates with SARS-CoV-2 aerostability and infection risk. *Nature Communications 2024 15:1* 15(1), pp. 1–11. Available at: https://www.nature.com/articles/s41467-024-47777-5 [Accessed: 3 May 2024].

Hanna, F., Alameddine, I., Zaraket, H., Alkalamouni, H., et al. (2023). Airborne influenza virus shedding by patients in health care units: Removal mechanisms affecting virus transmission. *PLOS ONE* 18(10), p. e0290124. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC10599543/ [Accessed: 24 October 2024].

Hastie, C.E., Lowe, D.J., McAuley, A., Mills, N.L., et al. (2023). True prevalence of long-COVID in a nationwide, population cohort study. *Nature Communications 2023 14:1* 14(1), pp. 1–6. Available at: https://www.nature.com/articles/s41467-023-43661-w [Accessed: 17 September 2024].

Haverinen-Shaughnessy, U., Moschandreas, D.J. and Shaughnessy, R.J. (2011). Association between substandard classroom ventilation rates and students' academic achievement. *Indoor Air* 21(2), pp. 121–131. doi: 10.1111/j.1600-0668.2010.00686.x.

Hawila, A.A.W., Diallo, T.M.O. and Collignan, B. (2023). Occupants' window opening behavior in office buildings: A review of influencing factors, modeling approaches and model verification. *Building and Environment* 242, p. 110525. doi: 10.1016/J.BUILDENV.2023.110525.

Heidemann, C., Sarganas, G., Du, Y., Gaertner, B., et al. (2023). Long-term health consequences among individuals with SARS-CoV-2 infection compared to individuals without infection: results of the population-based cohort study CoMoLo Follow-up. *BMC Public Health* 23(1), p. 1587. Available at: /pmc/articles/PMC10440884/ [Accessed: 17 September 2024].

Helleis, F., Klimach, T. and Pöschl, U. (2023). Wirksamkeit, Energieeffizienz und Nachhaltigkeit verschiedener Lüftungsmethoden hinsichtlich Luftqualität und Infektionsschutz in Innenräumen: Fensterlüften, Abluftventilatoren, Raumlufttechnik und Luftreiniger. Available at: https://zenodo.org/record/7586167 [Accessed: 4 August 2023].

Herath, S., Mansour, A. and Bentley, R. (2024). Urban density, household overcrowding and the spread of COVID-19 in Australian cities. *Health & Place* 89, p. 103298. doi: 10.1016/J.HEALTHPLACE.2024.103298.

HFCSE (2024). Legal framework regarding indoor air quality. Available at: https://www.health.belgium.be/en/closer-legal-framework-indoor-air-quality#principles [Accessed: 23 September 2024].

Hohenblum, P. (2008). *LUKI: Air and children - Influence of indoor air on the health of children in all-day schools - BML DaFNE*. Vienna. Available at: https://dafne.at/projekte/luki [Accessed: 24 September 2024].

Inness, A., Ades, M., Agustí-Panareda, A., Barr, J., et al. (2019). The CAMS reanalysis of atmospheric composition. *Atmospheric Chemistry and Physics* 19(6), pp. 3515–3556. doi: 10.5194/ACP-19-3515-2019.

ISO (2012). *ISO 16000-26:2012 - Indoor air – Part 26: Sampling strategy for carbon dioxide (CO2)*. Available at: https://bit.ly/3uyiJXF [Accessed: 28 March 2022].

ISO (2017). *ISO 17772-1:2017. Energy performance of buildings — Indoor environmental quality — Part 1: Indoor environmental input parameters for the design and assessment of energy performance of buildings*. Available at: https://www.iso.org/standard/60498.html [Accessed: 4 April 2022].

ISO (2023). *ISO 16000-41:2023 - Indoor air — Part 41: Assessment and classification*. Available at: https://www.iso.org/standard/76519.html [Accessed: 24 September 2024].

Janssen, H., Ford, K., Gascoyne, B., Hill, R., et al. (2023). Cold indoor temperatures and their association with health and well-being: a systematic literature review. *Public Health* 224, pp. 185–194. doi: 10.1016/J.PUHE.2023.09.006.

Jian, Y., Guo, Y., Liu, J., Bai, Z., et al. (2011). Case study of window opening behavior using field measurement results. *Building Simulation* 4(2), pp. 107–116. Available at: https://link.springer.com/article/10.1007/s12273-010-0012-5 [Accessed: 7 May 2025].

Jiminez, J. (2020). COVID-19 Is Transmitted Through Aerosols. We Have Enough Evidence, Now It Is Time to Act. Available at: https://time.com/5883081/covid-19-transmitted-aerosols/ [Accessed: 14 September 2020].

Johnson, K.E., Lachmann, M., Stoddard, M., Pasco, R., et al. (2021). Detecting in-school transmission of SARS-CoV-2 from case ratios and documented clusters. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8095228 [Accessed: 8 August 2024].

Katafygiotou, M.C. and Serghides, D.K. (2014). Indoor comfort and energy performance of buildings in relation to occupants' satisfaction: investigation in secondary schools of Cyprus. *Advances in Building Energy Research* 8(2), pp. 216–240. Available at: https://www.tandfonline.com/doi/abs/10.1080/17512549.2013.865554 [Accessed: 26 August 2024].

Klimach, T., Helleis, F., McLeod, R.S., Hopfe, C.J., et al. (2021). The Max Planck Institute for Chemistry mechanical extract ventilation (MPIC-MEV) system against aerosol transmission of COVID-19. Available at: https://zenodo.org/record/5802049 [Accessed: 13 May 2022].

Konstantopoulos, S. and Shen, T. (2023). Class size and teacher effects on non-cognitive outcomes in grades K-3: a fixed effects analysis of ECLS-K:2011 data. *Large-Scale Assessments in Education* 11(1), pp. 1–24. Available at: https://link.springer.com/article/10.1186/s40536-023-00182-8 [Accessed: 18 October 2024].

Kurnitski, J., Kiil, M., Mikola, A., Võsa, K.V., et al. (2023). Post-COVID ventilation design: Infection risk-based target ventilation rates and point source ventilation effectiveness. *Energy and Buildings* 296, p. 113386. doi: 10.1016/J.ENBUILD.2023.113386.

Kvalsvig, A., Tuari-Toma, B., Timu-Parata, C., Bennett, J., et al. (2023). Protecting school communities from COVID-19 and other infectious disease outbreaks: the urgent need for healthy schools in Aotearoa New Zealand. Available at: https://journal.nzma.org.nz/ [Accessed: 8 August 2024].

Laiman, R., He, C., Mazaheri, M., Clifford, S., et al. (2014). Characteristics of ultrafine particle sources and deposition rates in primary school classrooms. Available at: http://dx.doi.org/10.1016/j.atmosenv.2014.05.013 [Accessed: 10 September 2024].

Li, X., Qi, X., Ma, J., Pan, Y., et al. (2022). SARS-CoV-2 Remained Airborne for a Prolonged Time in a Lockdown Confined Space. *Aerosol and Air Quality Research* 22(2), p. 210131. Available at: https://aaqr.org/articles/aaqr-21-06-oa-0131 [Accessed: 30 August 2024].

Li, Y., Cheng, P. and Jia, W. (2022). Poor ventilation worsens short-range airborne transmission of respiratory infection. *Indoor Air* 32(1), p. e12946. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/ina.12946 [Accessed: 19 April 2022].

Li, Y., Gao, S., Fang, T., Gao, Y., et al. (2024). A method for estimating occupant carbon dioxide generation rates. *Energy and Buildings* 312, p. 114163. doi: 10.1016/J.ENBUILD.2024.114163.

Lowe, R., Chiu, L.F. and Oreszczyn, T. (2018). Socio-technical case study method in building performance evaluation. *Building Research & Information* 46(5). Available at: https://www.tandfonline.com/action/journalInformation?journalCode=rbri20 [Accessed: 16 October 2024].

Ludewig, E. and Senoner, W. (Eds.) (2024). *Sonnblick Observatorium - Scientific Activities*. Available at: https://www.sonnblick.net/ic-orig/4JvmRVGqHJ/InhalteBroschueren/SBO_Broschuere-Brochure_2024_FINAL_www.pdf

De Marco, A., Garcia-Gomez, H., Collalti, A., Khaniabadi, Y.O., et al. (2022). Ozone modelling and mapping for risk assessment: An overview of different approaches for human and ecosystems health. *Environmental Research* 211, p. 113048. doi: 10.1016/J.ENVRES.2022.113048.

Matthews, B., Luther, A., Fasano, E., Tang, H., et al. (2024). *Investigating Vienna's methane budget with local observations of turbulent fluxes and total column mole fractions*. Vienna: Copernicus Meetings. Available at: https://meetingorganizer.copernicus.org/EGU24/EGU24-12294.html [Accessed: 16 October 2024].

McLeod, R. and Swainson, M. (2017). Chronic overheating in low carbon urban developments in a temperate climate. *Renewable and Sustainable Energy Reviews* 74. Available at: https://www.sciencedirect.com/science/article/pii/S1364032116305925.

McLeod, Robert S., Hopfe, C.J., Bodenschatz, E., Moriske, H.J., et al. (2022). A multi-layered strategy for COVID-19 infection prophylaxis in schools: A review of the evidence for masks, distancing, and ventilation. *Indoor Air* 32(10), p. e13142. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/ina.13142 [Accessed: 15 December 2022].

McLeod, R. S., Mathew, M., Salman, D. and Thomas, C.L.P. (2022). An Investigation of Indoor Air Quality in a Recently Refurbished Educational Building. *Frontiers in Built Environment* 7, p. 769761. doi: 10.3389/FBUIL.2021.769761/BIBTEX.

Mendell, M.J., Eliseeva, E.A., Davies, M.M., Spears, M., et al. (2013). Association of classroom ventilation with reduced illness absence: A prospective study in California elementary schools. *Indoor Air* 23(6), pp. 515–528. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/ina.12042 [Accessed: 12 October 2020].

Mendell, M.J., Chen, W., Ranasinghe, D.R., Castorina, R., et al. (2024). Carbon dioxide guidelines for indoor air quality: a review. *Journal of Exposure Science & Environmental Epidemiology 2024 34:4* 34(4), pp. 555–569. Available at: https://www.nature.com/articles/s41370-024-00694-7 [Accessed: 18 September 2024].

Mendell, M.J. and Heath, G.A. (2005). Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air* 15(1), pp. 27–52. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/j.1600-0668.2004.00320.x [Accessed: 9 September 2024].

Mishra, J., Mishra, P. and Arora, N.K. (2021). Linkages between environmental issues and zoonotic diseases: with reference to COVID-19 pandemic. *Environmental Sustainability* 1, p. 3. Available at: https://doi.org/10.1007/s42398-021-00165-x [Accessed: 22 June 2021].

Morawska, L., Marks, G.B. and Monty, J. (2022). Healthy indoor air is our fundamental need: the time to act is now. *Medical Journal of Australia* 217(11), pp. 578–581. doi: 10.5694/MJA2.51768.

Morawska, L., Li, Y. and Salthammer, T. (2024). Lessons from the COVID-19 pandemic for ventilation and indoor air quality. *Science* 385(6707), pp. 396–401. Available at: https://www.science.org/doi/10.1126/science.adp2241 [Accessed: 18 September 2024].

Morawska, L., Allen, J., Bahnfleth, W., Bennett, B., et al. (2024). Mandating indoor air quality for public buildings If some countries lead by example, standards may increasingly become normalized. *Science* 383(6690), pp. 1418–1420. Available at: https://www.science.org/doi/10.1126/science.adl0677 [Accessed: 18 September 2024].

Müller, D., Burgholz, T.M., Rewitz, K., Bardey, J., et al. (2020). *Abschätzung des Infektionsrisikos durch aerosolgebundene Viren in belüfteten Räumen*. RWTH Aachen University, E.ON Energy Research Center, Institute for Energy Efficient Buildings and Indoor Climate (EBC). doi: 10.18154/RWTH-2020-11340.

Mustafa, M., Cook, M.J. and McLeod, R.S. (2025). A critical review of ventilation effectiveness in naturally ventilated spaces from the perspective of sustainability and health. *Building and Environment* 270, p. 112471. doi: 10.1016/J.BUILDENV.2024.112471.

Myatt, T.A., Staudenmayer, J., Adams, K., Walters, M., et al. (2002). A study of indoor carbon dioxide levels and sick leave among office workers. *Environmental Health 2002 1:1* 1(1), pp. 1–10. Available at: https://ehjournal.biomedcentral.com/articles/10.1186/1476-069X-1-3 [Accessed: 25 September 2024].

Nazaroff, W.W. (2022). Indoor aerosol science aspects of SARS-CoV-2 transmission. *Indoor Air* 32(1), p. e12970. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/ina.12970 [Accessed: 13 June 2022].

Ng, L. and Mills, D. (2024). The Impact of Outdoor Air Ventilation in School Corridors. *ASHRAE Journal* . Available at: ASHRAE.org [Accessed: 24 September 2024].

Nous aérons (2023). French regulations relating to direct-reading measurement of the CO2 level in daycare and schools indoor air | Version 2 UK of the 03.01.202. Available at: https://nousaerons.fr/regulations/french_regulations_direct-reading_measurement_co2_v2.pdf [Accessed: 23 September 2024].

OECD (2024). Student-teacher ratio and average class size. Available at: https://shorturl.at/IH3zb [Accessed: 18 October 2024].

Olesen, B. (2015). Indoor environmental input parameters for the design and assessment of energy performance of buildings. *REHVA Journal*

Pan, S., Xiong, Y., Han, Y., Zhang, X., et al. (2018). A study on influential factors of occupant window-opening behavior in an office building in China. *Building and Environment* 133, pp. 41–50. doi: 10.1016/J.BUILDENV.2018.02.008.

Parinduri, R.A. (2014). Do children spend too much time in schools? Evidence from a longer school year in Indonesia. *Economics of Education Review* 41, pp. 89–104. doi: 10.1016/J.ECONEDUREV.2014.05.001.

Pereira, A.R., Braga, D.F.O., Vassal, M., Gomes, I.B., et al. (2023). Ultraviolet C irradiation: A promising approach for the disinfection of public spaces? *Science of The Total Environment* 879, p. 163007. doi: 10.1016/J.SCITOTENV.2023.163007.

Persily, A. (2015). Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62. *Building and Environment* 91, pp. 61–69. doi: 10.1016/J.BUILDENV.2015.02.026.

Persily, A. (2021). *Evaluating Ventilation Performance*. Zhang, Y. et al. eds. Springer, Singapore. Available at: https://link.springer.com/referenceworkentry/10.1007/978-981-10-5155-5_20-1

[Accessed: 25 September 2024].

Persily, A. (2022). Development and application of an indoor carbon dioxide metric. *Indoor Air* 32(7), p. e13059. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/ina.13059 [Accessed: 17 October 2024].

Persily, A. and de Jonge, L. (2017). Carbon dioxide generation rates for building occupants. *Indoor Air* 27(5), pp. 868–879. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/ina.12383 [Accessed: 23 September 2024].

Persily, A.K. (2016). Field measurement of ventilation rates. *Indoor air* 26(1), pp. 97–111. Available at: https://pubmed.ncbi.nlm.nih.gov/25689218/ [Accessed: 18 October 2024].

Petersen, S., Jensen, K.L., Pedersen, A.L.S. and Rasmussen, H.S. (2016). The effect of increased classroom ventilation rate indicated by reduced CO2 concentration on the performance of schoolwork by children. *Indoor Air* 26(3), pp. 366–379. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/ina.12210 [Accessed: 25 September 2024].

Pollozhani, F., McLeod, R.S., Schwarzbauer, C. and Hopfe, C.J. (2024). Assessing school ventilation strategies from the perspective of health, environment, and energy. *Applied Energy* 353, p. 121961. doi: 10.1016/J.APENERGY.2023.121961.

Pope, C.A. and Dockery, D.W. (2012). Acute Health Effects of PM10 Pollution on Symptomatic and Asymptomatic Children. *https://doi.org/10.1164/ajrccm/145.5.1123* 145(5), pp. 1123–1128. doi: 10.1164/AJRCCM/145.5.1123.

Public Health Ontario (2022). Public Health Ontario (2022). COVID-19 Transmission through Short and Long-Range Respiratory Particles. Available at: https://shorturl.at/hSqQH [Accessed: 24 October 2024].

Raab, D. (2024). Telephone conversation with DI Raab of the ÖISS (8 October 2024).

REHVA (2021). REHVA COVID-19 guidance document version 4.1. Available at: https://shorturl.at/4Mevh [Accessed: 18 September 2024].

REHVA (2022). *Health-based target ventilation rates and design method for reducing exposure to airborne respiratory infectious diseases*. Available at: https://www.rehva.eu/fileadmin/user_upload/2022/Health_based_target_ventilation_09012023.pdf [Accessed: 13 September 2024].

Republik Österreich *BGBl. II Nr. 368/1998 (Arbeitsstättenverordnung – AStV)*. Republik Österreich.

Republik Österreich *Immissionsschutzgesetz – Luft, IG-L*. Wien. Available at: https://shorturl.at/Q2mMi [Accessed: 30 August 2024].

République Française *Arrêté du 27 décembre 2022 fixant les conditions de réalisation de la mesure à lecture directe de la concentration en dioxyde de carbone dans l'air intérieur au titre de l'évaluation annuelle des moyens d'aération* . Légifrance. Available at: https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000046830005 [Accessed: 23 September 2024].

République Française *Decree No. 2022-1690 of 27 December 2022 amending Decree No. 2012-14 of 5 January 2012 on the assessment of ventilation means and measurement of pollutants carried out under the indoor air quality monitoring of certain establishments receiving the public - Legifrance*. Légifrance . Available at: https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000046829352 [Accessed: 23 September 2024].

Rhodes, S., Wilkinson, J., Pearce, N., Mueller, W., et al. (2022). Occupational differences in SARS-CoV-2 infection: analysis of the UK ONS COVID-19 infection survey. *Journal of Epidemiology and Community*

Health 76(10), p. 841. Available at: /pmc/articles/PMC9484374/ [Accessed: 8 August 2024].

Riley, R. (1980). Prevention and control of airborne infection in the community. *Annals of the New York Academy of Sciences* 353(1), pp. 331–339. Available at: https://nyaspubs.onlinelibrary.wiley.com/doi/10.1111/j.1749-6632.1980.tb18936.x [Accessed: 1 October 2024].

RIS (2024). Schulzeitgesetz 1985 - Bundesrecht konsolidiert, Fassung vom 30.08.2024. Available at: https://shorturl.at/PvNSi [Accessed: 15 October 2024].

RIS *Arbeitsstättenverordnung - Bundesrecht konsolidiert, Fassung vom 03.10.2024*. Rechtsinformationssytem des Bundes. Available at: https://ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=10009098 [Accessed: 3 October 2024].

RIS *Bundesrecht konsolidiert: Gesamte Rechtsvorschrift für Arbeitsstättenverordnung, Fassung vom 03.10.2024*. Rechtsinformationssytem des Bundes. Available at: https://ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=10009098 [Accessed: 3 October 2024].

RIS *Ozongesetz Art. 1 § 4 - Bundesrecht konsolidiert, Fassung vom 01.01.2024*. Rechtsinformationssytem des Bundes. Available at: https://shorturl.at/QovZE [Accessed: 16 October 2024].

Rowe, B.R., Canosa, A., Meslem, A. and Rowe, F. (2022). Increased airborne transmission of COVID-19 with new variants, implications for health policies. *Building and Environment* 219, p. 109132. doi: 10.1016/J.BUILDENV.2022.109132.

Rudnick, S.N. and Milton, D.K. (2003). Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. *Indoor Air* 13(3), pp. 237–245. Available at: https://onlinelibrary.wiley.com/doi/full/10.1034/j.1600-0668.2003.00189.x [Accessed: 25 September 2024].

Sadick, A.M. and Issa, M.H. (2018). Differences in teachers' satisfaction with indoor environmental quality and their well-being in new, renovated and non-renovated schools. *Indoor and Built Environment* 27(9), pp. 1272–1286. doi: 10.1177/1420326X17717074.

Sadrizadeh, S., Yao, R., Yuan, F., Awbi, H., et al. (2022). Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment. *Journal of Building Engineering* 57, p. 104908. doi: 10.1016/J.JOBE.2022.104908.

Sanguinetti, A., Outcault, S., Pistochini, T. and Hoffacker, M. (2022). Understanding teachers' experiences of ventilation in California K-12 classrooms and implications for supporting safe operation of schools in the wake of the COVID-19 pandemic. *Indoor Air* 32(2), p. e12998. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/ina.12998 [Accessed: 13 June 2022].

Schwarzbauer, C. (2021). Studie zu Luftqualität und Ansteckungsrisiken in deutschen Klassenzimmern: Lüften, Luftreiniger und Lüftungsanlagen im Vergleich - Aktuelles - News.

Schwarzbauer, C. (2022). *Forschungsprojekt 'Sicheres Klassenzimmer': Wirkung verschiedener Lüftungsmethoden hinsichtlich Luftqualität und Infektionsschutz im realen Schulunterricht*. Muncih. Available at: https://zenodo.org/records/7496827 [Accessed: 21 August 2024].

von Seidlein, L., Alabaster, G., Deen, J. and Knudsen, J. (2020). Crowding has consequences: Prevention and management of COVID-19 in informal urban settlements. *Building and Environment* 188, p. 107472. Available at: /pmc/articles/PMC7680649/?report=abstract [Accessed: 21 January 2021].

Selgrade, M.K., Plopper, C.G., Gilmour, M.I., Conolly, R.B., et al. (2008). Assessing The Health Effects and Risks Associated with Children's Inhalation Exposures—Asthma and Allergy. *Journal of Toxicology and Environmental Health, Part A* 71(3), pp. 196–207. Available at: https://www.tandfonline.com/doi/abs/10.1080/15287390701597897 [Accessed: 30 October 2024].

Seppänen, O., Fisk, W.J. and Lei, Q.H. (2006). Ventilation and performance in office work. *Indoor Air* 16(1), pp. 28–36. doi: 10.1111/J.1600-0668.2005.00394.X.

Seppänen, O., Brelih, N., Goeders, G. and Brussels, A.L. (2012). *HealthVent Health-Based Ventilation Guidelines for Europe: WP5 final report*. Available at: https://www.rehva.eu/fileadmin/EU_projects/HealthVent/HealthVent_WP5_-_Final_Report.pdf [Accessed: 21 January 2021].

Shendell, D.G., Prill, R., Fisk, W.J., Apte, M.G., et al. (2004). Associations between classroom CO2 concentrations and student attendance in Washington and Idaho. *Indoor Air* 14(5), pp. 333–341. Available at: https://pubmed.ncbi.nlm.nih.gov/15330793/ [Accessed: 12 October 2020].

Stabile, L., Dell'Isola, M., Russi, A., Massimo, A., et al. (2017). The effect of natural ventilation strategy on indoor air quality in schools. *The Science of the total environment* 595, pp. 894–902. Available at: https://pubmed.ncbi.nlm.nih.gov/28432989/ [Accessed: 20 August 2024].

Der Standard (2016). Österreich: Hoher Anteil an berufsbildenden Schülern. *DerStandard OECD-Bericht* 16 September. Available at: https://www.derstandard.at/story/2000044473947/oesterreich-hoher-anteil-an-berufsbildenden-schuelern [Accessed: 18 October 2024].

Statista (2019). Average number of students per primary level class in selected European countriesa. Available at: https://www.statista.com/statistics/1078190/students-per-class-in-europe/ [Accessed: 18 October 2024].

Statista (2025). Wetter und Klima in Österreich - Statistiken und Fakten. Available at: https://de.statista.com/themen/4735/wetter-in-oesterreich/ [Accessed: 21 March 2025].

Statistik Austria (2024). Bildung in Zahlen . Available at: https://www.statistik.at/statistiken/bevoelkerung-und-soziales/bildung/bildung-in-zahlen [Accessed: 18 October 2024].

Szendi, D. and Sárosi-Blága, Á. (2022). Impact of the COVID-19 pandemic on smart city performance in Europe. *Észak-magyarországi Stratégiai Füzetek* 19(4), pp. 48–60. doi: 10.32976/STRATFUZ.2022.43.

Tak, S., Groenewold, M., Alterman, T., Park, R.M., et al. (2011). Excess Risk of Head and Chest Colds Among Teachers and Other School Workers. *The Journal of School Health* 81(9), p. 560. Available at: /pmc/articles/PMC7185491/ [Accessed: 6 September 2024].

Tans, P. and Thoning, K. (2020). How we measure background CO2 levels on Mauna Loa . Available at: https://gml.noaa.gov/ccgg/about/co2_measurements.html [Accessed: 29 September 2024].

Tellier, R., Li, Y., Cowling, B.J. and Tang, J.W. (2019). Recognition of aerosol transmission of infectious agents: a commentary. *BMC Infectious Diseases* 19(1), p. 101. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC6357359/ [Accessed: 24 October 2024].

Thangavel, P., Park, D. and Lee, Y.C. (2022). Recent Insights into Particulate Matter (PM2.5)-Mediated Toxicity in Humans: An Overview. *International Journal of Environmental Research and Public Health* 19(12). Available at: /pmc/articles/PMC9223652/ [Accessed: 29 September 2024].

The Lancet COVID-19 Commission (2021). *Designing infectious disease resilience into school buildings through improvements to ventilation and air cleaning*. Available at: https://covid-19.forhealth.org/lancet-covid-19-commission-task-force-on-safe-work-safe-school-and-safe-travel/

[Accessed: 24 September 2024].

The Lancet COVID-19 Commission (2022). *Proposed Non-infectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Infectious Diseases*. Available at: https://www.aph.gov.au/DocumentStore.ashx?id=07b78224-5e39-4ca4-8ed3-109f69e218a6&subId=726021.

Troeger, C., Forouzanfar, M., Rao, P.C., Khalil, I., et al. (2017). Estimates of the global, regional, and national morbidity, mortality, and aetiologies of lower respiratory tract infections in 195 countries: a systematic analysis for the Global Burden of Disease Study 2015. *The Lancet Infectious Diseases* 17(11), pp. 1133–1161. doi: 10.1016/S1473-3099(17)30396-1.

Uhde, E., Salthammer, T., Wientzek, S., Springorum, A., et al. (2022). Effectiveness of air-purifying devices and measures to reduce the exposure to bioaerosols in school classrooms. *Indoor Air* 32(8), p. e13087. Available at: https://onlinelibrary.wiley.com/doi/full/10.1111/ina.13087 [Accessed: 29 September 2022].

Untis GmbH (2024). WebUntis - Smarter und schneller Planen – mit Untis, der führenden Stundenplansoftware. Available at: https://www.untis.at/ [Accessed: 10 October 2024].

USEPA (1991). *Indoor Air Facts No. 4 Sick Building Syndrome*. Available at: https://www.epa.gov/sites/default/files/2014-08/documents/sick_building_factsheet.pdf

Wargocki, P. (2004). Sensory pollution sources in buildings. *Indoor air* 14 Suppl 7(SUPPL. 7), pp. 82–91. Available at: https://pubmed.ncbi.nlm.nih.gov/15330776/ [Accessed: 17 September 2024].

Wargocki, P., Porras-Salazar, J.A., Contreras-Espinoza, S. and Bahnfleth, W. (2020). The relationships between classroom air quality and children's performance in school. *Building and Environment* 173, p. 106749. doi: 10.1016/J.BUILDENV.2020.106749.

Wargocki, P. and Kostyrko, K. (2022). Measurements of Perceived Indoor Air Quality. *Handbook of Indoor Air Quality* , pp. 1–35. Available at: https://link.springer.com/referenceworkentry/10.1007/978-981-10-5155-5_81-1 [Accessed: 17 September 2024].

Wargocki, P. and Da Silva, N.A.. (2015). Use of visual CO2 feedback as a retrofit solution for improving classroom air quality. *Indoor air* 25(1), pp. 105–114. Available at: https://pubmed.ncbi.nlm.nih.gov/24735406/ [Accessed: 20 August 2024].

Wargocki, P. and Wyon, D.P. (2013). Providing better thermal and air quality conditions in school classrooms would be cost-effective. *Building and Environment* 59, pp. 581–589. doi: 10.1016/J.BUILDENV.2012.10.007.

Wargocki, P. and Wyon, D.P. (2017). Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. *Building and Environment* 112, pp. 359–366. doi: 10.1016/J.BUILDENV.2016.11.020.

White, L.F., Murray, E.J. and Chakravarty, A. (2022). The role of schools in driving SARS-CoV-2 transmission: Not just an open-and-shut case. *Cell Reports Medicine* 3(3). Available at: /pmc/articles/PMC8858687/ [Accessed: 8 August 2024].

WHO (2021a). *Roadmap to improve and ensure good indoor ventilation in the context of COVID-19*. Geneva. Available at: https://www.who.int/publications/i/item/9789240021280 [Accessed: 19 April 2022].

WHO (2021b). *WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. Available at:

https://iris.who.int/handle/10665/345329 [Accessed: 24 September 2024].

WHO (2024). Disability-adjusted life years (DALYs) attributable to the environment (%). Available at: https://www.who.int/data/gho/indicator-metadata-registry/imr-details/4657 [Accessed: 26 October 2024].

Williams, B.A., Jones, C.H., Welch, V. and True, J.M. (2023). Outlook of pandemic preparedness in a post-COVID-19 world. *npj Vaccines 2023 8:1* 8(1), pp. 1–12. Available at: https://www.nature.com/articles/s41541-023-00773-0 [Accessed: 24 October 2024].

Wojnarowska, M., Plichta, G., Sagan, A., Plichta, J., et al. (2020). Odour nuisance and urban residents' quality of life: A case study in Kraków's in Plaszow district. *Urban Climate* 34, p. 100704. doi: 10.1016/J.UCLIM.2020.100704.

Wood, S.G.A., Handy, A.E.E., Roberts, K. and Burridge, H.C. (2024). Assessing classroom ventilation rates using CO2 data from a nationwide study of UK schools and identifying school-wide correlation factors. *Developments in the Built Environment* 19, p. 100520. doi: 10.1016/J.DIBE.2024.100520.

Wouters, P., Delmotte, C., Faÿsse, J.C., Barles, P., et al. (2000). *Towards improved performances of mechanical ventilation systems*. Available at: https://shorturl.at/6BWfK [Accessed: 12 October 2024].

Wrona, M. and Skrypnik, D. (2022). New-Onset Diabetes Mellitus, Hypertension, Dyslipidaemia as Sequelae of COVID-19 Infection—Systematic Review. *International Journal of Environmental Research and Public Health* 19(20). Available at: /pmc/articles/PMC9602450/ [Accessed: 17 September 2024].

Wu, Y., Li, Y., Gao, S., Liu, S., et al. (2023). Carbon dioxide generation rates for children and adolescents. *Building and Environment* 237, p. 110310. doi: 10.1016/J.BUILDENV.2023.110310.

Xing, Z.Z., Yang, T., Shi, S., Meng, X., et al. (2023). Ambient particulate matter associates with asthma in high altitude region: A population-based study. *World Allergy Organization Journal* 16(5), p. 100774. doi: 10.1016/J.WAOJOU.2023.100774.

Zabihi, M., Li, R. and Brinkerhoff, J. (2024). Influence of indoor airflow on airborne disease transmission in a classroom. *Building Simulation* 17(3), pp. 355–370. Available at: https://link.springer.com/article/10.1007/s12273-023-1097-y [Accessed: 14 August 2024].

Zhang, D., Ding, E. and Bluyssen, P.M. (2022). Guidance to assess ventilation performance of a classroom based on CO2 monitoring. *Indoor and Built Environment* 31(4), pp. 1107–1126. Available at: https://journals.sagepub.com/doi/10.1177/1420326X211058743 [Accessed: 22 August 2024].

Zhang, X., Zhao, C., Zhang, T., Xie, J., et al. (2023). Association of indoor temperature and air quality in classrooms based on field and intervention measurements. *Building and Environment* 229, p. 109925. doi: 10.1016/J.BUILDENV.2022.109925.

Zhang, Y.P., Li, B.Z., Huang, C., Yang, X., et al. (2013). Ten cities cross-sectional questionnaire survey of children asthma and other allergies in China. *Chinese Science Bulletin* 58(34), pp. 4182–4189. Available at: https://link.springer.com/article/10.1007/s11434-013-5914-z [Accessed: 30 October 2024].

Zoho Corporation Pvt. Ltd. (2024). Zoho Cloud Software Suite for Businesses. Available at: https://www.zoho.com/ [Accessed: 11 October 2024].

Table of Contents – Appendix

A. Project timeline and work packages

A.1. ImpAQS project timeline

The scope of work addressed in this report covers the work packages AP3 – AP6 as shown in Fig A-1, as outlined in the ImpAQS project proposal.

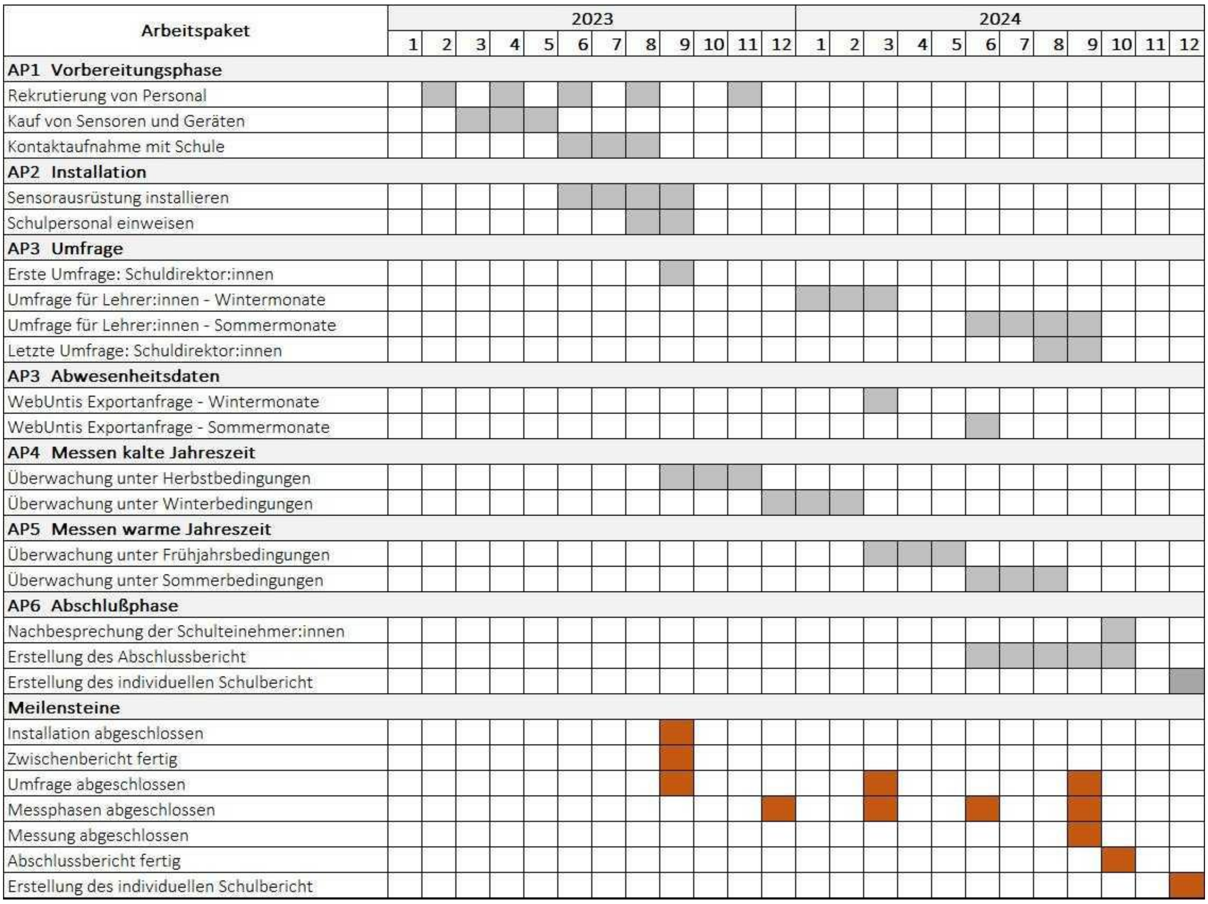


Figure A-1 ImpAQS project Gannt Chart

B. Methods

B.1. Letter to participating schools

The following letter was sent to the selected schools as the initial form of contact:

TU Graz
Graz University of Technology

ibpsc Institut für Bauphysik, Gebäudetechnik und Hochbau
Fakultät für Bauingenieurwissenschaften
Technische Universität Graz

[redacted]
Tel.: [redacted]
Mail [redacted]

[redacted]
Tel.: [redacted]
Mail [redacted]

[redacted]
Tel.: [redacted]
Mail [redacted]

Adresse: [redacted]
Web: [redacted]

DVR: 008 1833 UID: ATU 574 77 929

Graz, am 12. Juni 2023

Betreff: Teilnahme am ImpAQS-Projekt der TU Graz

Sehr geehrte(r) [redacted]

Wir schreiben Ihnen im Zusammenhang mit einem neuen nationalen Forschungsprojekt mit dem Titel "ImpAQS" (Improving Air Quality in Schools), das von der Technischen Universität Graz (TU Graz) in Zusammenarbeit mit dem Bundesministerium für Bildung, Wissenschaft und Forschung (BMBWF) in diesem Jahr ins Leben gerufen wurde. 120 Schulen in ganz Österreich wurden vom Institut des Bundes für Qualitätssicherung im österreichischen Schulwesen (IQS) für die Teilnahme an diesem Projekt ausgewählt (mittels einer statistischen Zufallsstichprobe). Wir freuen uns, Ihnen mitteilen zu können, dass Ihre Schule eine der ausgewählten Schulen ist, die an dieser spannenden Studie teilnimmt. Als Teilnehmender an diesem Projekt werden 10 Ihrer Klassenzimmer mit CO_2-Sensoren ausgestattet, die Sie am Ende des Projekts behalten können. Sie haben auch die Möglichkeit, von den Ergebnissen und Empfehlungen zu profitieren, die aus unserer Forschung hervorgehen werden (siehe www.impaqs.tugraz.at für weitere Details).

Dieses Schreiben enthält im folgenden Einzelheiten bzgl.

- Projekt ImpAQS
- **Erforderliche Informationen**
- Ihre Vorteile
- Datenspeicherung und DSGVO

Wir bitten Sie, uns die folgenden **Informationen zur Verfügung stellen** (weiter unten finden Sie genauere Angaben, warum diese Daten benötigt werden und wie sie behandelt werden):

ImpAQS ibpsc TU Graz
Graz University of Technology

- **Grundrisse Ihrer Schule**
- **Eine Liste der Klassenräume und die Anzahl der Schüler und Schülerinnen pro Klasse**
- **Angaben zu allen mechanischen Belüftungs- oder Filtersystemen und evtl. CO_2 Sensoren, die in den Räumlichkeiten verwendet werden**
- **Kontaktperson für die Installation der Sensoren**
- **Anwesenheitsdaten für teilnehmende zehn Klassen (wenn möglich)**

Im Laufe des Projekts stellen wir Ihnen zwei Online-Umfragen zur Verfügung, die von den jeweiligen Klassenlehrer/innen ausgefüllt werden müssen. Diese Formulare sind sehr kurz gehalten, um den Zeitaufwand für Ihr Personal möglichst gering zu halten.

Die Installationen der kabellosen Sensoren finden im Juni (oder in Ausnahmefällen im Juli) statt. Hierfür sind wir auf einen Besuch in Ihrer Schule angewiesen. Unser Team besteht aus erfahrenen Mitarbeitenden der Technischen Universität Graz, die die Installation durchführen werden. Es ist wichtig, dass wir den Namen und die Kontaktdaten (E-Mail-Adresse und Mobiltelefonnummer) einer verantwortlichen Person in Ihrer Schule haben (z.B. den Schulwart), welche direkt erreichbar sein sollte und mit der wir den Zeitpunkt der Installation und die Positionierung der Sensoren optimal koordinieren können.

Wir bitten Sie, die erforderlichen Informationen (die in den oben genannten Punkten aufgeführt sind) bis zum **23.06.2023** an die folgende E-Mail-Adresse senden könnten: [redacted]

Ihre Daten sind für unsere Forschung von großem Wert und werden mit äußerster Vertraulichkeit behandelt. Wir sind Ihnen sehr dankbar für Ihre Unterstützung und Teilnahme an diesem Projekt. Sollten Sie Bedenken haben oder mehr über einen Aspekt der Studie wissen wollen, können Sie uns gerne unter [redacted] kontaktieren.

Mit freundlichen Grüßen,

Univ.-Prof. Dipl.-Ing. Dr. Christina J. Hopfe

TU Graz, Graz University of Technology
Bundesministerium Bildung, Wissenschaft und Forschung
Institut des Bundes für Qualitätssicherung im österreichischen Schulwesen

Figure A-2 Example of the invitation letter sent to participating schools

B.2. Data cleaning for matched-pair analyses

The following table reports the dynamic cut-off values used to clean the matched-pairs data.

Table A-1 Examples of dynamic cut-off values.

Date and Time	Threshold [ppm]
2023-09-18 08:00:00	547.125
2023-09-18 09:00:00	535.6125
2023-09-18 10:00:00	523.375
2023-09-18 11:00:00	510.18125
2023-09-18 12:00:00	508.825
2023-09-18 13:00:00	502.5
2023-09-18 14:00:00	499.85
2023-09-18 15:00:00	494.73125
2023-09-18 16:00:00	478.4
2023-09-19 08:00:00	544.033333333333
2023-09-19 09:00:00	537.5
2023-09-19 10:00:00	525.4
2023-09-19 11:00:00	513.6625
…	…
Date and Time	Threshold [ppm]
…	…
2024-07-04 13:00:00	499.1
2024-07-04 14:00:00	494.1
2024-07-04 15:00:00	511
2024-07-04 16:00:00	494.4
2024-07-05 08:00:00	539.05
2024-07-05 09:00:00	580.1
2024-07-05 10:00:00	539.9
2024-07-05 11:00:00	528.9
2024-07-05 12:00:00	520.25
2024-07-05 13:00:00	511.2
2024-07-05 14:00:00	511.525
2024-07-05 15:00:00	543.65
2024-07-05 16:00:00	534.7

B.3. Altitude compensation algorithm

Figure A-3 provides a visual representation of the altitude compensation process outlined in Section 3.5.3.3. On the primary y-axis, altitude above sea level is shown, while the x-axis represents the altitude compensation factor, which increases linearly with elevation. The secondary y-axis displays the compensated CO_2 concentration, which reflects the adjusted CO_2 value the sensor would read in outdoor air after applying the manufacturer's altitude compensation algorithm.

The red and orange dashed lines highlight the altitudes of key locations: Vienna serving as the lowest altitude in the ImpAQS project, Graz the location of calibration, and Semmering as the highest altitude. As the graph indicates, sensors installed at higher altitudes, such as Semmering, require a greater compensation factor to account for reduced atmospheric pressure, ensuring that CO_2 measurements remain consistent regardless of elevation.

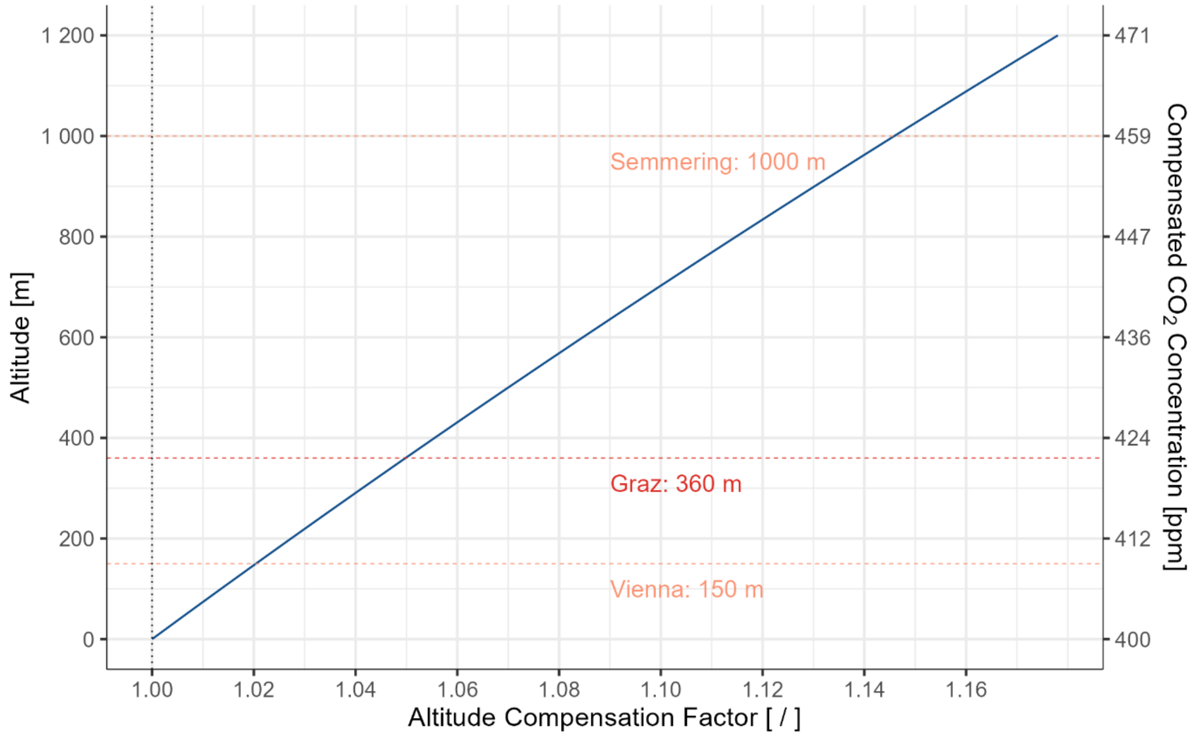


Figure A-3 Altitude compensation algorithm

B.4. Installation manual

At the start of the installation process, the technicians underwent practical training at TU Graz and were provided with an installation manual, as shown in Figure A-4. The manual included details on how to install the gateway and how to position and mount the indoor and outdoor sensors so that the devices would receive optimal signals and be able to send the data to the cloud.

3. Aufstellung des Gateways

1. Aufstellung des Gateways

Das Gateway muss das ganze Jahr über an einem sicheren Ort aufbewahrt werden, um Diebstahl, Ausstöpseln und den damit verbundenen Datenverlust zu vermeiden. Mögliche geeignete Orte sind das Sekretariat oder das Büro des Schulleiters. Platzieren Sie das Gateway so zentral und hoch wie möglich. Achten Sie darauf, dass das Gateway möglichst freistehend platziert wird. Montieren Sie das Kabelmodem möglichst in einem Abstand von mindestens 20 cm zu Wand und Decke. Vermeiden Sie auf jeden Fall die Montage in Schaltschränken oder ähnlichen Schränken.

2. Ersteinrichtung des Gateways

Das Gateway enthält eine LTE/4G-Simkarte. Eine WLAN/LAN-Verbindung ist daher nicht erforderlich. Das Gateway muss lediglich an eine 220V-Steckdose angeschlossen werden, die Verbindung zur Cloud wird dann automatisch hergestellt.

3. Überprüfung der Funktionsfähigkeit

Um den Status eines Gateways zu überprüfen, haben Sie zwei Möglichkeiten. Scannen Sie den QR-Code auf dem Gateway mit Ihrem Smartphone, um zu den Geräteinformationen zu gelangen (ohne Login-Daten möglich) oder prüfen Sie das jeweilige Gateway in der LineMerics Cloud unter „Geräte & Hardware" mit Hilfe der Projektkoordination.

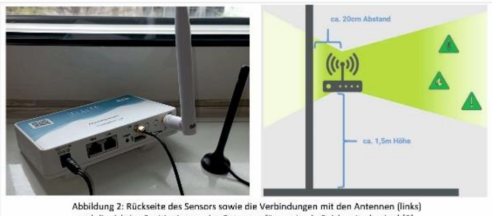


Abbildung 2: Rückseite des Sensors sowie die Verbindungen mit den Antennen (links) und die richtige Positionierung des Gateways für maximale Reichweite (rechts) [3].

4. Aufstellung der Innensensoren

1. Überprüfung der Signalqualität der Sensoren

Es ist wichtig zu prüfen, ob die Sensoren eine angemessene Signalstärke vom Gateway erhalten, um einen schnellen Batterieverlust zu vermeiden. Dazu nimmt man einige T-Sensoren und bringt sie in die Klassenzimmer, die am weitesten vom Gateway entfernt sind, und prüft die Signalstärke durch Scannen des QR-Codes.

Ein Indikator für eine gute/akzeptable Signalqualität wird in der nachstehenden Tabelle erläutert:

RSSI	> -110 dbm
SNR	> 0 dB
dR	5

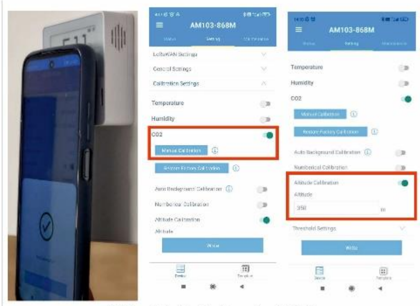


Abbildung 3: Zugriff auf den Sensor über NFC (links) Einrichten der manuellen Kalibrierung (Mitte) und Einstellen der Meereshöhe (rechts)

2. Platzierung der Sensoren

Montieren Sie den CO_2-Sensor nicht direkt neben offenen Fenstern, Türen oder Zulufteinlässen, da dies zu nicht repräsentativen Messwerten führt. Der Sensor sollte auf Atemhöhe im Sitzen (ca. 1,2 m über dem Boden), weit entfernt von der Frischluftzufuhr, nicht direkt im Atemluftstrom von Personen (z. B. auf einem Schreib- oder Arbeitstisch), in ausreichendem Abstand zu seinen Nutzern (ca. 1 m Abstand) oder mittig an einer Innenwand gegenüber den Fenstern angebracht werden (siehe Figur 4).

Versuchen Sie, elektrische Leitungen (wie in Figur 6 dargestellt), Wasserleitungen und zentrale Schächte zu vermeiden.

Beachten Sie die nachstehenden Hinweise:

- Kabel werden in der Regel senkrecht und waagerecht verlegt
- Kabel haben in der Regel einen Abstand von 15 - 30 cm von der Wandkante und dem Boden
- Versuchen Sie, in ausreichendem Abstand zu Lichtschaltern, Steckdosen, Wasserleitungen und Waschbecken zu bohren
- Verwenden Sie immer einen isolierten Schraubendreher

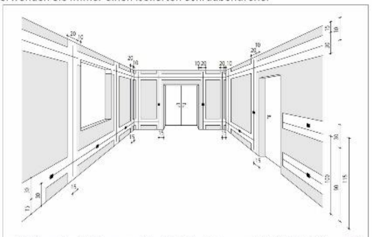


Abbildung 5: Installationszonen für elektrische Anlagen nach DIN 18015-3. [5, p. 441]

4. Funktions- und Signalprüfung

Um den Status eines Sensors zu überprüfen, haben Sie zwei Möglichkeiten. Scannen Sie den QR-Code auf dem Sensor mit Ihrem Smartphone, um zu den Geräteinformationen zu gelangen (ohne Login-Daten möglich), oder überprüfen Sie den betreffenden Sensor in der LineMerics Cloud unter „Geräte & Hardware" mit Hilfe des Projektkoordinationsteams.

Wenn Sie den QR-Code scannen, können Sie den Signalstatus wie unten abgebildet sehen:

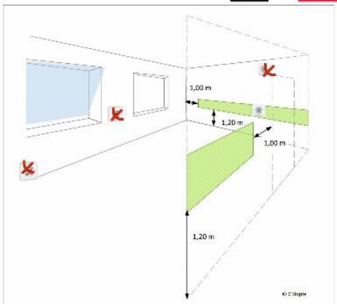


Abbildung 4: Beispiel für geeignete Bereiche (grün) und ungeeignete Positionen (rot durchgestrichen) für CO_2-Sensoren in Innenräumen ca. 1,2 m über dem Boden in einem Abstand von mindestens 1 m zu Türen und Fenstern, möglichst weit entfernt von Fensteröffnungen und Personen.

3. Montage des Sensors

Die Milesight AM 103 CO_2-Sensoren [4] werden mit den mitgelieferten Sicherheits-Torx-Schrauben montiert. Dazu muss jedoch zunächst die Rückseite des Sensors geöffnet werden. Diese Sicherheits-Torx-Schrauben sind wichtig, um den Diebstahlschutz während der Messzeit zu gewährleisten.

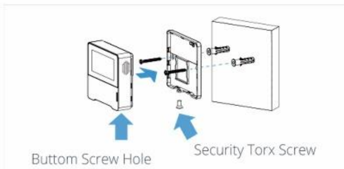
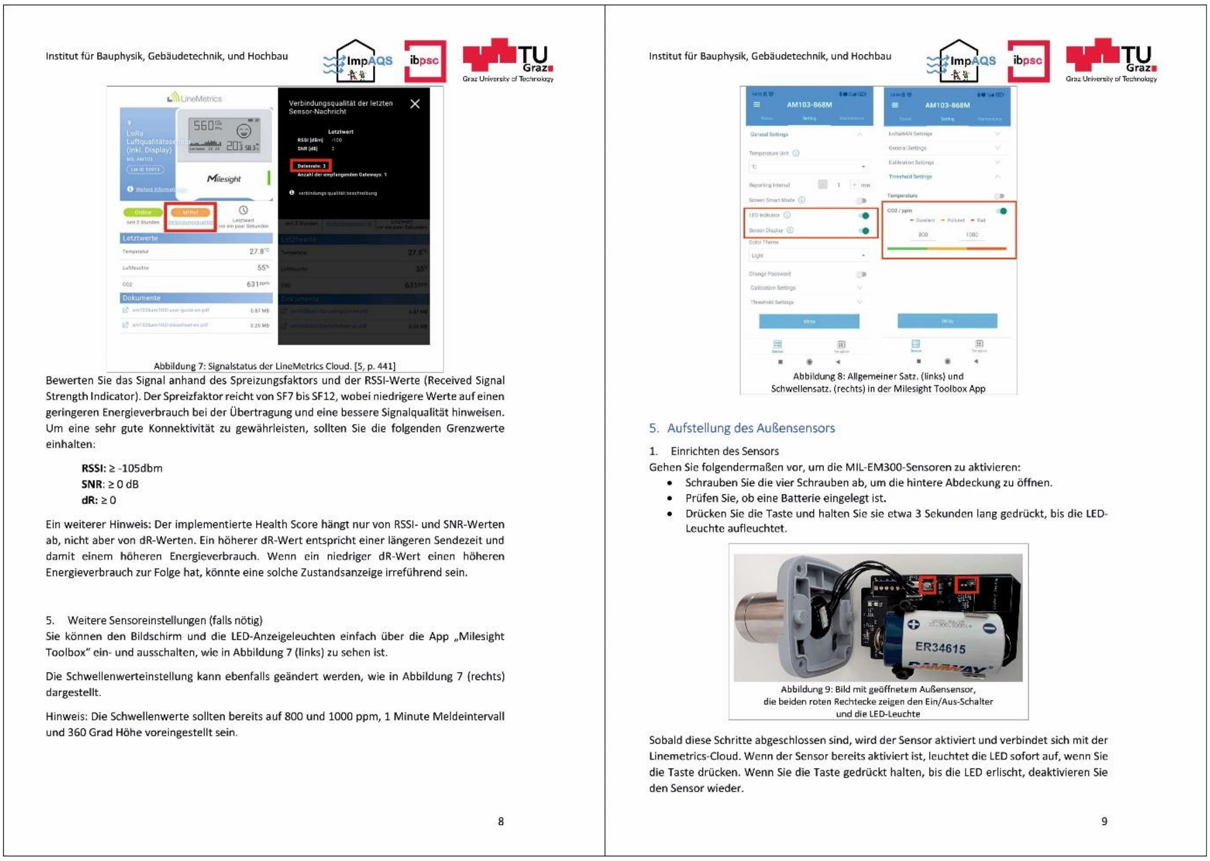


Abbildung 5: Installation des Milesight AM 103 unter Verwendung der mitgelieferten Sicherheits-Torx-Schrauben. Hinweis: Die hintere Abdeckung des Sensors muss zu diesem Zweck geöffnet werden.[4]



Institut für Bauphysik, Gebäudetechnik, und Hochbau

Abbildung 7: Signalstatus der LineMetrics Cloud. [5, p. 441]

Bewerten Sie das Signal anhand des Spreizungsfaktors und der RSSI-Werte (Received Signal Strength Indicator). Der Spreizfaktor reicht von SF7 bis SF12, wobei niedrigere Werte auf einen geringeren Energieverbrauch bei der Übertragung und eine bessere Signalqualität hinweisen. Um eine sehr gute Konnektivität zu gewährleisten, sollten Sie die folgenden Grenzwerte einhalten:

RSSI: ≥ -105dbm
SNR: ≥ 0 dB
dR: ≥ 0

Ein weiterer Hinweis: Der implementierte Health Score hängt nur von RSSI- und SNR-Werten ab, nicht aber von dR-Werten. Ein höherer dR-Wert entspricht einer längeren Sendezeit und damit einem höheren Energieverbrauch. Wenn ein niedriger dR-Wert einen höheren Energieverbrauch zur Folge hat, könnte eine solche Zustandsanzeige irreführend sein.

5. Weitere Sensoreinstellungen (falls nötig)

Sie können den Bildschirm und die LED-Anzeigeleuchten einfach über die App „Milesight Toolbox" ein- und ausschalten, wie in Abbildung 7 (links) zu sehen ist.

Die Schwellenwerteinstellung kann ebenfalls geändert werden, wie in Abbildung 7 (rechts) dargestellt.

Hinweis: Die Schwellenwerte sollten bereits auf 800 und 1000 ppm, 1 Minute Meldeintervall und 360 Grad Höhe voreingestellt sein.

8

Institut für Bauphysik, Gebäudetechnik, und Hochbau

Abbildung 8: Allgemeiner Satz. (links) und Schwellensatz. (rechts) in der Milesight Toolbox App

5. Aufstellung des Außensensors

1. Einrichten des Sensors

Gehen Sie folgendermaßen vor, um die MIL-EM300-Sensoren zu aktivieren:

- Schrauben Sie die vier Schrauben ab, um die hintere Abdeckung zu öffnen.
- Prüfen Sie, ob eine Batterie eingelegt ist.
- Drücken Sie die Taste und halten Sie sie etwa 3 Sekunden lang gedrückt, bis die LED-Leuchte aufleuchtet.

Abbildung 9: Bild mit geöffnetem Außensensor, die beiden roten Rechtecke zeigen den Ein/Aus-Schalter und die LED-Leuchte

Sobald diese Schritte abgeschlossen sind, wird der Sensor aktiviert und verbindet sich mit der Linemetrics-Cloud. Wenn der Sensor bereits aktiviert ist, leuchtet die LED sofort auf, wenn Sie die Taste drücken. Wenn Sie die Taste gedrückt halten, bis die LED erlischt, deaktivieren Sie den Sensor wieder.

9

Figure A-4 ImpAQS installation manual showing guidance for technicians installing sensors in the selected schools

B.5. Room selection hierarchy

The classrooms are paired following a predefined hierarchy as follows:

Table A-2 Matched-pairs room pairing hierarchy

Hierarchy	Criteria
1	Same ventilation system (similar windows or mechanical ventilation systems)
2	Same floor
3	Same orientation (i.e. same side of the building/same direction)
4	Similar floor area and ceiling height
5	Same grade, age and class size (preferably, but this is not always possible)

Once room pairs are chosen, the ‘T’ and ‘C’ room designation is randomly assigned using the Excel tool.

B.6. Room-display posters

Two wall mounted display documents were created to provide clear guidance to students and staff in the Test (T) rooms:

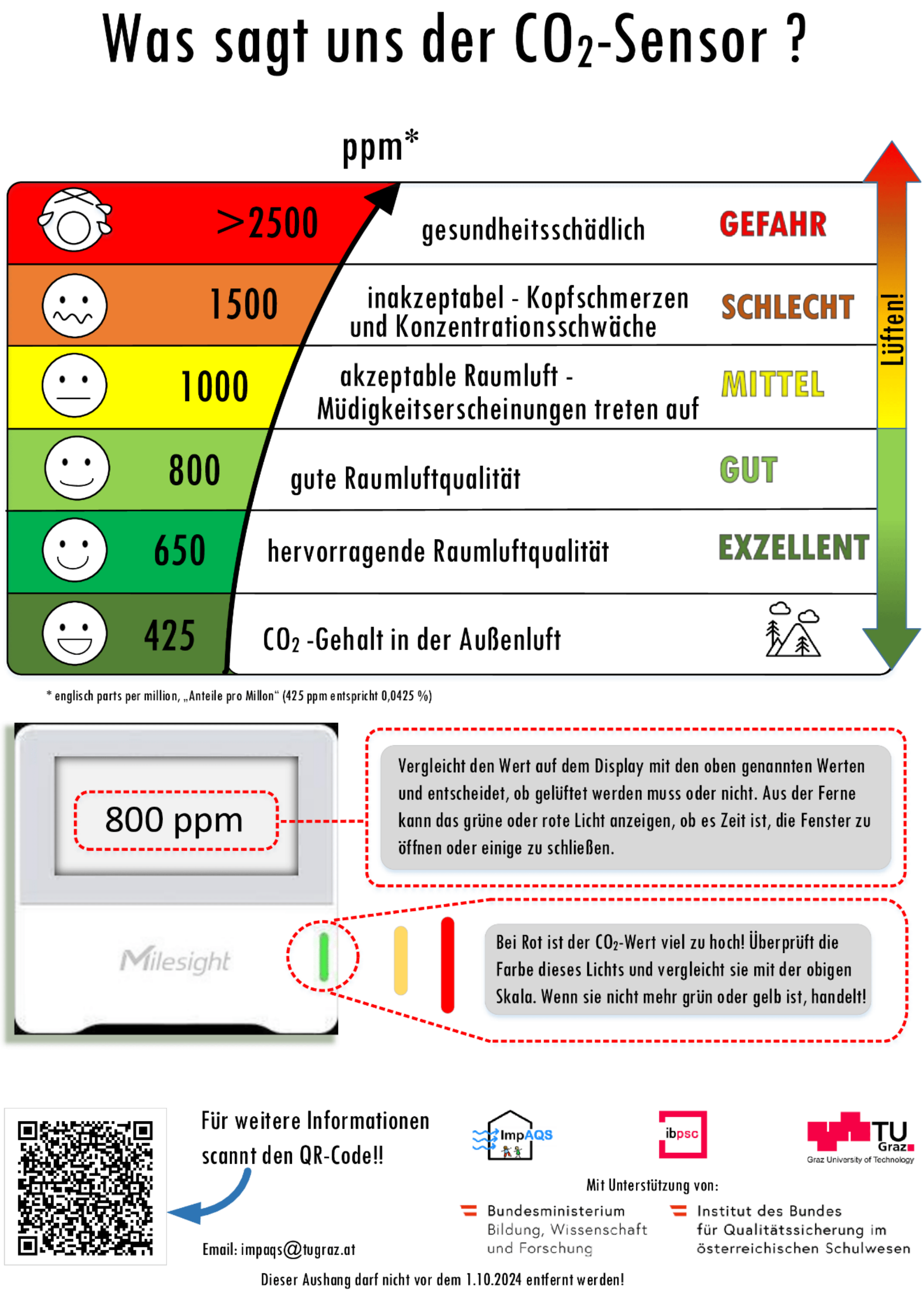


Figure A-5 Room poster 1 – “What does a CO_2 sensor tell you”

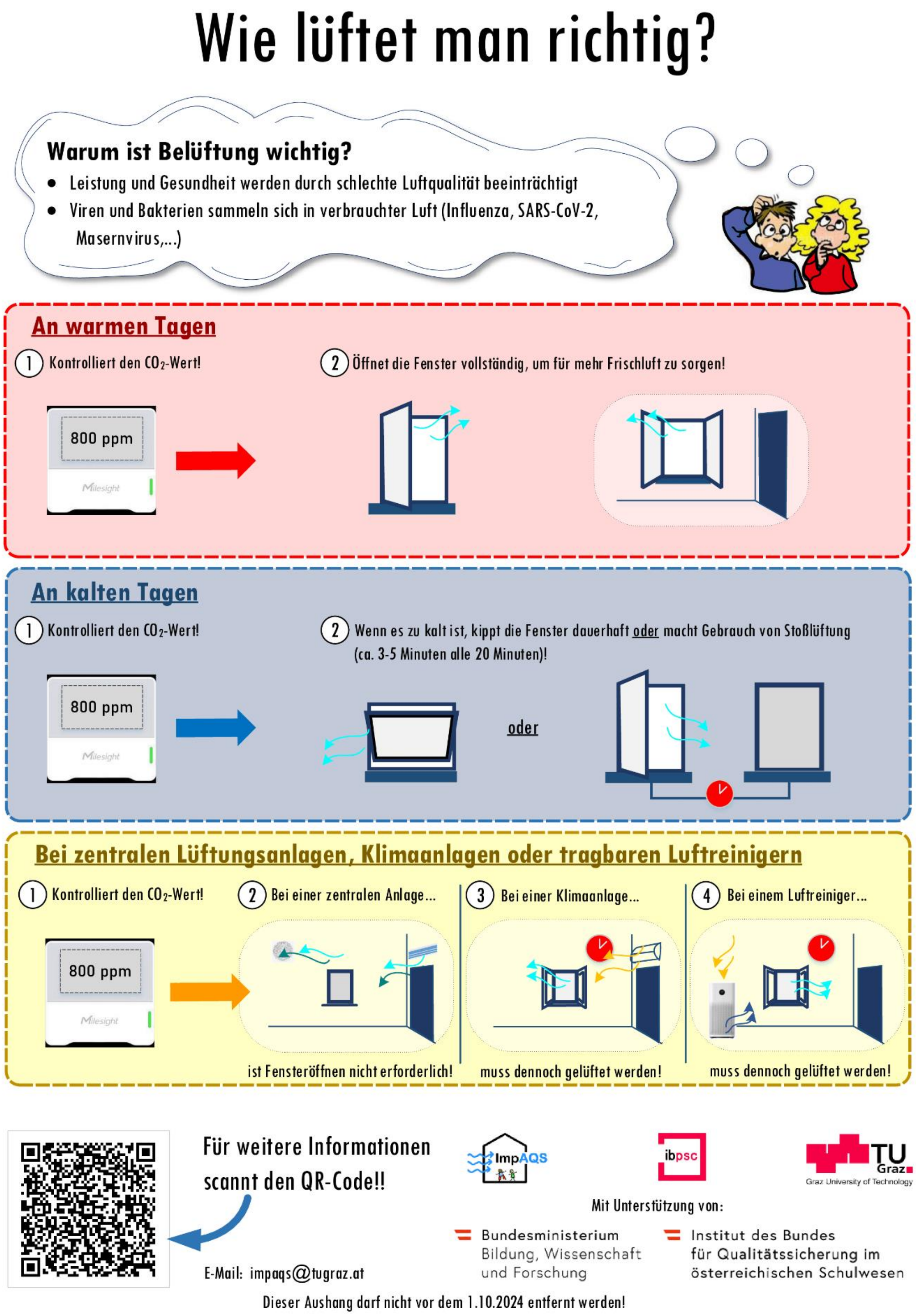


Figure A-6. Room poster 2 – "How to ventilate correctly"

Each of the room-display documents included a QR code that links to a dedicated webpage on the www.impaqs.tugraz.at project portal. This additional information can be seen on the following web-pages:

(i) https://www.tugraz.at/institute/ibpsc/forschung/forschungsprojekte/laufende-projekte/impaqs/co2

(ii) https://www.tugraz.at/institute/ibpsc/forschung/forschungsprojekte/laufende-projekte/impaqs/lueftung

On these web pages the information summarised on the wall mounted posters is explained in more detail. In this way students in a Test classroom could scan the QR codes and receive further information. As well the project team's contact details were provided in case they had further questions.

B.7. Quality assurance - bias testing

To ensure the reliability of in-situ sensor measurements, over the duration of the study, a comparative analysis was conducted using a high-quality pre-calibrated CO_2 sensor from the manufacturer LI-COR (LI-850, LI-COR Environmental USA). Through the comparison with the high-quality reference sensor, the bias or measurement inaccuracy of the ImpAQS sensors could be assessed. Over a 20-minute period, measurements from both sensors were taken side by side under controlled conditions, and the paired differences were compared. Since the LI-COR sensor measured once per second, while the ImpAQS sensor recorded data once every two minutes, the LI-COR values were aggregated into 2-minute intervals to ensure direct comparability. Additionally, a 1-minute timestamp shift was applied to the LI-COR data to account for the delay between the ImpAQS sensor measurement and its cloud data logging. Prior to testing, the room was thoroughly ventilated to stabilize CO_2 levels; and during testing, windows remained closed with no occupants present to maintain consistent environmental conditions.

To assess whether the differences between the sensor measurements were substantial relative to natural variability, a Cohen's d analysis was used. Cohen's d is typically calculated as the difference between the two arithmetic means (i.e., μ_{ImpAQS} and μ_{LI-COR}), divided by their pooled standard deviation. A pilot investigation on 10 sensors installed in a single ImpAQS school revealed pooled standard deviations ranging from 3.3 ppm and 16.8 ppm. However, the accuracy declared by the manufacturer for the AM103 CO_2 sensors is 42.6 ppm at a concentration of 420 ppm. The large discrepancy between the pooled standard deviation and the manufacturer's declared accuracy arises because the pooled standard deviation only accounts for within-sensor variability, ignoring other sources of variation such calibration, altitude, and resolution. Since the pooled standard deviation underestimates the overall variability of the entire population of installed sensors, it is not a suitable metric for the current study. To derive a more representative measure of variability, that captures both within-sensor and between-sensors variability, we considered the standard deviation from CO_2 measurements taken across the 1200 installed sensors during a period when the classrooms were unoccupied for a period of several days (i.e. New Year's Eve 2024). The standard deviation across all installed ImpAQS sensors sampled during this procedure ($s_{installed}$) was determined to be 61.85 ppm. The resulting Cohen's d metric

$$d = \frac{\mu_{ImpAQS} - \mu_{LI-COR}}{s_{installed}}$$

provides a standardized, dimensionless measure of effect size that better aligns with the manufacturer's declared accuracy and the expected performance of the sensor system as a whole. A threshold of Cohen's d greater or equal than 0.8 was set to classify differences as significant. Devices exceeding this threshold - or equivalently showing a difference of means greater than or equal to 49.48 ppm (i.e. 61.85 ppm $\cdot$ 0.8) - were deemed unreliable and were recalibrated in the field. Sensors with smaller discrepancies (Cohen's d smaller 0.8) underwent a mean bias correction during the final data processing stage.

To validate whether the findings from the sample measurements could be extrapolated to a larger group of sensors, Yamane's method was employed. This method provides a simplified formula for determining the required sample size for a given population, ensuring statistical representativeness (see Equation 3-1 in section 3.3.1 of main report). For a calibration batch of 500 sensors (all calibrated at the same time) and an accepted error margin of 0.10, a required sample size of 84 sensors was determined. This subset then underwent a bias test, revealing a mean bias of -27.31 ppm. Assuming this bias was representative of the entire batch, a grouped correction of +27.31 ppm was applied in the final data processing stage to account for the systematic offset. Figure A-7 illustrates this process graphically. The time series data of an ImpAQS outdoor sensor is shown in orange, while the LI-COR sensor data is shown in blue. The dashed lines represent the respective mean values during the 20-minute comparison period. In this example, the mean of paired differences (MPD) was 67 ppm, corresponding to a Cohen's d value of 1.09. As a result, the sensor was classified as unreliable and recalibrated.

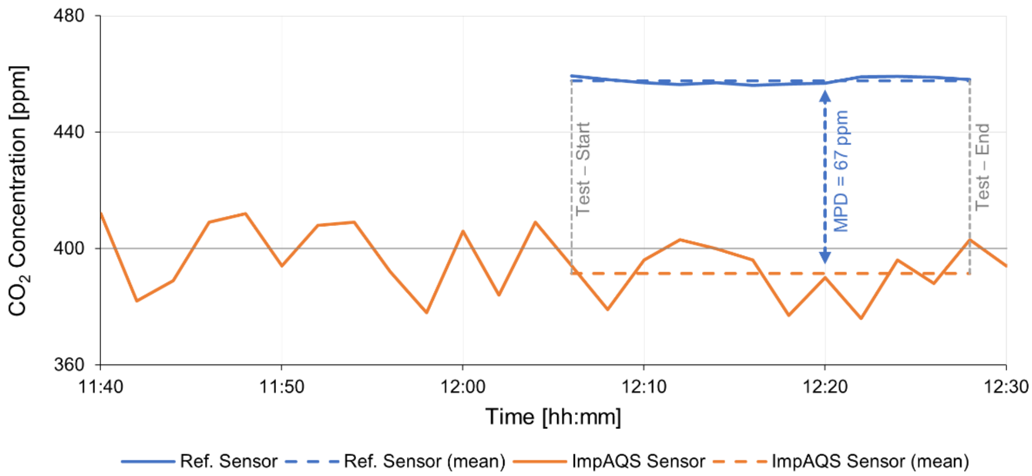


Figure A-7 Mean bias testing of a faulty outdoor sensor

B.8. School data collection

The school (Figure A-8) and classroom data (Figure A-9) are recorded using a Zoho form tool to identify the main physical characteristics of the selected schools and classrooms.

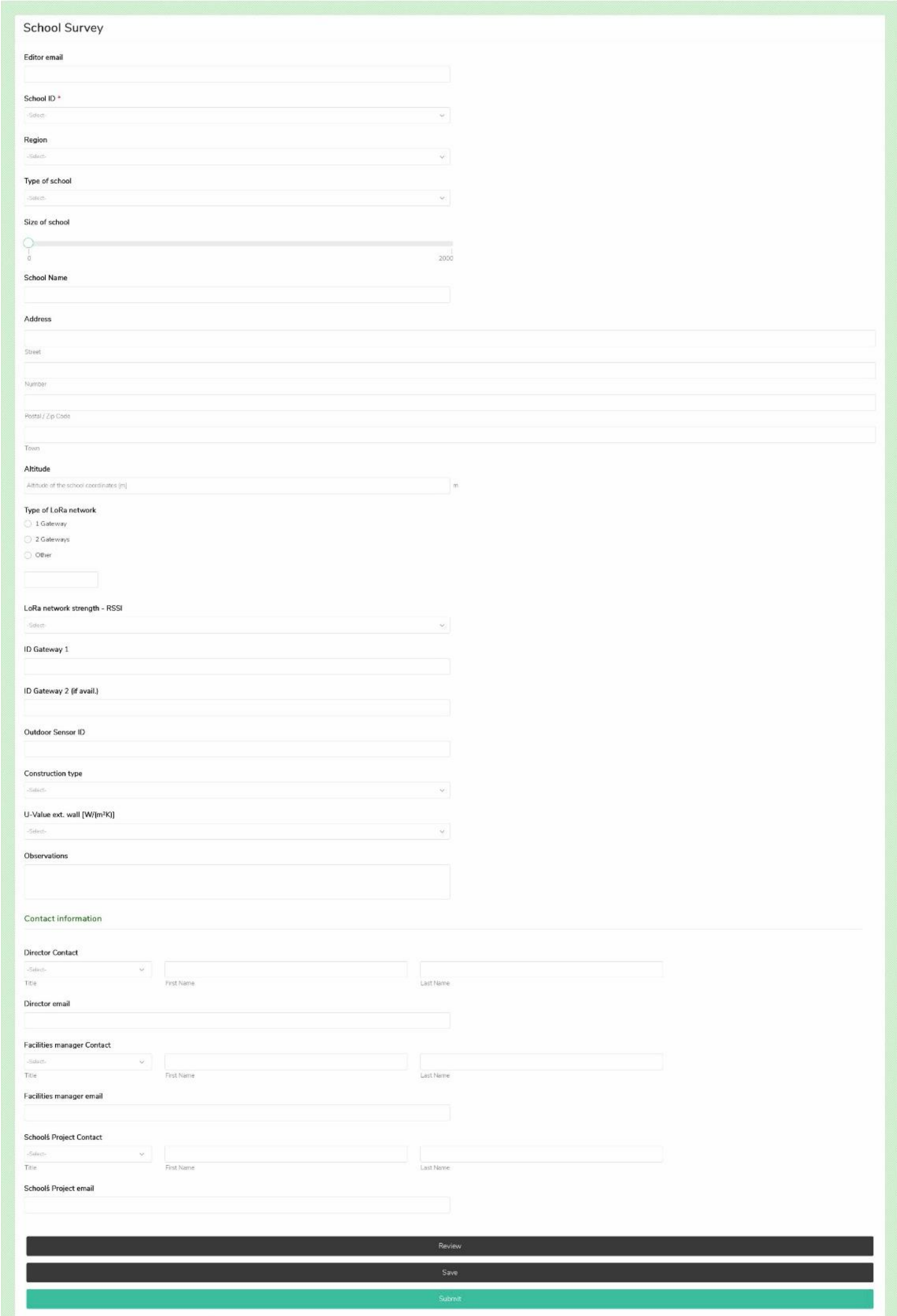


Figure A-8 Zoho Form to record the data on the characteristic of the school - example

Classroom Survey

Editor Email

Room ID, location, size and occupancy inputs

School ID

Classroom ID

Matching class ID (comparison classroom)

Classroom Pair

LM-ID

Room number (acc. to plan or alt. door sign)

Control or Test

Control

Test

Network strength

Room type

Grade Level

Open-plan class

Classroom floor level

Total floors AGL

Room width (m)

Room length (m)

Room height (m)

Actual occupancy

Max occupancy

Table layout

Plants in class

Ventilation Type

Vent. type

Mech/hybr vent system

Portable filters

Glazing

Window aspect(s)

Glazing Sides

Orientation glaz	Rooflite window	Ext. facade total glazed area	Max openable area	Openable window type 1	Restriction window type 1	Openable window type 2	Restriction window type 2

Building services and controls

CO2 sensor already present

Heating system

Cooling system

Noise inputs

Background noise

Time, date and conditions and observations

Date & Time of survey

Weather conditions

CO2 sensor position installed

Sensor height

1.2 m

Other height

Observations

Repeated entry due to error

Rep. entry

Repetition No

Review

Save

Submit

Figure A-9 Zoho Form to record the data on the characteristics of the classroom - example

B.9. List of outdoor contaminants and UBA measurement stations

The following table links the UBA outdoor measurement station (4 letter) reference code for each individual pollutant to the associated school ID number.

Table A-3 List of UBA outdoor stations

School-IDs 1-30

School-ID	$PM_{2.5}$-Code	$PM_{2.5}$-Distance (km)	PM_{10}-Code	PM_{10}-Distance (km)	NO_2-Code	NO_2-Distance (km)	O_3-Code	O_3-Distance (km)
1	GAUD	1,7	GAUD	1,7	GAUD	1,7	STEF	2,0
2	0AKC	4,6	0AKC	4,6	0AKC	4,6	STEF	2,5
3	0AKC	2,4	0AKC	2,4	0AKC	2,4	STEF	2,0
4	BELG	3,7	BELG	3,7	BELG	3,7	STEF	4,8
5	BELG	1,2	BELG	1,2	BELG	1,2	STEF	4,7
6	STAD	3,4	STAD	3,4	STAD	3,4	LOB	7,0
7	KEND	2,6	KEND	2,6	KEND	2,6	STEF	7,3
8	GAUD	1,0	GAUD	1,0	GAUD	1,0	STEF	3,3
9	GAUD	1,3	GAUD	1,3	GAUD	1,3	STEF	3,0
10	KEND	1,9	KEND	1,9	KEND	1,9	STEF	3,0
11	SCHA	3,6	SCHA	3,6	SCHA	1,9	0ZA	1,9
12	0AKC	1,4	0AKC	1,4	0AKC	1,4	STEF	2,0
13	GAUD	5,9	GAUD	5,9	GAUD	5,9	STEF	3,2
14	STAD	5,1	STAD	5,1	STAD	5,1	LOB	13,6
15	STAD	5,1	STAD	5,1	STAD	5,1	LOB	13,6
16	STAD	4,7	STAD	4,7	STAD	4,7	LOB	5,5
17	LIES	1,7	LIES	1,7	LIES	1,7	LIES	1,7
18	0AKC	2,1	0AKC	2,1	0AKC	2,1	STEF	1,1
19	0FLO	1,0	0FLO	1,0	0FLO	1,0	LOB	13,5
20	BELG	3,3	BELG	3,3	BELG	3,3	STEF	2,6
21	0FLO	1,2	0FLO	1,2	0MBA	12,0	0LOB	15,0
22	0001	1,9	0001	1,9	0001	1,9	0001	1,9
23	0001	30,7	0001	30,7	0001	30,7	0001	30,7
24	0179	14,6	0178	40,8	0179	14,6	0179	14,6
25	0001	0,9	0001	0,9	0001	0,9	0001	0,9
26	0198	18,6	0178	55,3	0198	18,6	0198	18,6
27	2401	1,2	0201	16,4	2401	1,2	2401	1,2
28	2401	1,8	0201	15,2	2401	1,8	2401	1,8
29	0401	1,0	0301	28,0	0401	1,0	0401	1,0
30	1301	17,0	1901	31,3	0401	34,8	0401	34,8

School-IDs 31-60

School-ID	$PM_{2.5}$-Code	$PM_{2.5}$-Distance (km)	PM_{10}-Code	PM_{10}-Distance (km)	NO_2-Code	NO_2-Distance (km)	O_3-Code	O_3-Distance (km)
31	0902	12,2	1901	20,3	0902	12,2	1901	20,3
32	2604	18,6	0104	35,7	2604	18,6	2604	18,6
33	2604	27,4	0104	41,8	1204	9,9	1204	9,9
34	2401	19,7	0201	29,7	2401	19,7	2401	19,7
35	2604	8,7	0104	20,1	2604	8,7	2604	8,7
36	1901	0,4	1901	0,4	1901	0,4	1901	0,4
37	ZOE2	105,9	ZOE2	105,9	1502	4,5	1502	4,5
38	2604	34,3	0104	41,5	2604	34,3	2604	34,3
39	1301	37,5	1901	25,7	0401	54,8	0401	54,8
40	2301	1,1	2301	1,1	2301	1,1	2301	1,1
41	0301	18,6	0301	18,6	0301	18,6	0301	18,6
42	1401	4,9	1401	4,9	1401	4,9	1401	4,9
43	2401	0,4	2401	0,4	2401	0,4	2401	0,4
44	0101	0,2	0101	0,2	0101	0,2	0101	0,2
45	2701	1,4	2701	1,4	2701	1,4	2701	1,4
46	1401	2,8	1401	2,8	1401	2,8	1401	2,8
47	0172	2,6	0138	5,4	0172	2,6	0170	2,6
48	0172	1,6	0138	2,2	0172	1,6	0170	4,6
49	0139	0,6	0138	2,5	0139	0,6	0138	2,5
50	0172	1,7	0138	4,4	0172	1,7	0170	3,1
51	0172	1,5	0138	3,5	0172	1,5	0170	3,8
52	0172	0,6	0138	3,6	0172	0,6	0170	2,7
53	0172	1,3	0138	2,2	0172	1,3	0170	4,3
54	0172	1,3	0138	4,1	0172	1,3	0170	2,8
55	0138	0,9	0138	0,9	0138	0,9	0138	0,9
56	0172	1,4	0138	1,7	0172	1,4	0170	4,3
57	0139	3,1	0138	5,9	0139	3,1	0138	5,9
58	KLH1	35,5	0178	28,8	KLH1	35,5	0185	35,5
59	0172	0,5	0138	2,6	0172	0,5	0170	3,5
60	0107	11,4	0107	11,4	0107	11,4	0107	11,4

School-IDs 61-90

School-ID	$PM_{2.5}$-Code	$PM_{2.5}$-Distance (km)	PM_{10}-Code	PM_{10}-Distance (km)	NO_2-Code	NO_2-Distance (km)	O_3-Code	O_3-Distance (km)
61	0178	1,0	0178	1,0	0178	1,0	0178	1,0
62	KLH1	15,2	0178	41,1	KLH1	15,2	0185	15,2
63	0172	1,9	0138	1,8	0172	1,9	0170	4,4
64	0172	0,8	0170	2,5	0172	0,8	0170	2,5
65	KA21	0,5	KA21	0,5	KA21	0,5	KA71	1,3
66	KA71	1,5	KA71	1,5	KA71	1,5	KA71	1,5
67	VI12	0,5	KA71	34,6	VI12	0,5	M121	12,4
68	SP18	35,0	KA71	31,7	SP18	35,0	SP18	35,0
69	0114	41,5	KA71	30,4	0114	41,5	KA71	30,4
70	KA71	1,9	KA71	1,9	KA71	1,9	KA71	1,9
71	VI12	1,2	KA71	34,9	VI12	1,2	M121	11,8
72	S184	0,2	S184	0,2	S184	0,2	S184	0,2
73	S416	2,3	S416	2,3	S416	2,3	S416	2,3
74	S184	1,3	S184	1,3	S184	1,3	S184	1,3
75	S184	3,8	S184	3,8	S184	3,8	S184	3,8
76	S409	3,3	S409	3,3	S409	3,3	S409	3,3
77	S406	1,3	S406	1,3	S406	1,3	S406	1,3
78	S184	1,0	S184	1,0	S184	1,0	S184	1,0
79	S156	33,2	S156	33,2	S156	33,2	S156	33,2
80	S404	18,8	S404	18,8	S404	18,8	S404	18,8
81	S407	25,1	S407	25,1	S407	25,1	S407	25,1
82	ENK1	28,5	ENK1	28,5	ENK1	28,5	ENK1	28,5
83	S416	2,3	S416	2,3	S416	2,3	S416	2,3
84	S409	2,7	S409	2,7	S409	2,7	S409	2,7
85	S407	0,6	S407	0,6	S407	0,6	S407	0,6
86	S184	4,5	S184	4,5	S184	4,5	S184	4,5
87	S184	0,8	S184	0,8	S184	0,8	S184	0,8
88	S409	28,7	S409	28,7	S409	28,7	S409	28,7
89	S416	2,3	S416	2,3	S416	2,3	S416	2,3
90	S184	1,4	S184	1,4	S184	1,4	S184	1,4

School-IDs 91-120

School-ID	$PM_{2.5}$-Code	$PM_{2.5}$-Distance (km)	PM_{10}-Code	PM_{10}-Distance (km)	NO_2-Code	NO_2-Distance (km)	O_3-Code	O_3-Distance (km)
91	S184	3,6	S184	3,6	S184	3,6	S184	3,6
92	S125	1,8	S125	1,8	S125	1,8	S125	1,8
93	S407	84,3	S407	84,3	S407	84,3	S108	5,4
94	S406	1,5	S406	1,5	S406	1,5	S406	1,5
95	S415	2,2	S415	2,2	S415	2,2	S184	1,0
96	1200	2,4	1200	2,4	1200	2,4	1200	2,4
97	1200	0,4	1200	0,4	1200	0,4	1200	0,4
98	1200	2,7	1200	2,7	1200	2,7	1200	2,7
99	1200	15,5	1200	15,5	1200	15,5	1200	15,5
100	1200	1,5	1200	1,5	1200	1,5	1200	1,5
101	1200	2,8	1200	2,8	1200	2,8	1200	2,8
102	1200	15,9	1200	15,9	2100	1,6	2100	1,6
103	2106	0,8	2110	1,3	2106	0,8	2106	0,8
104	2106	0,6	2110	2,7	2106	0,6	2106	0,6
105	2227	20,6	2110	11,5	2227	20,6	2106	13,4
106	2710	43,1	2710	43,1	2710	43,1	2710	43,1
107	SP18	55,1	KA71	118,7	SP18	55,1	SP18	55,1
108	SP18	56,0	KA71	119,5	SP18	56,0	SP18	56,0
109	2552	0,1	2110	68,4	2552	0,1	2547	0,2
110	2106	1,3	2110	2,1	2106	1,3	2106	1,3
111	2106	3,3	2110	1,2	2106	3,3	2106	3,3
112	2106	1,3	2110	1,5	2106	1,3	2106	1,3
113	0807	2,3	0807	2,3	0807	2,3	0706	8,0
114	0807	20,2	0807	20,2	0807	20,2	0706	17,9
115	0807	1,1	0807	1,1	0807	1,1	0706	5,7
116	0807	10,7	0807	10,7	0807	10,7	0706	12,9
117	0807	1,6	0807	1,6	0807	1,6	0706	5,2
118	0201	5,5	0201	5,5	0201	5,5	0201	5,5
119	0AKC	1,8	0AKC	1,8	0AKC	1,8	STEF	3,9
120	0138	3,1	0138	3,1	0138	3,1	0138	3,1

B.10. Infection risk model

The risk of infection for long range aerosol transmission of the SARS-CoV-2 virus was estimated with an analytical method developed by researchers from the MPIC, Germany, and the Cyprus Institute, Cyprus (Lelieveld et al., 2020). Table A.4 shows the parameters used for the calculations in this study. Eq. A.2.1 to Eq. A.2.7 show the equations used for this analysis. This method calculates the time-dependent concentration of airborne virus particles, and the accumulated number of inhaled virus particles based on human aerosol emissions and viral removal rate, which results from the air exchange rate and virus lifetime in aerosols.

Table A-4 Parameters used in Lelieveld et al. method (Lelieveld, 2020; MPIC 2024)

Parameters	value	unit	notes
Virus			
Virus lifetime - t_{virus}	1.7	h	lifetime (e-folding time) in aerosol
Viral load for - c_v	9.00E+08	cop/ml	for original Omicron variant
Infective dose - D_{50}	154	RNA copies	for original Omicron variant
Inf. risk for single virus part. - P_{RNA}	0.00449	1/RNA copies	$PRNA = 1 - e^{\ln(0,5)/D50}$
Aerosol			
Wet aerosol diameter -da	5	µm	
Particle emission breathing - pe,b	0.06	No./cm³	
Particle emission speaking - pe,s	0.6	No./cm³	
Speaking/ breathing ratio	10	%	
Resulting particle emission - pe,t	0.11	#/cm³	pe,t = pe,s·0,1 + (1-0,1)·pe,b
Infected person			
Mask factor (exhalation) - $f_{mask,e}$	0.2	[-]	with filter efficiency of 80% (1=no mask)
Mask factor (inhalation) - $f_{mask,in}$	0.3	[-]	with filter efficiency of 70% (1=no mask)
Lung deposition factor - f_{lung}	0.5	[-]	
Breathing rate - qb,e	10	l/min	
Effective breathing rate $q_{b,eff}$	5	l/min	qb,eff = qb,e*$f_{mask,in}$*f_{lung}
RNA conc. exhaled breath - CRNA,b	6.72	RNA/l	CRNA,b = $\pi/6 \cdot da^3 \cdot c_v \cdot 10^{-12} \cdot pe,t \cdot 10^3$
Emission factor - E	4029	No./h	E =CRNA,b *qb,e*$f_{mask,e}$

For the original Omicron variant of the SARS-CoV-2 virus, 154 inhaled RNA copies were expected to correspond to an infectious dose (D_{50}), the mean dose that causes an infection in 50% of susceptible subjects (Lelieveld, 2020). The individual infection risk $R_i(t)$ (for each susceptible individual) and the group infection risk $R(t)$ (for a group of susceptible people) is calculated with the following formulas (Eq. A.4.1 and Eq. A.4.2) depending on the number of inhaled virus particles $nv(t)$ and the probability P_{RNA} that a single virus particle causes an infection:

$$R_i(t) = \left[1 - (1 - P_{RNA})^{n_v(t)}\right] * 100 \quad \text{(Eq. A.2.1)}$$

$$R(t) = \left[1 - (1 - P_{RNA})^{(n_v(t)*n)}\right] * 100 \quad \text{(Eq. A.2.2)}$$

Where,

$R_i(t)$ is the individual infection risk for each person [%],

$R(t)$ is the probability of at least one person getting infected in a group of susceptible people [%],

n is the number of susceptible (i.e. non-infected) individuals in the room

$n_v(t)$ is the number of virus particles inhaled per person,

and P_{RNA} is the probability that a single virus particle causes an infection.

The time-dependent airborne virus concentration ($c_v(t)$) building up in a room and the resulting quantity of inhaled virus particles per occupant ($n_v(t)$) can be determined with the following formulas:

$$c_v(t) = \frac{E}{V * \lambda} * \left(1 - e^{-\lambda * t}\right) + c_{v0} * e^{-\lambda * t} \quad \text{(Eq. A.2.3)}$$

$$c_v(t) = \frac{E}{V * \lambda} * \left(1 - e^{-\lambda * t}\right); \quad \text{when } c_{v0} = 0 \quad \text{(Eq. A.2.4)}$$

$$n_v(t) = n_{v0} + q_{b,eff} * \frac{E}{V * \lambda} * t * \left(1 - \frac{1 - e^{-\lambda * t}}{\lambda * t}\right) + c_{v0} * q_{b,eff} * \frac{\left(1 - e^{-\lambda * t}\right)}{\lambda} \quad \text{(Eq. A.2.5)}$$

$$n_v(t) = q_{b,eff} * \frac{E}{V * \lambda} * t * \left(1 - \frac{1 - e^{-\lambda * t}}{\lambda * t}\right); \quad \text{when } c_{v0} \text{ and } n_{v0} = 0 \quad \text{(Eq. A.2.6)}$$

Where,

$c_v(t)$ is the number of particles building up in the indoor air

n_{v0} is the number of virus particles already inhaled by a person [No.],

c_{v0} is the previously built up virus concentration in the room air [No./m^3],

$q_{b,eff}$ is the effective breathing rate (as shown in Table A.4.1)

E is the Emission factor [No./h] (as shown in Table A.4.1)

V is the internal room air volume [m^3],

λ is the loss coefficient [h^{-1}], (as determined in (Eq. A.4.7)),

t is the duration of exposure [h]

and e is Euler's number.

The loss coefficient λ is calculated from the addition of the air exchange rate n [h^{-1}] and the reciprocal of the mean virus lifetime in an aerosol state t_{virus} of 1.7 [h] as follows:

$$\lambda = n + \frac{1}{t_{virus}} \quad \text{(Eq. A.2.7)}$$

Where,

n is the total air exchange rate [h^{-1}] (including infiltration and ventilation),

t_{virus} is the virus lifetime [h] (shown in Table A.4.1)

B.11. Infection risk calculation reference scenario

The calculation of the daily average group infection risks was also compared to a reference scenario. This reference scenario was defined similarly to the one outlined in the position paper on the evaluation of indoor spaces regarding the infection risk of SARS-CoV-2 by the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation, and Technology (BMK, 2021), with the following parameters:

- 10 l/(s·person) ventilation rate
- One infectious person
- 24 susceptible persons
- Infectious person with fraction of speaking of 10%
- No protective masks worn
- 210 m^3 room volume
- Exposure duration from 8 a.m. until 2 p.m. (i.e. 6 hours)

The ventilation rate of the reference scenario was set at 10 l/(s·person), as this corresponds to IEQ_1 category for users with special needs (such as children) from EN 16798.1 (CEN, 2024). Additionally, a ventilation rate of 10 l/(s·person) and a standard CO_2 emission of 20 l/(h·person) would result in a steady-state concentration of approximately 1000 ppm, which aligns with the standard values in ISO 16000-41 for Quality Class A for continuous stay and intellectual activities (ISO, 2023) and ÖNORM H 6039 (ASI, 2023).

C. Results

C.1. Supplementary data analysis

C.1.1. Analysis of ZOHO data (physical characteristics of schools and classrooms)

C.1.1.1. School characteristics

Table A-5 Characteristics of schools in the ImpAQS project

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
1	VIE	Medium and large cities	Central	KMS	180	7	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
2	VIE	Medium and large cities	Central	ABHS	170	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
3	VIE	Medium and large cities	Central	ABHS	200	5	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
4	VIE	Medium and large cities	Suburb	ABHS	170	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
5	VIE	Medium and large cities	Suburb	TGS	240	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Lightweight construction
6	VIE	Medium and large cities	Suburb	ABHS	170	4	10	Radiators - hydronic	Thermal component activation	Mechanical Ventilation	Central ventilation system	None	Heavy construction
7	VIE	Medium and large cities	Suburb	VS	210	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
8	VIE	Medium and large cities	Central	VS	200	5	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
9	VIE	Medium and large cities	Central	ABHS	190	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
10	VIE	Medium and large cities	Central	VS	210	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
11	VIE	Medium and large cities	Suburb	WS	230	3	10	Not known	None	Natural ventilation	None	None	Heavy construct ion
12	VIE	Medium and large cities	Central	ABHS	160	5	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
13	VIE	Medium and large cities	Suburb	TGS	170	17	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
14	VIE	Medium and large cities	Suburb	VS	160	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
15	VIE	Medium and large cities	Suburb	VS	160	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
16	VIE	Medium and large cities	Suburb	VS	150	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
17	VIE	Medium and large cities	Suburb	MS	200	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
18	VIE	Medium and large cities	Central	ABHS	180	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
19	VIE	Medium and large cities	Suburb	ABHS	160	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
20	VIE	Medium and large cities	Central	TGS	180	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
21	VIE	Medium and large cities	Suburb	ABHS	160	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
22	BUR	Towns	Suburb	ABHS	260	4	10	Floor Heating	None	Natural ventilation	None	None	Heavy construct ion
23	BUR	Village	-	VS	190	3	10	Radiators - hydronic	None	Mechanical Ventilation	Central ventilation system	None	Heavy& Lightweig ht construct ion
24	BUR	Village	-	TGS	390	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
25	BUR	Towns	Central	KMS	160	4	10	Radiators - hydronic	None	Mechanical Ventilation	Central ventilation system	None	Heavy construct ion
26	BUR	Village	-	ABHS	210	2	10	Radiators - hydronic	None	Both ventilation types	Dec. vent. system in multiple rooms	None	Heavy construct ion

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
27	LOA	Small cities	Central	ABHS	270	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
28	LOA	Small cities	Central	TGS	270	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
29	LOA	Towns	Central	KMS	170	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
30	LOA	Village	-	MS	310	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
31	LOA	Towns	Central	VS	170	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
32	LOA	Village	-	MS	250	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
33	LOA	Village	-	TGS	230	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
34	LOA	Towns	Central	ABHS	410	2	10	Radiators - hydronic	Chilled beams	Mechanical Ventilation	Central ventilation system	None	Heavy construct ion
35	LOA	Village	-	ABHS	350	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
36	LOA	Towns	Suburb	ABHS	180	3	10	Not known	None	Natural ventilation	None	None	Heavy construct ion

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
37	LOA	Village	-	WS	1020	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
38	LOA	Village	-	WS	490	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
39	LOA	Towns	Suburb	TGS	230	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
40	LOA	Small cities	Central	TGS	280	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
41	LOA	Village	-	KMS	160	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
42	LOA	Towns	Suburb	VS	290	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
43	LOA	Small cities	Central	KMS	270	3	10	Radiators - hydronic	None	Both ventilation types	Central ventilation system in multiple classroom s	None	Heavy construct ion
44	LOA	Towns	Suburb	KMS	270	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
45	LOA	Towns	Suburb	MS	160	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
46	LOA	Village	-	ABHS	280	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
47	STY	Medium and large cities	Central	MS	360	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
48	STY	Medium and large cities	Central	ABHS	360	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
49	STY	Medium and large cities	Suburb	VS	370	1	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
50	STY	Medium and large cities	Central	ABHS	360	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy& Lightweig ht construct ion
51	STY	Medium and large cities	Central	ABHS	360	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
52	STY	Medium and large cities	Central	ABHS	350	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
53	STY	Medium and large cities	Central	VS	350	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
54	STY	Medium and large cities	Central	VS	350	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
55	STY	Medium and large cities	Suburb	TGS	370	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
56	STY	Medium and large cities	Suburb	WS	360	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
57	STY	Medium and large cities	Suburb	VS	360	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
58	STY	Village	-	MS	350	1	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
59	STY	Medium and large cities	Central	ABHS	350	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
60	STY	Village	-	MS	400	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
61	STY	Towns	Suburb	TGS	480	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
62	STY	Village	-	VS	290	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
63	STY	Medium and large cities	Suburb	ABHS	370	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
64	STY	Medium and large cities	Central	KMS	405	4	12	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
65	CAR	Medium and large cities	Central	ABHS	450	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
66	CAR	Medium and large cities	Suburb	VS	450	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
67	CAR	Small cities	Central	ABHS	510	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
68	CAR	Small cities	Suburb	VS	505	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
69	CAR	Village	-	KMS	625	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
70	CAR	Medium and large cities	Suburb	ABHS	450	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
71	CAR	Small cities	Suburb	TGS	505	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
72	UPA	Medium and large cities	Central	ABHS	305	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
73	UPA	Medium and large cities	Central	ABHS	270	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
74	UPA	Medium and large cities	Suburb	ABHS	270	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
75	UPA	Medium and large cities	Suburb	MS	290	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
76	UPA	Towns	Suburb	VS	315	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
77	UPA	Small cities	Suburb	ABHS	320	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
78	UPA	Medium and large cities	Central	TGS	270	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
79	UPA	Towns	Suburb	MS	445	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
80	UPA	Village	-	VS	345	2	10	Floor Heating	None	Natural ventilation	None	None	Heavy construct ion
81	UPA	Village	-	VS	355	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
82	UPA	Village	-	MS	340	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
83	UPA	Medium and large cities	Suburb	ABHS	290	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
84	UPA	Towns	Suburb	WS	325	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
85	UPA	Towns	Suburb	KMS	440	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
86	UPA	Medium and large cities	Suburb	ABHS	285	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
87	UPA	Medium and large cities	Central	KMS	270	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
88	UPA	Village	-	ABHS	455	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
89	UPA	Medium and large cities	Suburb	WS	285	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
90	UPA	Medium and large cities	Central	WS	270	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
91	UPA	Medium and large cities	Suburb	KMS	265	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
92	UPA	Towns	Suburb	WS	485	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
93	UPA	Village	-	WS	565	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
94	UPA	Small cities	Suburb	WS	325	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
95	UPA	Medium and large cities	Suburb	TGS	260	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
96	SAL	Medium and large cities	Suburb	ABHS	450	3	10	Radiators - hydronic	None	Both ventilation types	Dec. vent. system in multiple rooms	None	Heavy construct ion
97	SAL	Medium and large cities	Central	MS	425	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
98	SAL	Medium and large cities	Central	ABHS	425	5	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
99	SAL	Towns	Central	TGS	455	4	10	Radiators - hydronic	None	Mechanical Ventilation	Central ventilation system	None	Heavy construct ion
100	SAL	Medium and large cities	Suburb	SS	430	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
101	SAL	Medium and large cities	Suburb	VS	450	3	10	Floor Heating	Not known	Mechanical Ventilation	Central ventilation system	None	Heavy construct ion
102	SAL	Towns	Suburb	ABHS	475	2	10	Radiators - hydronic	Not known	Natural ventilation	None	None	Heavy construct ion
Schoo l-Nr.	Region	City size	Location	Schoo l Type	Altitude	Number of floors above ground	Number of surveyed classrooms	Heating	Cooling	Ventilation	Details of Ventilatio n	Portable air filters	Construc tion type
103	TIR	Medium and large cities	Central	VS	585	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
104	TIR	Medium and large cities	Suburb	MS	580	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
105	TIR	Village	-	MS	610	2	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
106	TIR	Village	-	MS	880	3	10	Radiators - hydronic	None	Natural ventilation	Decentral ventilation system, not in use	None	Heavy construct ion
107	TIR	Towns	Suburb	ABHS	685	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
108	TIR	Towns	Suburb	KMS	685	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
109	TIR	Towns	Central	ABHS	495	4	10	Air conditioning	Air conditioning	Mechanical Ventilation	Central ventilation system	None	Heavy construct ion
110	TIR	Medium and large cities	Suburb	ABHS	580	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
111	TIR	Medium and large cities	Suburb	TGS	580	5	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
112	TIR	Medium and large cities	Suburb	KMS	580	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construct ion
113	VOR	Small cities	Suburb	VS	445	2	10	Radiator - electric	Thermal component activation	Mechanical Ventilation	Central ventilation system	None	Heavy construct ion

School -Nr.	Region	City size	Location	School Type	Altitude	Number of floors above ground	Number of classrooms surveyed	Heating	Cooling	Ventilation	Details of Ventilation	Portable air filters	Construc-tion type
114	VOR	Small cities	Suburb	ABHS	460	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
115	VOR	Small cities	Central	ABHS	435	4	10	Radiators - hydronic	None	Mechanical Ventilation	Central ventilation system	None	Heavy construction
116	VOR	Towns	Central	TGS	410	5	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
117	VOR	Small cities	Suburb	TGS	435	3	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
118	LOA	Village	-	VS	240	3	10	Radiators - hydronic	None	Natural ventilation	None	Single room HEPA filter	Heavy construction
119	VIE	Medium and large cities	Central	SS	210	4	10	Radiators - hydronic	None	Natural ventilation	None	None	Heavy construction
120	STY	Medium and large cities	Suburb	VS	415	3	8	Radiators - hydronic	None	Mechanical Ventilation	Central ventilation system	None	Lightweight construction

C.1.1.2. Actual and maximum classroom occupancy by school type and region

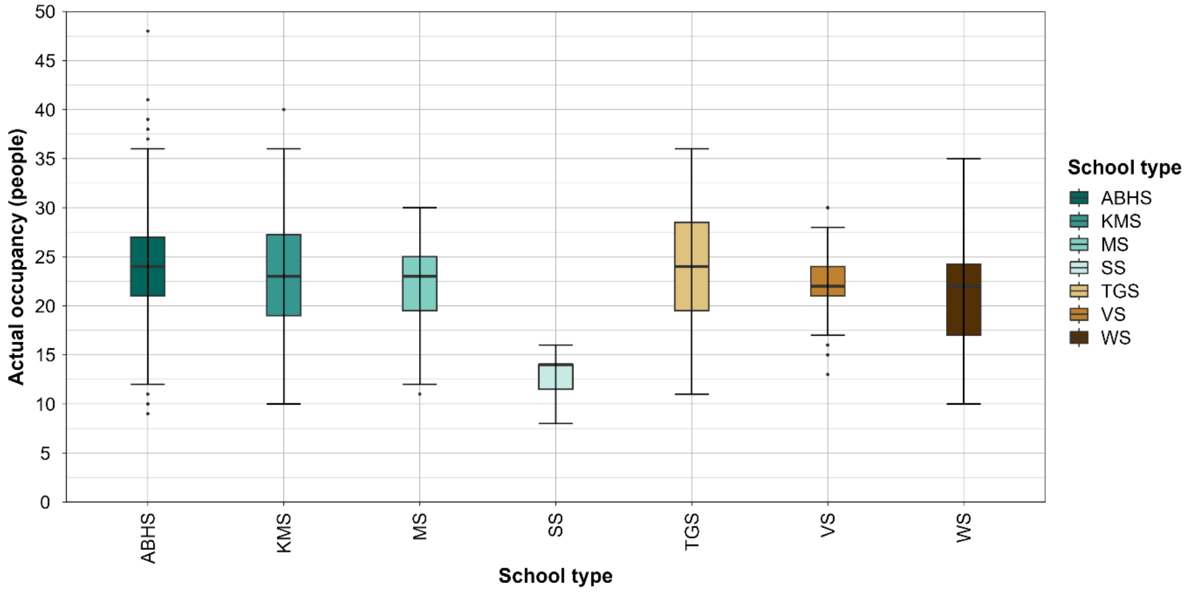


Figure A-9 Actual occupancy, i.e. number of pupils in classrooms sorted by school type.

The actual classroom occupancy (number of pupils) varies from 6 up to 47 people, with special schools (SS) having significantly lower occupant densities[1].

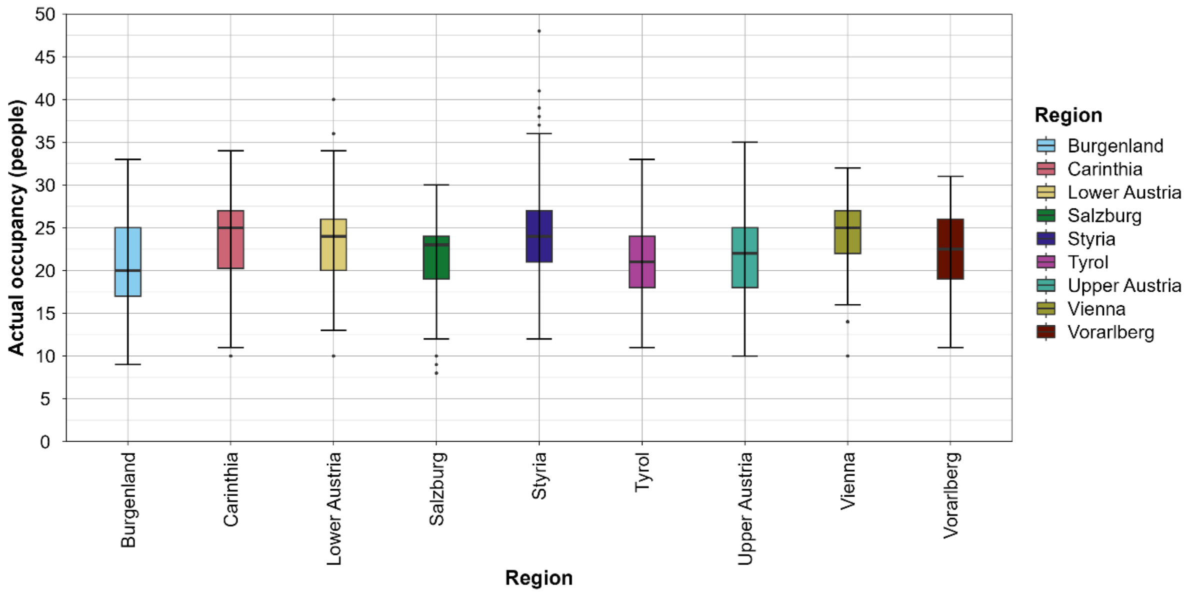


Figure A-11 Actual occupancy, i.e. number of pupils in classrooms sorted by region.

[1] Note care should be taken in interpreting this finding as there were only two SS schools included in the study.

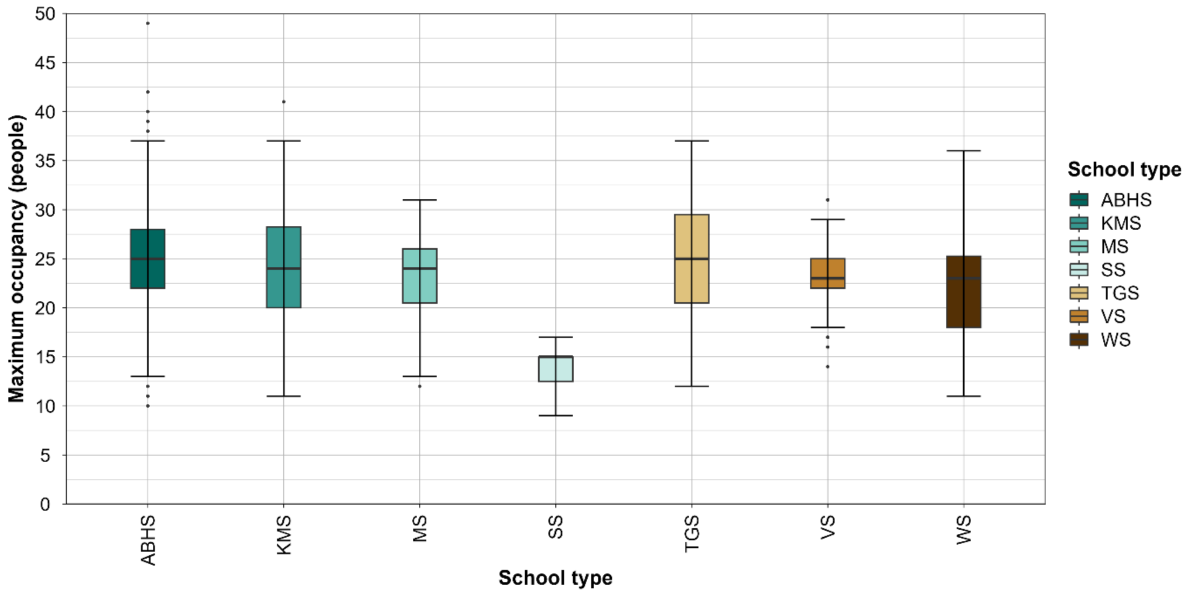


Figure A-12 Maximum classroom occupancy (including the teacher) sorted by school type.

The maximum classroom occupancy (students plus teacher) varies from 7 up to 48 people.

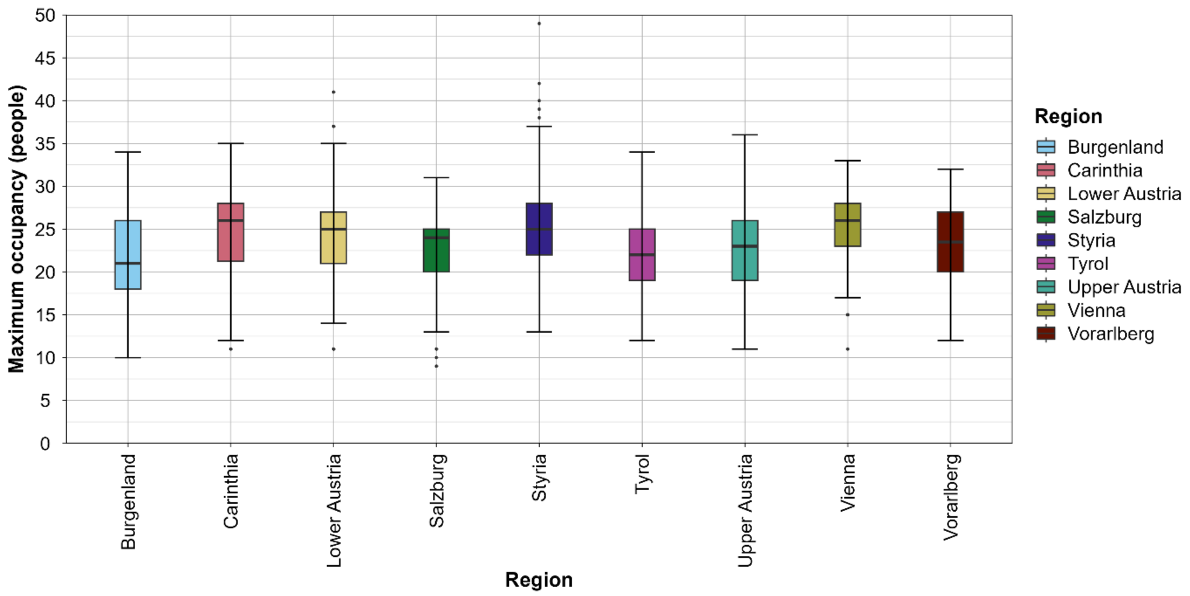


Figure A-13 Maximum classroom occupancy (including the teacher) sorted by region.

C.1.1.3. Classroom floor area by school type and region

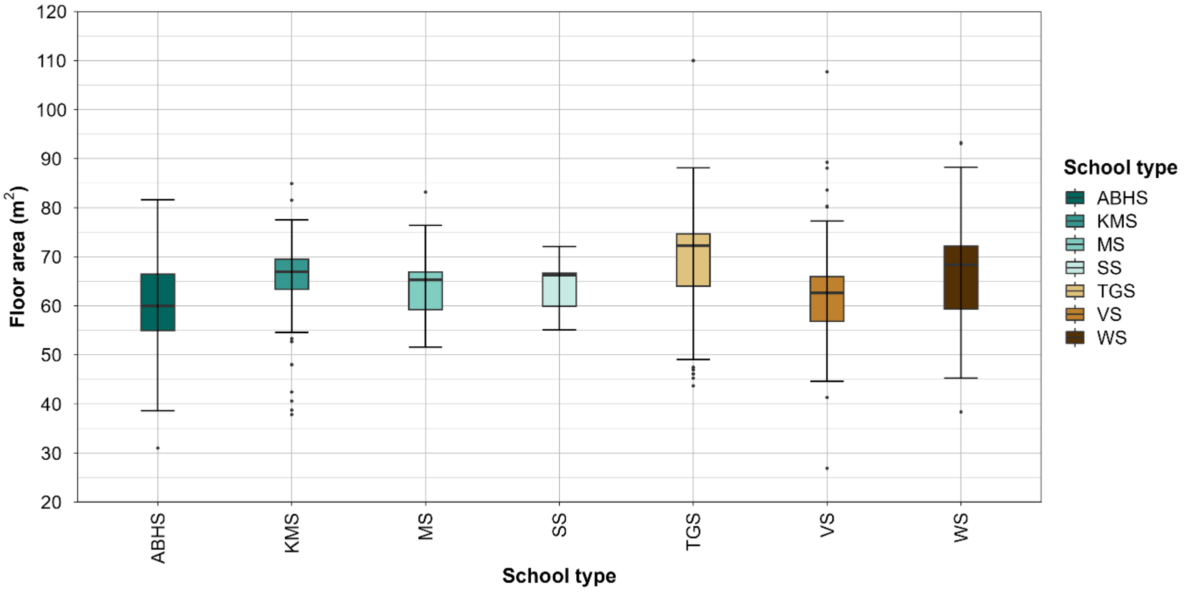


Figure A-10 Floor area in m² of all classrooms sorted by school types.

Figure A-13 shows that in absolute terms TGS and WS schools have the largest classrooms by floor area, whilst ABHS has the smallest sized classrooms

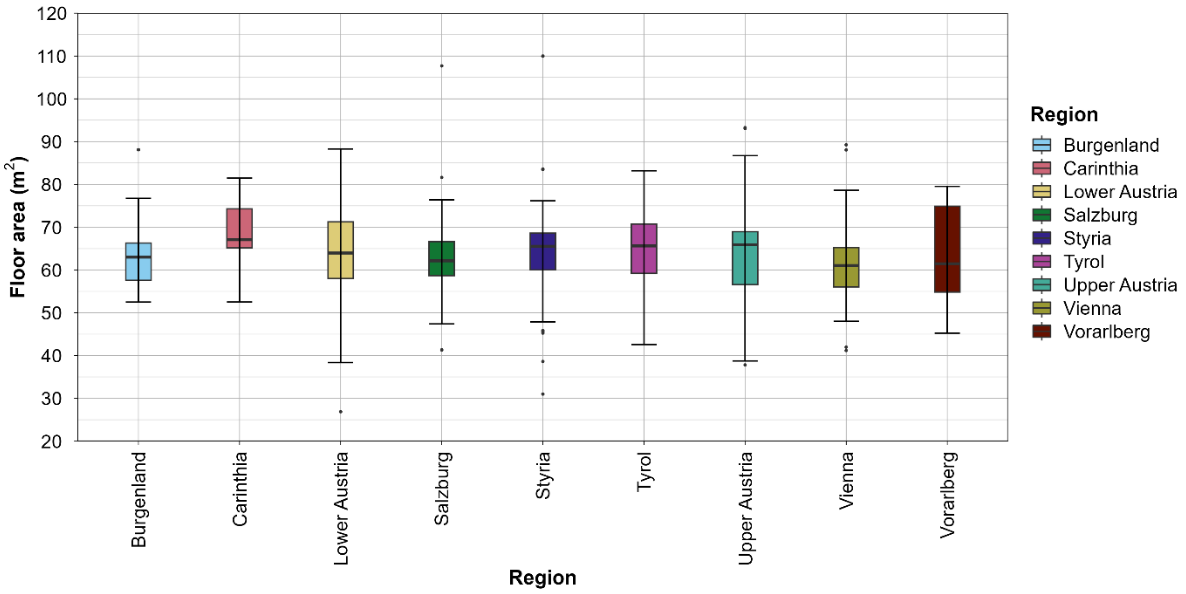


Figure A-11 Floor area in m² of all classrooms sorted by region.

Figure A-14 shows that Carinthia has the largest median classroom sizes whilst Lower and Upper Austria have the widest range of classroom sizes

C.1.1.4. Classroom occupant density [m²/person] by school region

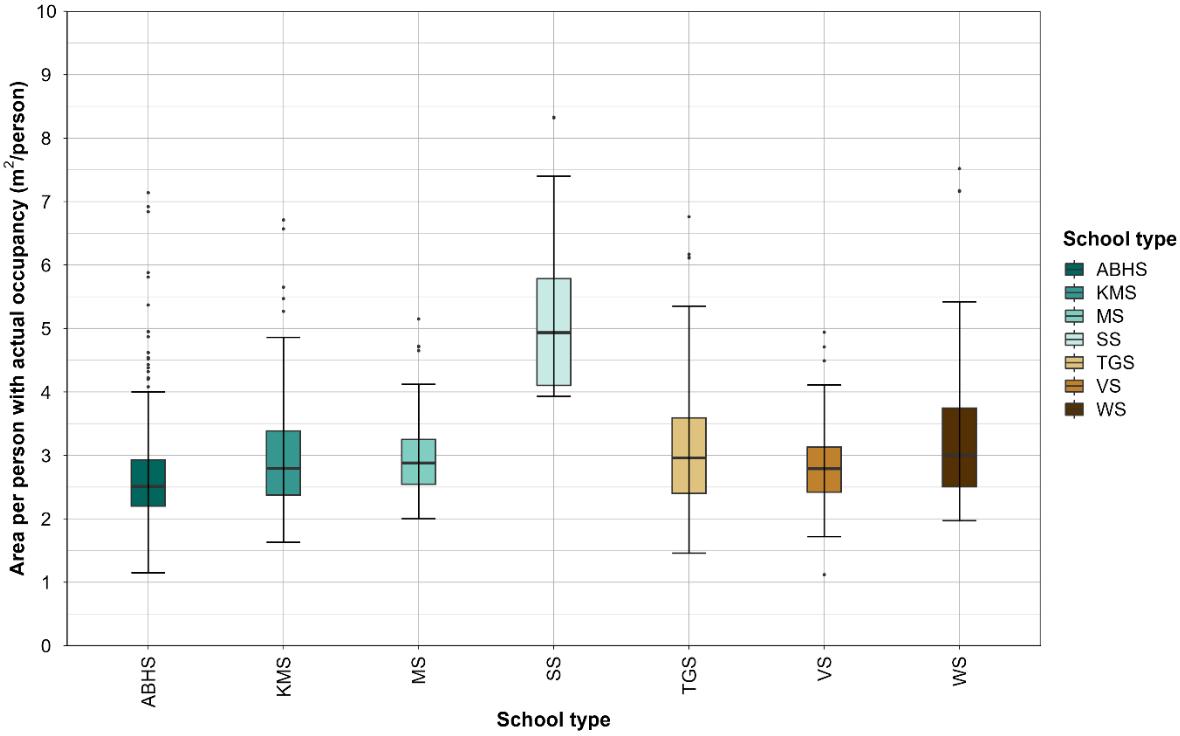


Figure A-12 Area per person with actual occupancy classified by school type.

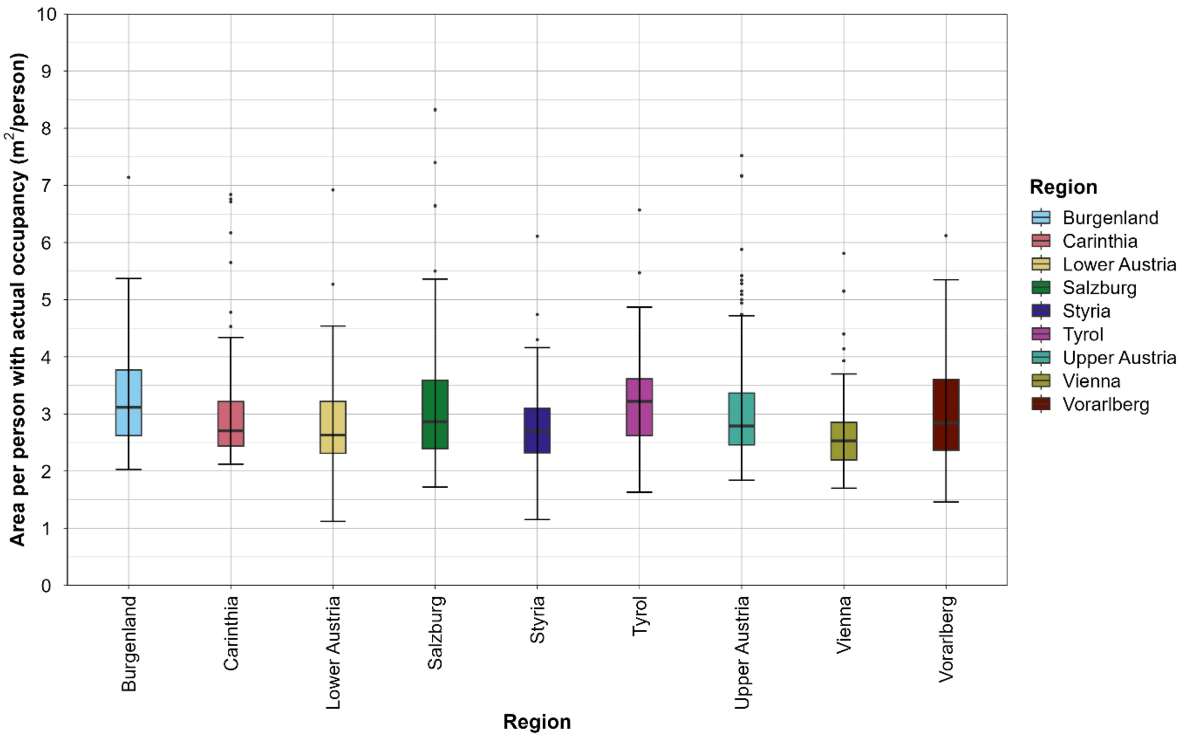


Figure A-13 Area per person with actual occupancy classified by region.

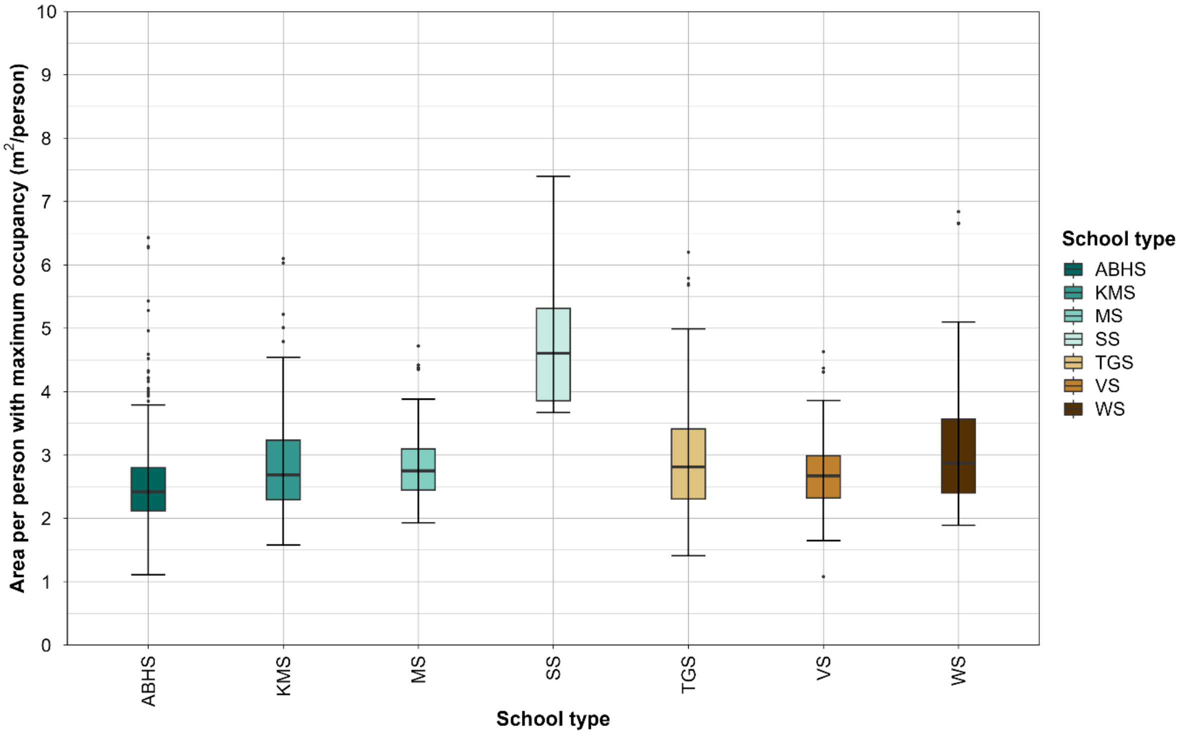


Figure A-14 Area per person with maximum occupancy (i.e. including the teacher) sorted by school type with special schools

Figure A-17 shows that special schools (SS) have significantly higher amounts of space per person[2].

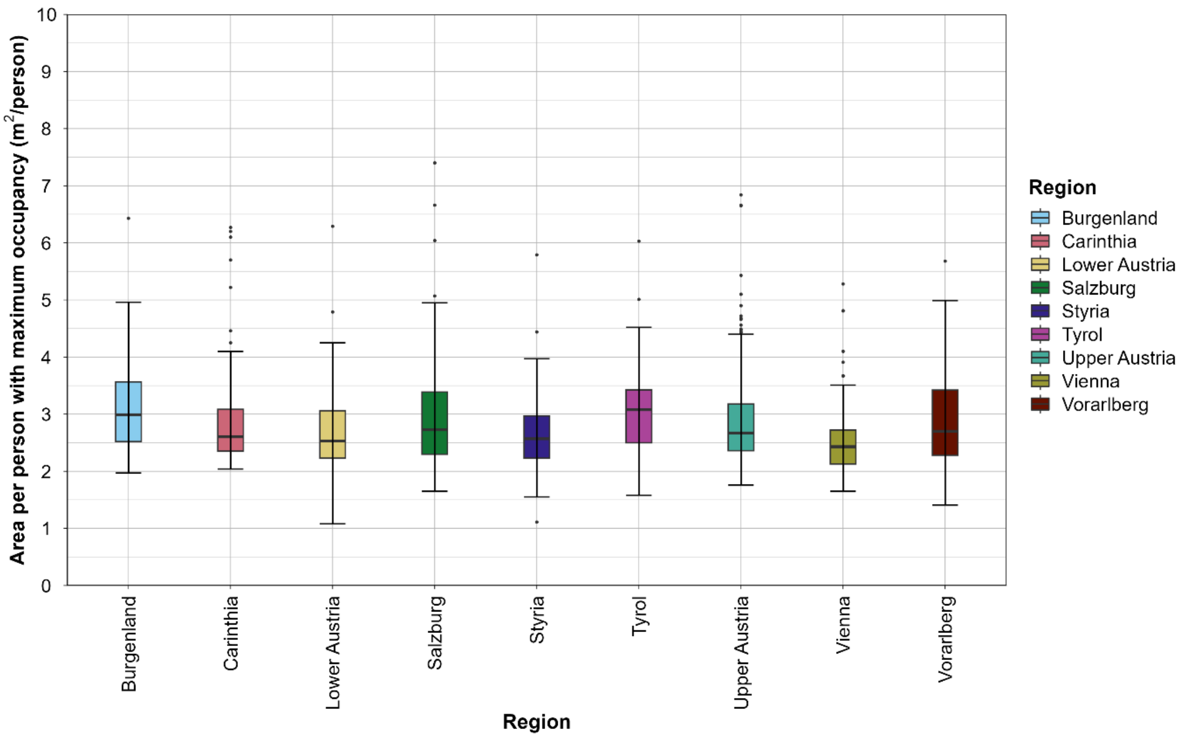


Figure A-15 Occupant density based on actual occupancy sorted by region.

[2] Note care should be taken in interpreting this finding as there were only two SS schools included in the study.

C.1.1.5. Classroom volume by school type and region

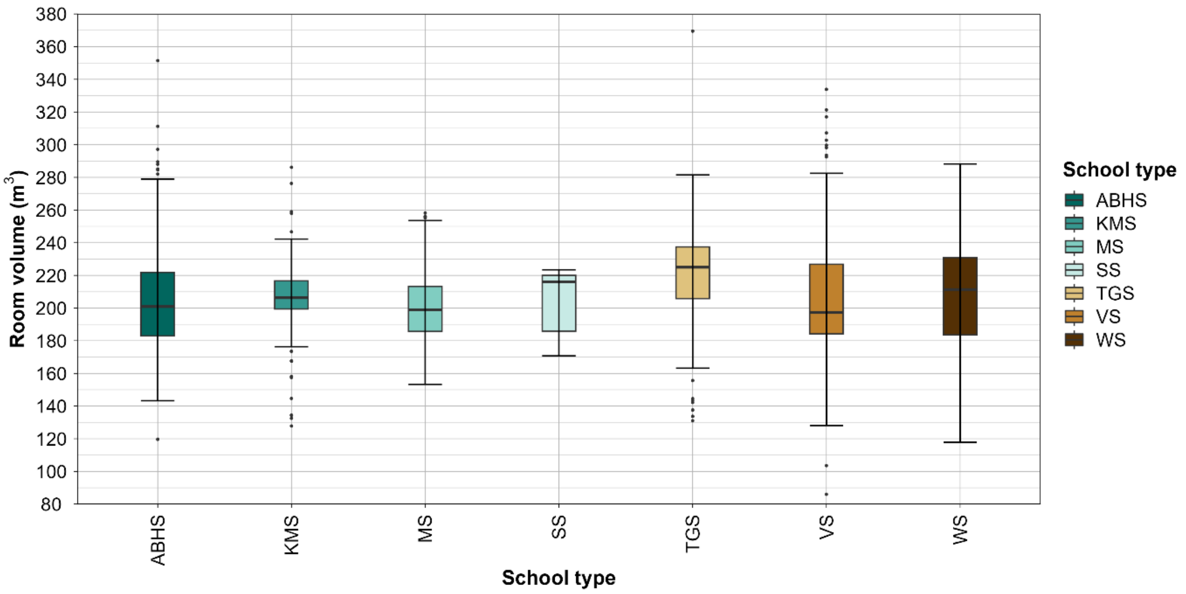


Figure A-16 Room volume of the classrooms sorted by school type

Figure A-19 illustrates the range of room volumes (90 m^3 to 360 m^3). Whilst ABHS schools have the smallest floor area (Fig. A-13) their comparatively larger volume indicates higher ceilings.

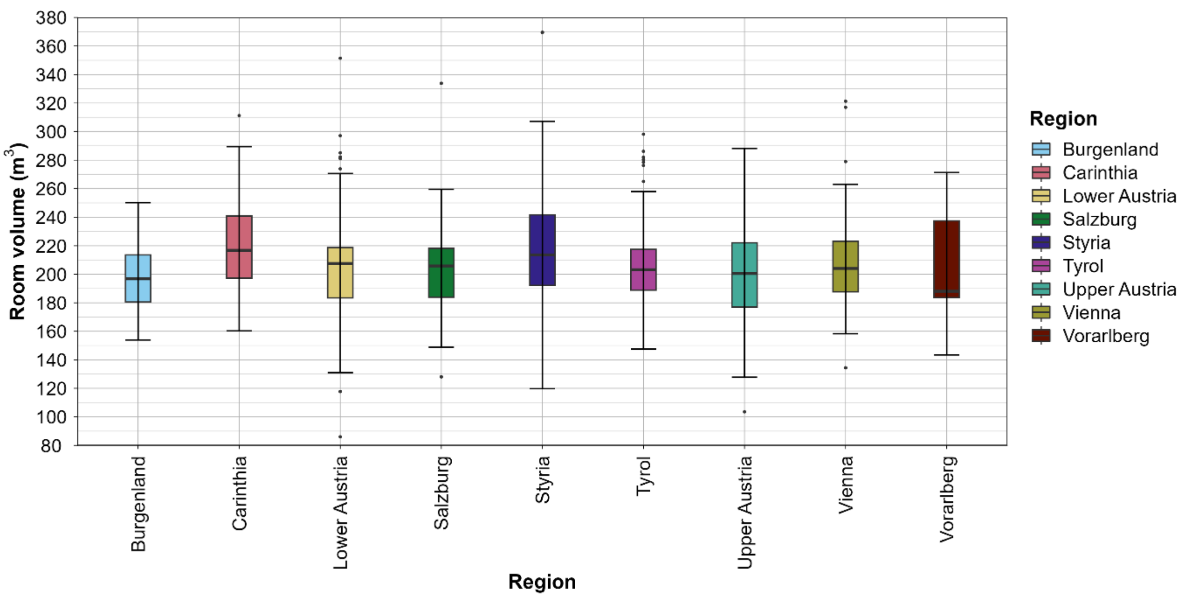


Figure A-21 Room volume of the classrooms sorted by region

On a regional basis, classrooms in Styria can be seen (Fig. A-20) to have the widest range of room volumes.

C.1.1.6. Classroom spatial volume per person [m³/person] by school type and region

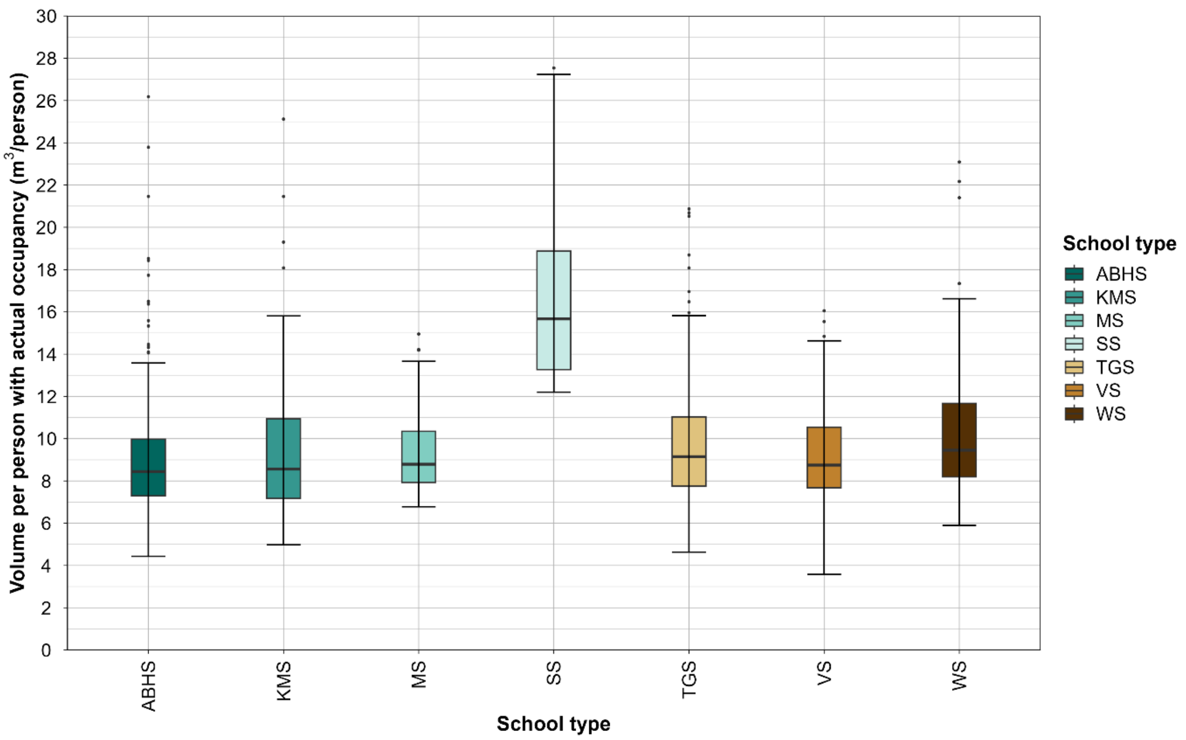


Figure A-17 Room volume per person with actual occupancy sorted by school type

Figure A-21 shows that Special schools (SS) provide significantly higher volumes of room space per person.

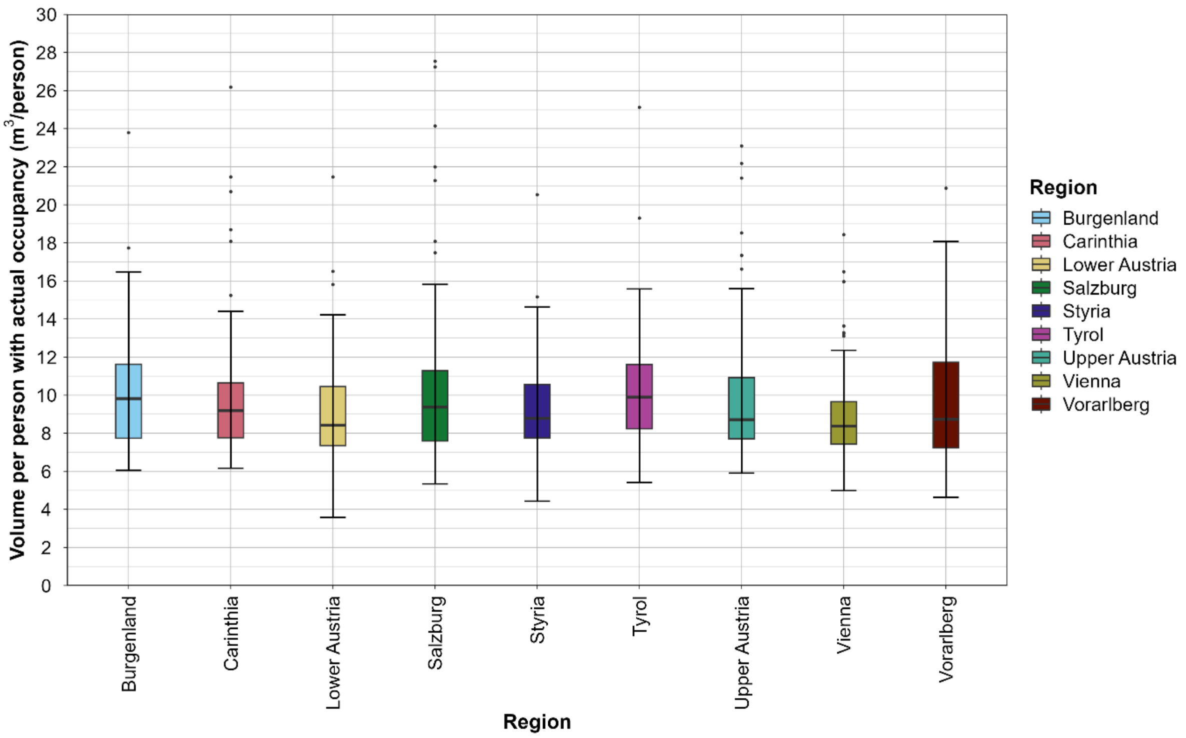


Figure A-18 Room volume per person based on actual occupancy, sorted by region.

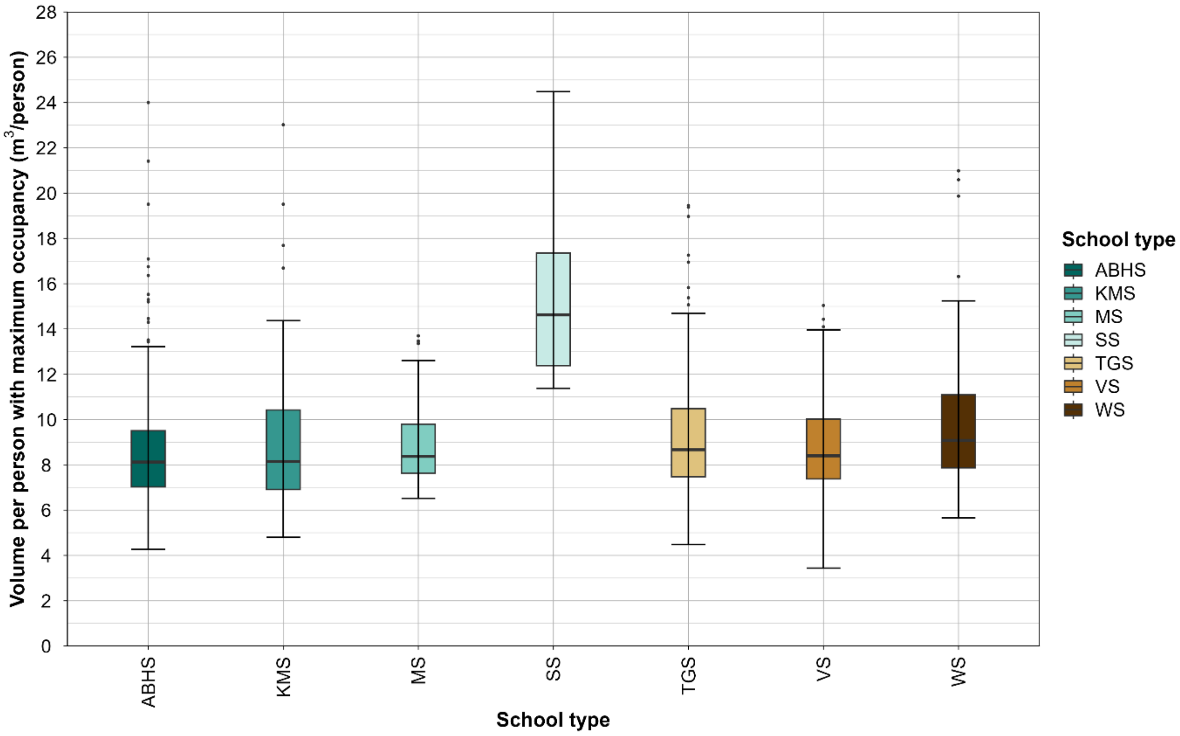


Figure A-19 Room volume per person with maximum occupancy (i.e. including the teacher) classified by school type

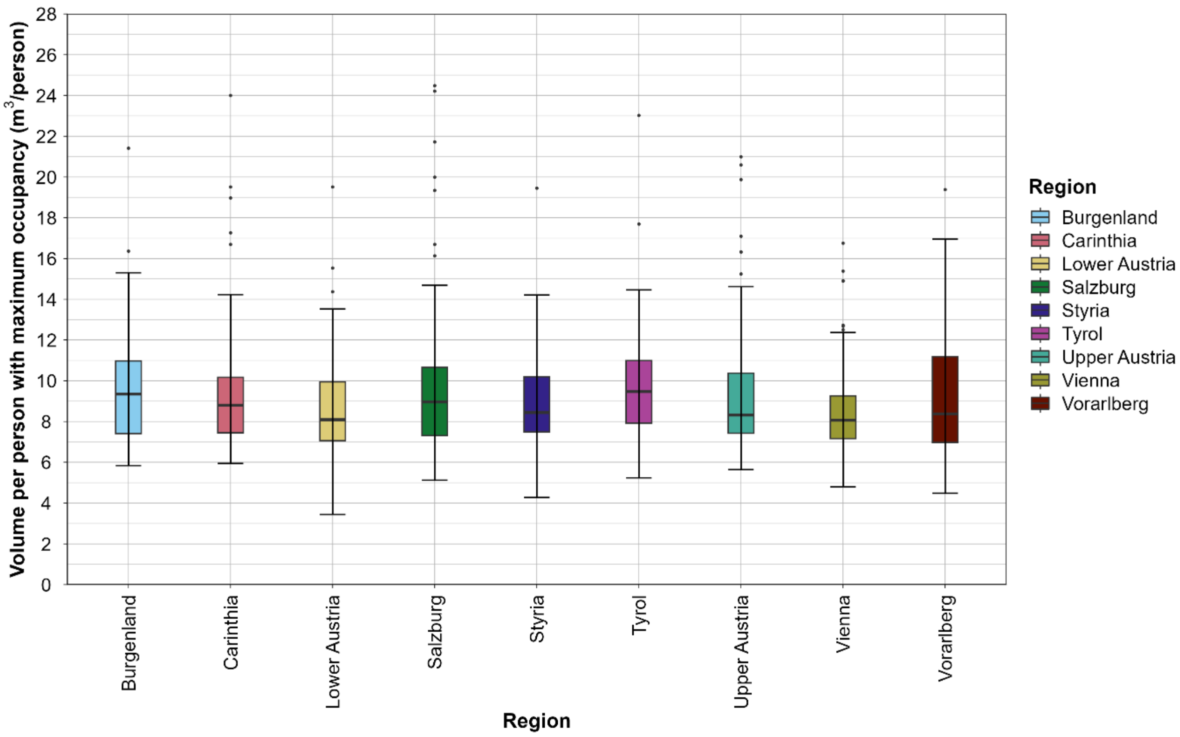


Figure A-20 Room volume per person with maximum occupancy (i.e. including the teacher) sorted by region.

C.1.1.7. External façade of the total glazed area in m^2

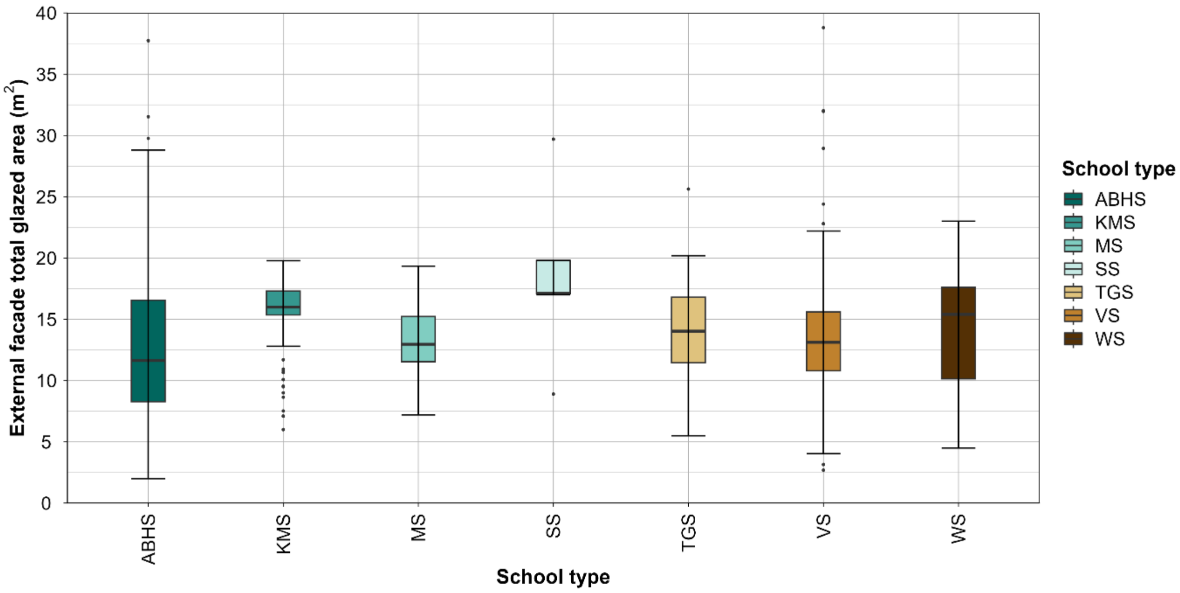


Figure A-21 External facade of classrooms showing the total glazed area in m^2 sorted by school type.

Figure A-25 shows that ABHS schools have the widest range of total glazed façade areas, ranging from 2 m^2 to 36 m^2; with 39 m^2 (in a VS school) being the largest glazed area of a single classroom.

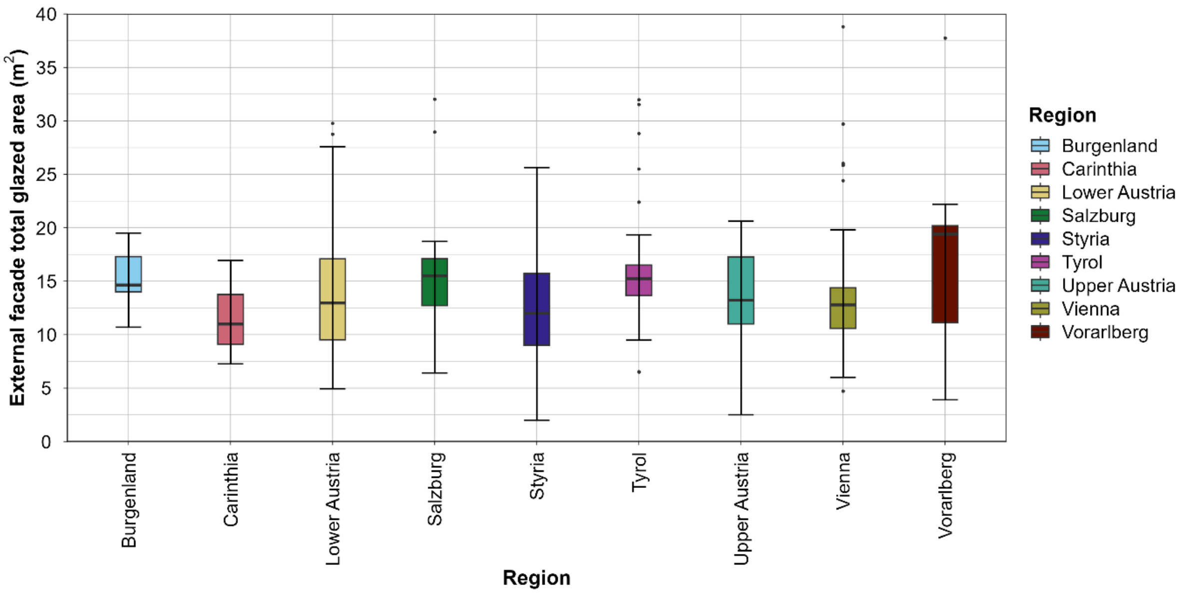


Figure A-22 External facade of classrooms showing the total glazed area in m^2 sorted by region.

It is shown that schools in Styria and Lower Austria have the widest range of total glazed areas, ranging from 2 m^2 to 29m^2; with 39 m^2 being the highest glazed area in a Vienna school.

C.1.1.8. Maximum openable window area per classroom [m²]

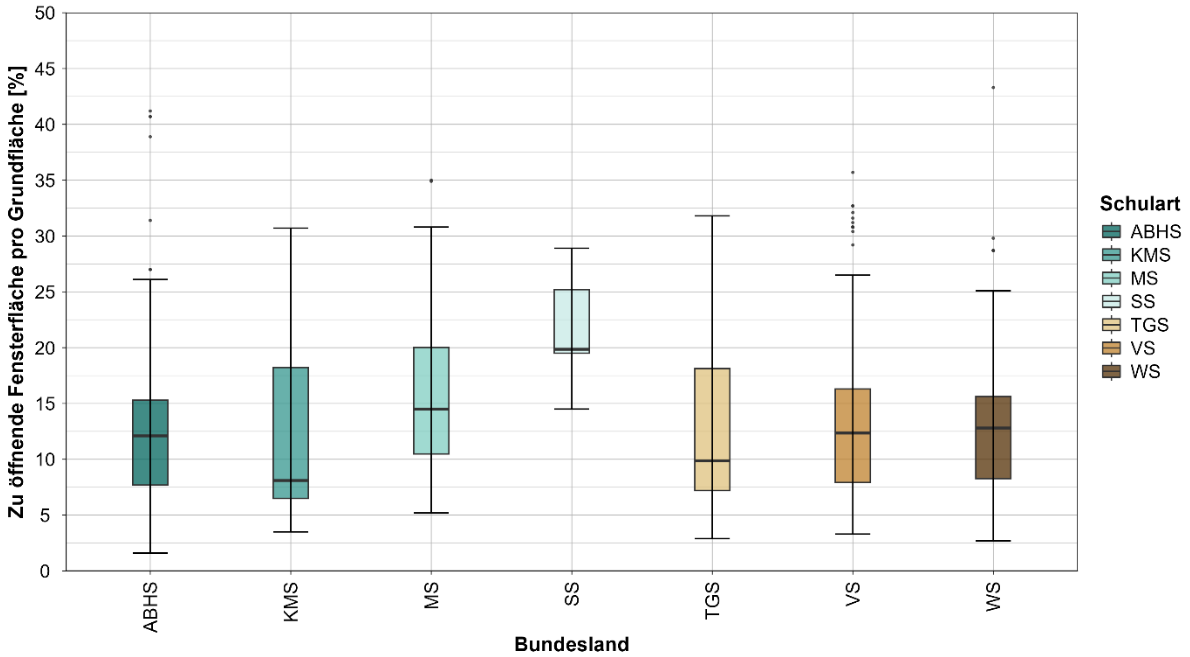


Figure A-23 Maximum openable area in m² sorted by school type.

The maximum openable window area ranges from 1 m² up to nearly 26 m², with special schools having significantly higher median openable window areas.

C.1.1.9. Window and shading information

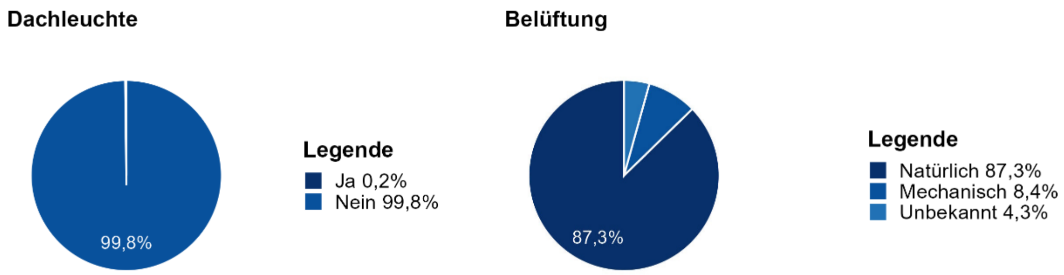


Figure A-24 Additional information on window and shading.

C.1.1.10. Examples of different window openings

Figure A-29 below illustrates the different types of window openings in the selected schools:

- 1st row: 1, windows blocked by posters; 2, shading devices interfering; 3, window handles removed.
- 2nd row: 1, ceiling windows; 2, ceiling windows with electric window opening mechanism; 3, large window with three opening possibilities, top having restrictors.
- 3rd row: 1, large glazed façade with only door to outside being openable; 2, large glazed area, top windows cannot be opened; 3, large older window with internal shading device.
- 4th row: 1, a large glazed area with only some windows opening but interfering with tables; 2, large window areas, fully openable; 3, window opening interfering with tables.
- 5th row: 1, ceiling windows; 2, two-rows of openable windows; 3, large glazed area, top windows can be tilted, the bottom row has handles removed.

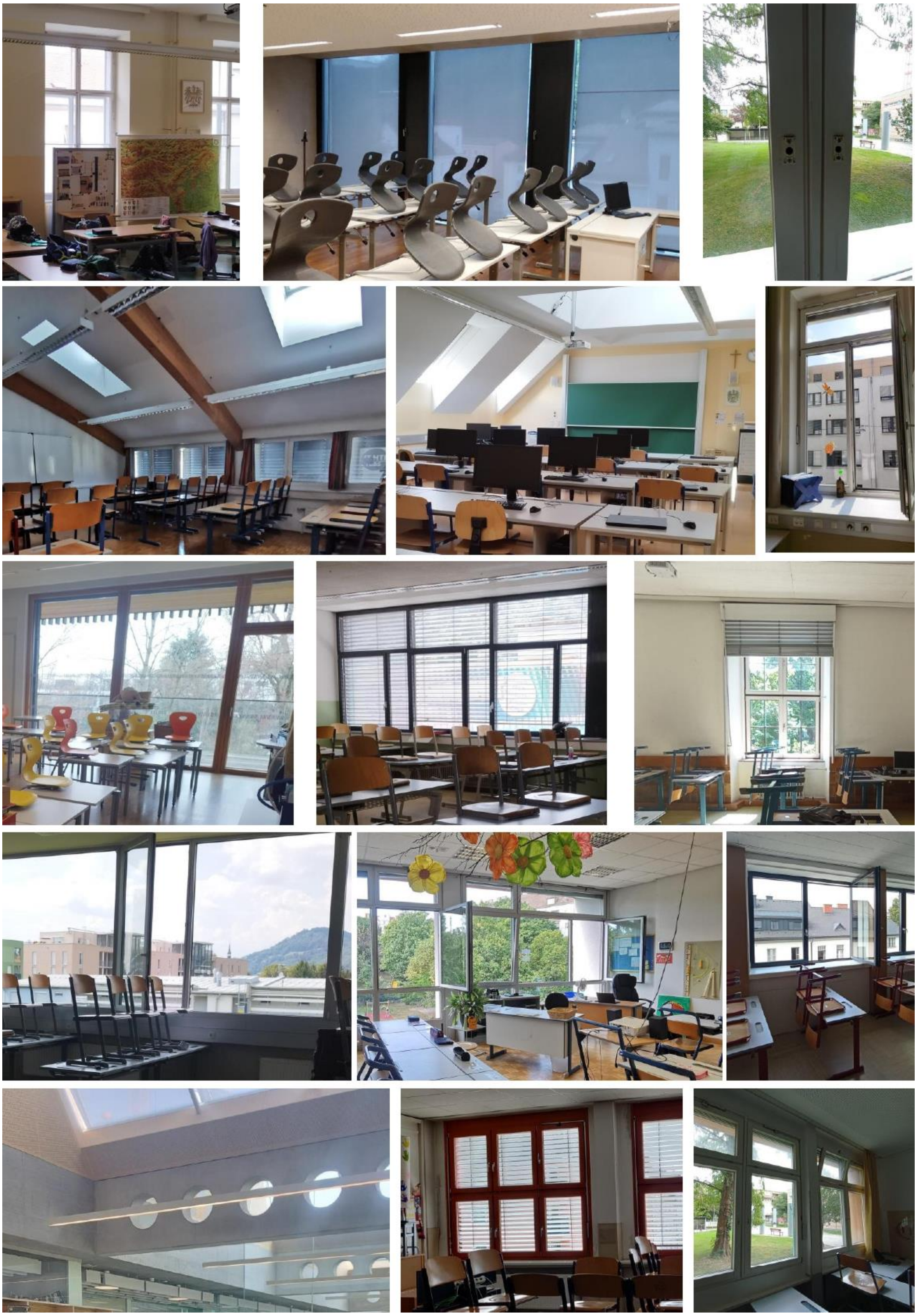


Figure A-30 Examples of different types of window openings and ventilation obstructions.

C.1.1.11. Examples of different mechanical ventilation types

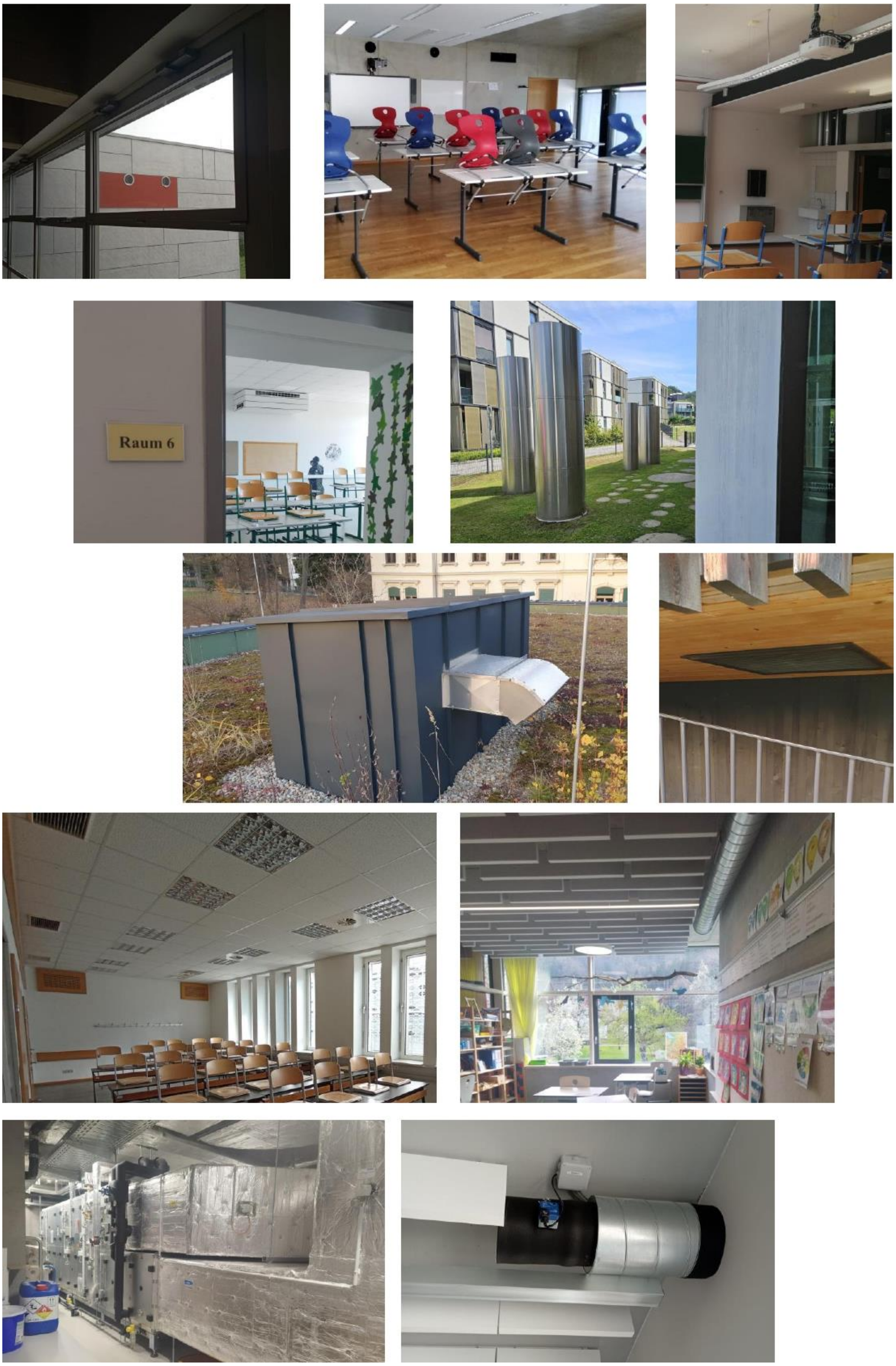


Figure A-25 Pictures of different mechanical ventilation systems used in some of the schools

C.1.2. Analysis of CO_2 concentrations in Austrian classrooms

C.1.2.1. CO_2 concentrations in 120 schools

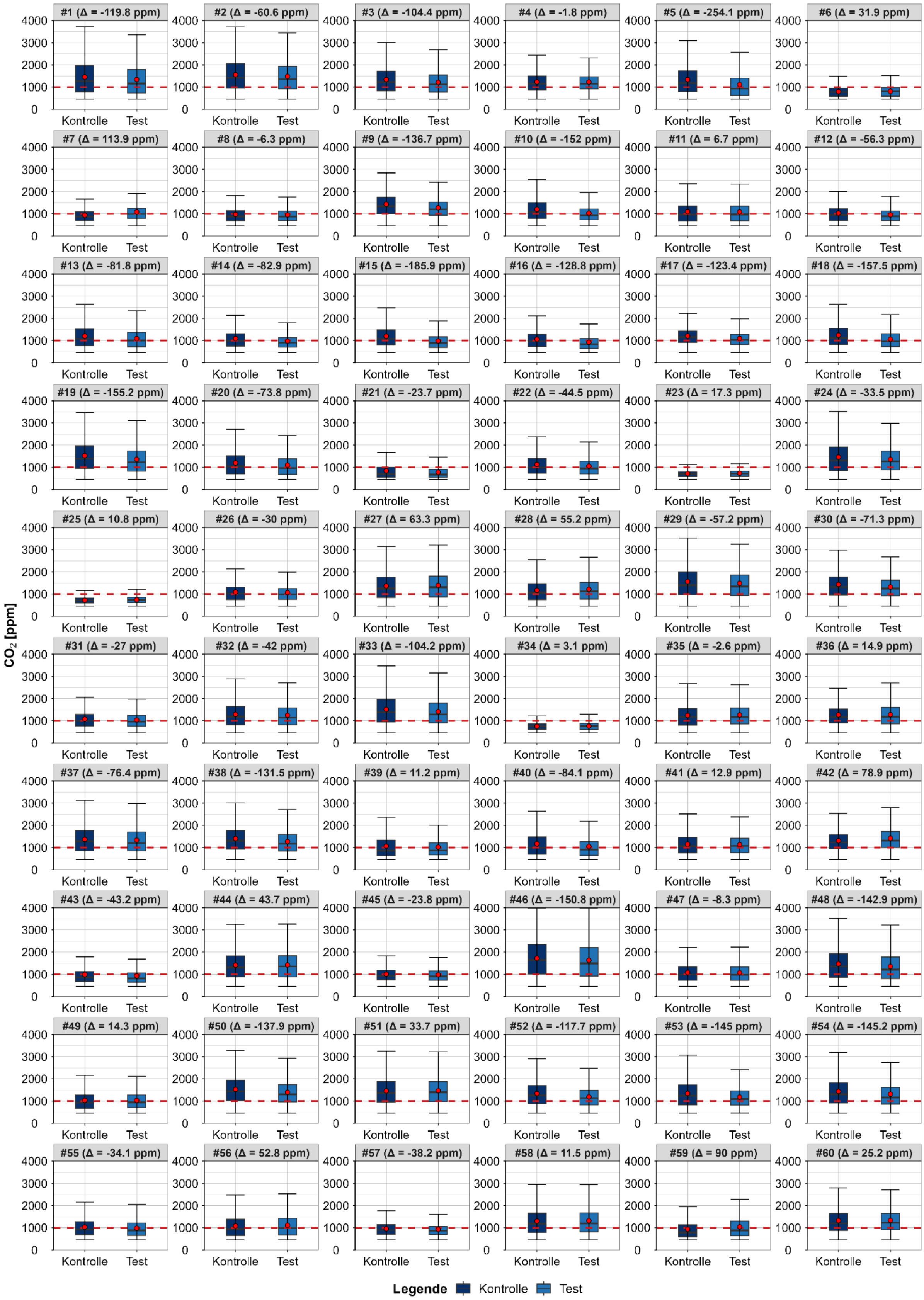


Figure A-26 Box plots of annual CO_2 IQR in each of the 120 schools

C.1.2.2. Variation in classroom CO_2 concentrations by season

Fig. A-33 and Tbl. A-6 describe the distribution of the daily mean CO_2 concentrations categorized by season. They show that CO_2 concentrations are elevated in autumn and winter, with 65% and 75% of the observations exceeding the compliance threshold of 1000 ppm, respectively.

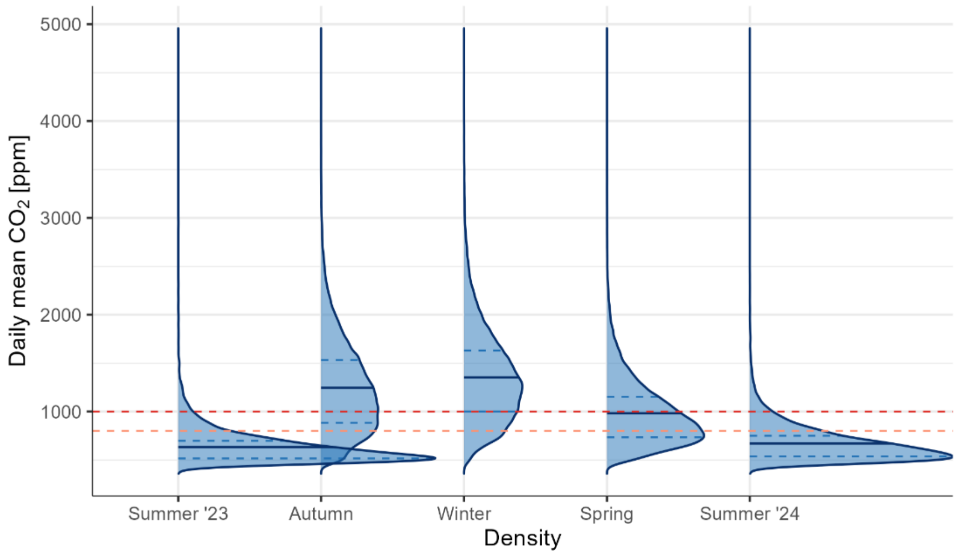


Figure A-27 Seasonal distribution of daily mean CO_2 concentration in classrooms, including CO_2 indoor compliance threshold (1000 ppm, dashed red line) and target threshold (800 ppm, dashed pink line). The solid line within each distribution indicates the mean, whereas the dashed lines mark the 25th and 75th percentiles.

The plot depicts the distribution of CO_2 concentrations from combined control and test sensors by season. As in the previous plot, the red and light red dotted lines indicate the indoor CO_2 compliance and target thresholds. The blue solid line within each distribution indicates the mean, whereas the dashed light blue lines indicate the 25th and 75th percentiles.

Table A-6 Seasonal statistical summary of daily mean CO_2 concentrations in classrooms, including frequency of CO_2 indoor threshold exceedances relative to 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances. [LV

Season	Min [ppm]	Max [ppm]	Percentile [ppm]			IQR	Mean [ppm]	Threshold exceedance	
			25.	50.	75.			>1000 ppm	>800 ppm
Summer ‘23	460	2947	516	586	698	182	634	4 %	12 %
Autumn	460	4184	884	1178	1532	648	1245	65 %	82 %
Winter	461	4856	1001	1294	1630	630	1353	75 %	89 %
Spring	460	3759	734	910	1153	418	983	39 %	65 %
Summer ‘24	460	2401	537	624	750	213	671	6 %	19 %

C.1.2.3. CO_2 concentration according to sensor type

Fig. A-34 and Tbl. A-7 describe the distribution of the daily mean CO_2 concentrations categorized by month. The monthly trend is clearly visible with higher CO_2 concentrations in the colder months, where it is more visible also the performance difference between Control and Test sensors.

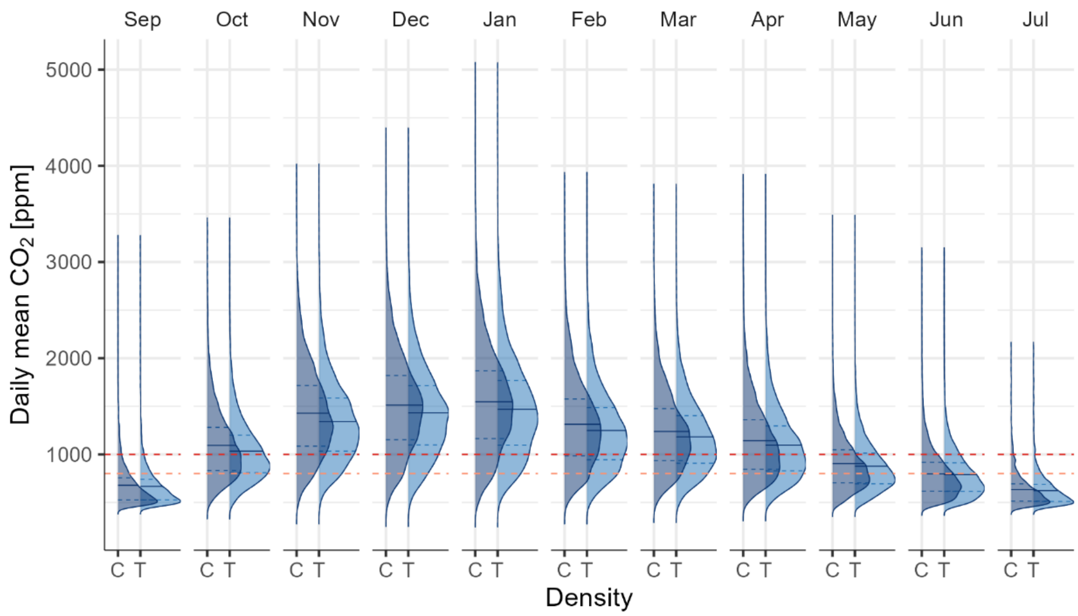


Figure A-34 Monthly distribution of daily mean CO_2 concentration in classrooms categorized by room type (C = Control, T = Test), including CO_2 indoor compliance threshold (1000 ppm, dotted red line) and target threshold (800 ppm, dotted pink line). The solid line within each distribution indicates the mean, whereas the dashed lines mark the 25th and 75th percentiles.

Table A-7 Monthly statistical summary of the daily mean CO_2 concentrations in classrooms categorized by room type (C = Control, T = Test), including frequency of CO_2 indoor threshold exceedances relative to 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances.

Month	Sensor type	Min [ppm]	Max [ppm]	Percentile [ppm] 25.	50.	75.	IQR	Mean [ppm]	Threshold exceedance >1000 ppm	>800 ppm
Sep	C	460	3197	527	614	756	229	679	8 %	20 %
	T	460	2984	527	613	740	213	667	6 %	18 %
Oct	C	464	3326	833	1032	1281	448	1094	54 %	79 %
	T	462	3029	810	978	1200	390	1033	47 %	76 %
Nov	C	462	3833	1086	1374	1716	630	1428	82 %	93 %
	T	465	3625	1033	1289	1586	552	1340	78 %	92 %
Dec	C	460	4165	1153	1479	1820	667	1513	84 %	93 %
	T	462	4184	1098	1397	1715	617	1432	82 %	93 %
Jan	C	463	4856	1164	1504	1868	704	1547	84 %	93 %
	T	464	4084	1097	1420	1769	672	1469	81 %	93 %
Feb	C	461	3683	985	1267	1576	591	1313	74 %	88 %
	T	465	3748	944	1201	1487	542	1248	70 %	87 %
Mar	C	461	3569	936	1184	1476	540	1238	69 %	87 %
	T	463	3641	908	1133	1403	495	1182	65 %	85 %
Apr	C	462	3759	846	1074	1360	514	1142	58 %	80 %
	T	461	3589	829	1036	1296	467	1097	54 %	78 %
May	C	460	2740	704	854	1048	344	904	30 %	59 %
	T	460	3379	694	829	1013	319	877	26 %	55 %
Jun	C	460	2984	618	744	918	300	798	17 %	41 %
	T	460	3055	615	740	912	297	789	17 %	40 %
Jul	C	460	2084	514	589	694	180	634	4 %	13 %
	T	460	2069	511	582	689	178	623	3 %	10 %

C.1.2.4. CO_2 concentration according to ventilation system type

The monthly plot and summary statistics of the daily mean CO_2 concentrations (Fig. A-35, Tbl. A-6) show a clear distinction between mechanical ventilation (MV) and natural ventilation (NV), with mechanical systems largely outperforming the natural ones throughout the school year.

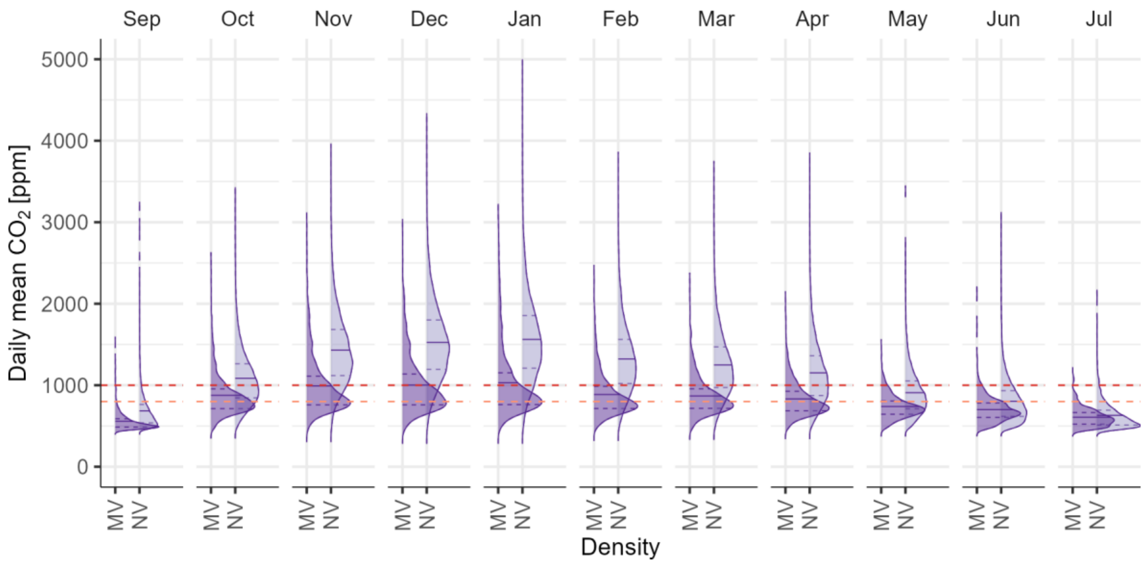


Figure A-28 Monthly distribution of daily mean CO_2 concentration in classrooms categorized by ventilation type, including CO_2 indoor compliance threshold (1000 ppm, dotted red line) and target threshold (800 ppm, dotted pink line). The solid line within each distribution indicates the mean, whereas the dashed lines mark the 25th and 75th percentiles.

Table A-8 Monthly statistics of daily mean CO_2 concentrations in classrooms categorized by ventilation type, including frequency of CO_2 indoor threshold exceedances relative to 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances.

Month	Sensor type	Min [ppm]	Max [ppm]	Percentile [ppm]			IQR [ppm]	Mean [ppm]	Threshold exceedance	
				25.	50.	75.			>1000 ppm	>1000 ppm
Sep	MV	460	1526	486	516	588	103	557	1 %	4 %
	NV	460	3197	538	627	764	226	686	8 %	21 %
Oct	MV	464	2509	713	811	955	242	877	21 %	53 %
	NV	462	3326	845	1031	1263	418	1085	54 %	81 %
Nov	MV	468	2950	760	888	1112	352	991	36 %	67 %
	NV	462	3833	1118	1373	1684	565	1430	85 %	96 %
Dec	MV	460	2845	760	906	1138	378	1002	37 %	68 %
	NV	461	4184	1194	1479	1800	607	1525	88 %	96 %
Jan	MV	466	3036	762	888	1152	390	1031	36 %	67 %
	NV	463	4856	1209	1511	1855	646	1562	88 %	96 %
Feb	MV	463	2316	715	811	987	272	885	24 %	52 %
	NV	461	3748	1021	1273	1562	541	1323	77 %	91 %
Mar	MV	468	2243	716	812	956	239	868	21 %	53 %
	NV	461	3641	972	1199	1471	498	1249	72 %	90 %
Apr	MV	465	2028	687	776	926	239	832	18 %	44 %
	NV	461	3759	874	1091	1362	489	1152	60 %	83 %
May	MV	460	1470	644	714	807	163	739	6 %	26 %
	NV	460	3379	712	862	1052	339	908	31 %	60 %
Jun	MV	461	2121	604	679	783	179	702	4 %	21 %
	NV	460	3055	618	754	933	314	804	18 %	42 %

Jul	MV	460	1112	523	587	666	143	607	1 %	6 %
	NV	460	2084	512	587	694	182	631	4 %	12 %
Year	MV	460	3036	676	784	950	275	856	21 %	46 %
	NV	460	4856	819	1103	1456	637	1178	59 %	77 %

C.1.2.5. CO_2 concentration according to school type

Tbl. A-9 summarizes the seasonal CO_2 levels and quantifies threshold exceedances as described in the Main report.

Table A-9 Seasonal statistics of daily mean CO_2 concentrations in classrooms categorized by school type, including frequency of CO_2 indoor threshold exceedances relative to 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances.CO_2 concentration.

Season	School type	Min [ppm]	Max [ppm]	Percentile [ppm]			IQR	Mean [ppm]	Threshold exceedance	
				25.	50.	75.			> 1000 ppm	>800 ppm
Summer '23	ABHS	460	1953	515	589	707	191	640	4 %	14 %
	KMS	461	2947	512	589	717	206	648	5 %	14 %
	MS	461	1240	525	597	709	184	631	2 %	12 %
	SS	461	1056	508	562	650	142	615	2 %	13 %
	TGS	460	1620	523	594	689	166	635	4 %	12 %
	VS	460	2308	503	561	648	145	605	3 %	7 %
	WS	462	1951	542	615	736	193	665	6 %	17 %
Autumn	ABHS	460	4184	913	1230	1582	669	1282	68 %	84 %
	KMS	461	4165	917	1287	1677	760	1346	70 %	83 %
	MS	462	3831	952	1202	1520	568	1268	70 %	87 %
	SS	473	1711	635	755	890	255	786	14 %	41 %
	TGS	461	3684	908	1215	1574	666	1273	68 %	84 %
	VS	460	3907	807	1020	1307	501	1094	52 %	76 %
	WS	463	3378	981	1267	1592	611	1314	74 %	87 %
Winter	ABHS	461	4484	1065	1358	1689	625	1409	80 %	91 %
	KMS	462	4856	1094	1407	1767	673	1464	80 %	90 %
	MS	461	3954	1060	1312	1631	571	1384	80 %	94 %
	SS	492	1686	664	770	920	256	827	18 %	43 %
	TGS	465	3943	1044	1343	1679	636	1396	79 %	92 %
	VS	461	3532	875	1099	1384	509	1169	61 %	83 %
	WS	461	3688	1077	1364	1672	594	1409	82 %	94 %
Spring	ABHS	460	3759	769	958	1200	431	1024	45 %	71 %
	KMS	460	3650	722	909	1193	471	1001	41 %	63 %
	MS	460	3569	794	953	1175	381	1019	44 %	74 %
	SS	463	1774	546	617	736	190	664	5 %	16 %
	TGS	461	3097	700	871	1112	412	942	35 %	60 %
	VS	460	3394	717	860	1066	349	935	31 %	60 %
	WS	461	3431	713	916	1176	462	988	40 %	64 %
Summer '24	ABHS	460	2401	540	641	784	244	690	8 %	23 %
	KMS	460	2258	512	586	711	199	638	4 %	14 %
	MS	461	2084	584	686	820	235	724	9 %	29 %
	SS	464	1133	503	554	654	151	599	1 %	12 %
	TGS	460	1632	508	570	682	174	617	3 %	10 %
	VS	461	2191	572	640	747	174	687	6 %	18 %
	WS	460	1336	500	558	668	168	602	2 %	10 %
Year	ABHS	460	4484	819	1111	1475	656	1187	59 %	77 %
	KMS	460	4856	782	1133	1539	757	1216	59 %	73 %
	MS	460	3954	848	1097	1418	570	1173	59 %	80 %
	SS	461	1774	585	698	840	254	743	11 %	31 %
	TGS	460	3943	779	1070	1449	671	1155	56 %	73 %
	VS	460	3907	744	946	1231	487	1028	44 %	68 %
	WS	460	3688	811	1119	1478	667	1184	60 %	76 %

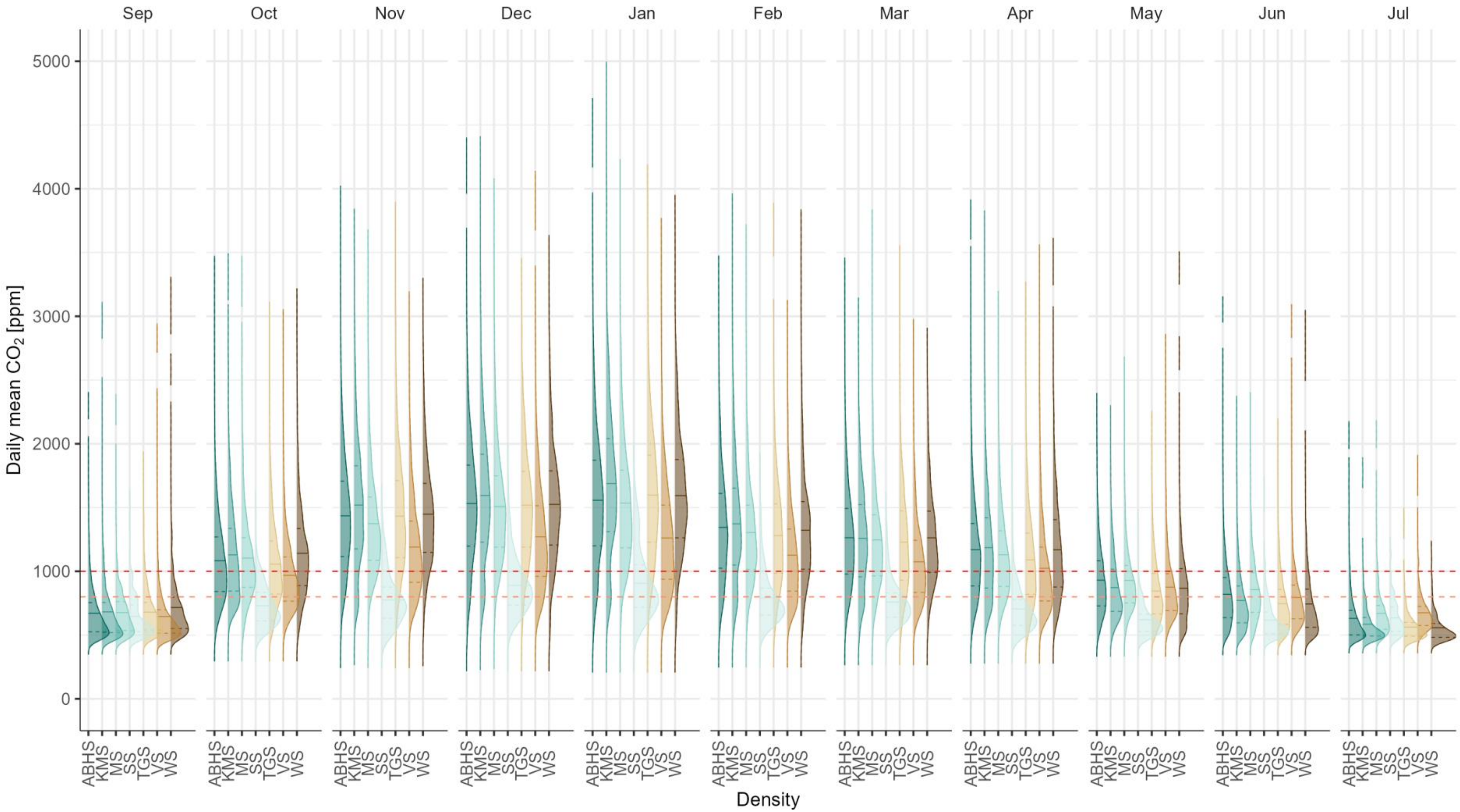


Figure A-29 Monthly distribution of daily mean CO_2 concentration in classrooms categorized by school type, including CO_2 indoor compliance threshold (1000 ppm, dotted red line) and target threshold (800 ppm, dotted pink line). The solid line within each distribution indicates the mean, whereas the dashed lines mark the 25th and 75th percentiles

Table A-10 Monthly statistics of daily mean CO_2 concentrations in classrooms categorized by school type, including frequency of CO_2 indoor threshold exceedances relative to 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances.CO_2 concentration.

Month	School type	Min [ppm]	Max [ppm]	Percentile [ppm] 25.	50.	75.	IQR [ppm]	Mean [ppm]	Threshold exceedance >1000 ppm	>800 ppm
Sep	ABHS	460	2299	525	612	755	230	672	7 %	20 %
	KMS	461	2992	520	614	756	236	682	9 %	20 %
	MS	461	2268	536	632	762	226	676	6 %	20 %
	SS	461	1501	526	586	737	210	647	3 %	18 %
	TGS	460	1819	541	628	756	215	680	7 %	20 %
	VS	460	2831	515	583	699	184	645	6 %	14 %
	WS	462	3197	551	649	797	245	717	10 %	25 %
Oct	ABHS	462	3326	842	1032	1269	428	1083	54 %	80 %
	KMS	468	3311	845	1060	1337	491	1129	57 %	81 %
	MS	463	3308	874	1042	1263	388	1103	56 %	84 %
	SS	473	1432	612	690	835	224	730	6 %	31 %
	TGS	465	2944	822	1003	1238	416	1056	50 %	78 %
	VS	468	2898	766	909	1112	346	968	37 %	69 %
	WS	464	3044	888	1096	1336	448	1142	62 %	84 %
Nov	ABHS	462	3833	1116	1399	1707	591	1435	83 %	94 %
	KMS	514	3625	1176	1474	1827	651	1519	85 %	92 %
	MS	465	3446	1086	1300	1583	498	1374	84 %	97 %
	SS	487	1415	632	738	876	244	775	16 %	35 %
	TGS	466	3684	1108	1379	1711	603	1433	84 %	94 %
	VS	471	2991	913	1126	1393	480	1190	65 %	87 %
	WS	502	3076	1149	1408	1690	541	1448	89 %	96 %
Dec	ABHS	462	4184	1198	1504	1832	634	1532	86 %	94 %
	KMS	490	4165	1229	1564	1918	689	1595	86 %	94 %
	MS	488	3831	1190	1458	1748	559	1509	90 %	98 %
	SS	532	1711	735	842	996	261	890	25 %	63 %
	TGS	492	3202	1190	1483	1784	595	1518	88 %	96 %
	VS	460	3907	960	1208	1514	555	1271	71 %	88 %
	WS	461	3378	1206	1497	1788	581	1525	88 %	96 %
Jan	ABHS	464	4484	1200	1526	1871	671	1557	86 %	94 %
	KMS	478	4856	1310	1642	2041	730	1688	87 %	94 %
	MS	463	3954	1185	1466	1793	609	1534	89 %	97 %
	SS	492	1686	718	838	1052	334	906	28 %	57 %
	TGS	466	3943	1228	1552	1911	682	1598	89 %	97 %
	VS	491	3532	938	1205	1520	582	1261	68 %	88 %
	WS	480	3688	1263	1547	1876	614	1594	91 %	96 %
Feb	ABHS	461	3289	1024	1302	1611	586	1344	77 %	90 %
	KMS	468	3748	1049	1329	1652	603	1372	78 %	88 %
	MS	461	3509	1015	1245	1519	503	1304	77 %	93 %
	SS	504	1673	655	730	868	213	792	14 %	35 %
	TGS	465	3683	985	1241	1530	545	1280	73 %	90 %
	VS	463	2918	845	1066	1332	487	1127	58 %	80 %
	WS	464	3621	1016	1273	1546	530	1322	77 %	92 %
Mar	ABHS	462	3284	979	1221	1493	514	1263	73 %	90 %
	KMS	462	2948	957	1233	1523	567	1258	72 %	86 %
	MS	464	3641	965	1183	1443	478	1246	71 %	90 %
	SS	523	1385	640	722	830	190	760	9 %	31 %
	TGS	470	3364	931	1175	1474	543	1229	68 %	87 %
	VS	461	2782	834	1017	1243	409	1074	52 %	79 %
	WS	493	2702	991	1208	1472	480	1263	74 %	92 %

Continued on the next page

Month	School type	Min [ppm]	Max [ppm]	Percentile [ppm]			IQR [ppm]	Mean [ppm]	Threshold exceedance	
				25.	50.	75.			>1000 ppm	>800 ppm
Apr	ABHS	462	3759	885	1116	1376	490	1169	63 %	84 %
	KMS	462	3650	869	1122	1420	551	1186	62 %	82 %
	MS	461	3015	882	1072	1318	436	1130	60 %	86 %
	SS	474	1774	576	649	779	203	705	7 %	23 %
	TGS	462	3097	820	1031	1299	480	1090	54 %	77 %
	VS	472	3394	768	944	1190	422	1024	43 %	70 %
	WS	464	3431	877	1107	1405	528	1169	60 %	83 %
May	ABHS	460	2280	729	886	1083	354	931	35 %	63 %
	KMS	460	2178	686	813	1016	330	872	27 %	52 %
	MS	470	2554	752	880	1046	294	929	30 %	66 %
	SS	463	1332	529	580	664	135	621	2 %	11 %
	TGS	461	2132	666	795	983	317	845	23 %	50 %
	VS	460	2740	692	816	981	289	875	23 %	53 %
	WS	461	3379	666	831	1020	354	867	27 %	55 %
Jun	ABHS	460	3055	637	776	951	314	820	20 %	46 %
	KMS	460	2258	596	712	885	289	771	15 %	35 %
	MS	460	2289	678	810	989	311	856	24 %	52 %
	SS	464	1604	512	567	681	169	617	3 %	12 %
	TGS	460	2087	584	696	858	274	746	12 %	32 %
	VS	462	2984	628	739	892	264	794	15 %	38 %
	WS	460	2932	561	677	860	299	744	14 %	31 %
Jul	ABHS	460	2069	501	574	694	192	631	5 %	14 %
	KMS	460	1773	492	533	638	146	585	1 %	8 %
	MS	463	2084	545	625	732	187	670	5 %	17 %
	SS	465	1133	529	608	721	192	635	2 %	14 %
	TGS	460	1377	490	529	599	108	563	0 %	3 %
	VS	461	1797	575	637	725	150	675	4 %	14 %
	WS	460	1116	482	518	591	109	558	1 %	5 %

C.1.2.6. CO_2 concentration according to urban/rural location

The monthly distribution plot and summary statistics are reported in Fig. A-37 and Tbl. A-11, which reports also the percentages of threshold exceedances.

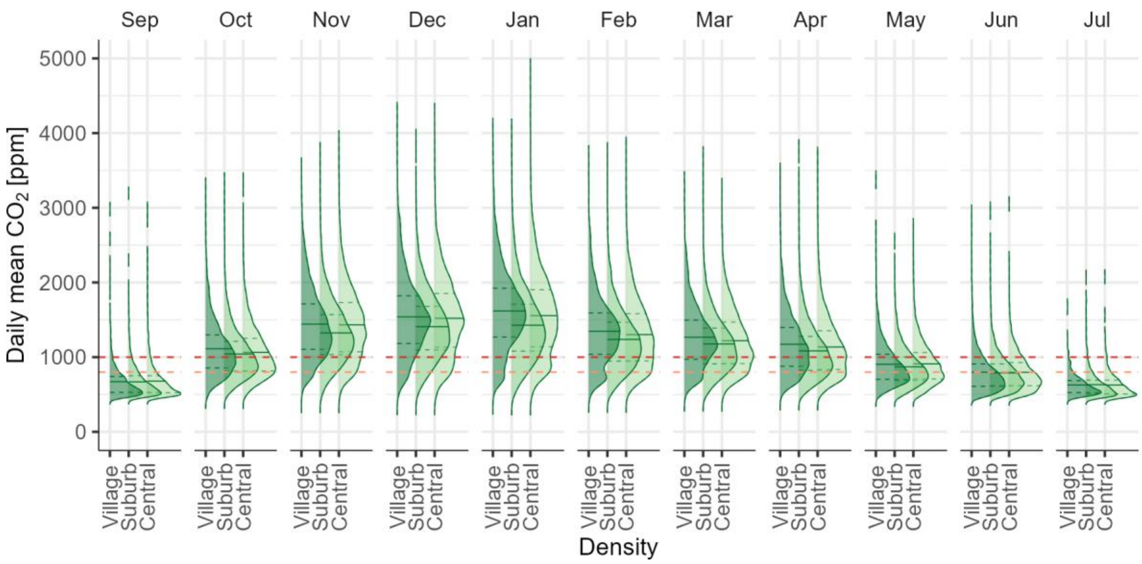


Figure A-30 Monthly distribution of daily mean CO_2 concentration in classrooms categorized by area type (rural: village, urban: central, outskirt) including CO_2 indoor compliance threshold (1000 ppm, dotted red line) and target threshold (800 ppm, dotted pink line). The solid line within each distribution indicates the mean, whereas the dashed lines mark the 25th and 75th percentiles.

Table A-11 Monthly statistics of daily mean CO_2 concentrations in classrooms categorized by area type, including frequency of CO_2 indoor threshold exceedances relative to 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances.

Month	Area type	Min [ppm]	Max [ppm]	Percentile [ppm] 25.	50.	75.	IQR ppm]	Mean [ppm]	Threshold exceedance >1000 ppm	>800 ppm
Sep	Village	461	2984	528	610	742	214	671	7	18
	Suburb	460	3197	529	615	751	221	669	6	19
	Central	460	2992	523	614	751	228	679	8	20
Oct	Village	462	3245	855	1050	1299	444	1112	57	81
	Suburb	464	3326	812	988	1213	400	1042	49	77
	Central	463	3311	815	1001	1253	437	1064	50	77
Nov	Village	469	3446	1105	1375	1713	608	1442	83	94
	Suburb	462	3684	1033	1278	1570	537	1325	78	92
	Central	478	3833	1072	1388	1732	660	1433	80	92
Dec	Village	463	4184	1183	1495	1821	638	1539	86	94
	Suburb	460	3831	1099	1372	1679	580	1408	83	93
	Central	464	4165	1133	1488	1852	719	1521	82	93
Jan	Village	516	3954	1269	1583	1923	654	1618	87	94
	Suburb	464	3954	1080	1376	1709	629	1428	81	93
	Central	463	4856	1138	1513	1902	765	1556	82	93
Feb	Village	461	3621	1038	1313	1591	554	1346	78	88
	Suburb	461	3683	947	1191	1468	521	1237	70	88
	Central	462	3748	950	1246	1582	632	1302	71	87
Mar	Village	461	3284	972	1218	1496	524	1266	73	87
	Suburb	462	3641	909	1132	1389	480	1177	64	86
	Central	468	3215	914	1155	1469	555	1221	66	86
Apr	Village	474	3431	878	1110	1398	520	1173	62	83
	Suburb	461	3759	823	1022	1278	454	1084	53	78
	Central	465	3650	835	1067	1354	519	1135	57	79
May	Village	460	3379	702	842	1040	338	904	29	58
	Suburb	460	2556	691	826	1003	313	871	25	55
	Central	460	2740	708	864	1061	353	910	31	59
Jun	Village	460	2932	610	737	908	299	798	17	39
	Suburb	460	2984	617	743	908	290	789	16	40
	Central	460	3055	617	746	928	311	797	18	41
Jul	Village	461	1676	526	591	686	160	626	2	11
	Suburb	460	2069	511	586	693	182	632	4	12
	Central	460	2084	507	585	693	185	626	4	12

C.1.2.7. CO_2 concentration according to region

Statistics and threshold exceedances for the daily mean CO_2 concentrations are reported by season (Tbl. A-12) and by month (Tbl. A-13). The corresponding monthly distribution plot is shown in Fig. A-38.

Table A-12 Seasonal statistics of daily mean CO_2 concentrations in classrooms categorized by area region and season, including frequency of CO_2 indoor threshold exceedances relative to 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances.

Season	Region	Min [ppm]	Max [ppm]	Percentile [ppm] 25.	50.	75.	IQR [ppm]	Mean [ppm]	Threshold exceedance >1000 ppm	>800 ppm

Summer '23	BUR	461	1483	486	541	624	138	578	1 %	5 %
	CAR	463	1862	561	638	761	200	693	7 %	21 %
	LOA	460	2947	515	583	696	181	631	4 %	11 %
	UPA	461	1317	527	599	702	175	640	4 %	13 %
	SAL	461	1504	506	564	691	184	629	4 %	14 %
	STY	461	2308	506	579	692	186	632	4 %	12 %
	TYR	461	1734	506	567	685	179	619	3 %	10 %
	VOR	460	1310	499	554	656	157	611	3 %	12 %
	VIE	460	1953	520	592	702	182	638	4 %	13 %
Autumn	BUR	461	3326	728	931	1276	548	1052	44 %	63 %
	CAR	464	3303	1028	1334	1697	670	1385	77 %	89 %
	LOA	462	4184	887	1221	1596	709	1292	66 %	83 %
	UPA	460	3831	986	1266	1584	597	1313	74 %	87 %
	SAL	460	2680	778	990	1279	500	1057	49 %	72 %
	STY	461	3907	906	1188	1562	656	1270	66 %	84 %
	TYR	462	3400	911	1188	1499	587	1236	67 %	85 %
	VOR	464	2950	785	1093	1496	711	1168	57 %	74 %
	VIE	460	3833	854	1111	1434	580	1186	61 %	80 %
Winter	BUR	463	3667	725	934	1371	646	1098	46 %	61 %
	CAR	462	3505	1164	1417	1712	548	1467	88 %	97 %
	LOA	461	4543	1025	1358	1709	684	1412	77 %	89 %
	UPA	464	3954	1157	1408	1714	557	1467	88 %	96 %
	SAL	463	2757	831	1065	1365	534	1123	57 %	78 %
	STY	461	3954	1022	1315	1668	645	1382	77 %	92 %
	TYR	462	3683	1002	1251	1580	578	1321	75 %	91 %
	VOR	468	3943	916	1239	1616	700	1306	69 %	84 %
	VIE	461	4856	923	1176	1506	583	1259	67 %	87 %
Spring	BUR	460	2754	663	766	992	329	865	24 %	44 %
	CAR	460	3259	859	1050	1307	448	1122	57 %	82 %
	LOA	462	3431	728	902	1181	453	995	40 %	64 %
	UPA	460	3569	756	945	1181	425	1006	43 %	69 %
	SAL	460	3055	690	831	1040	350	892	29 %	55 %
	STY	460	3394	758	929	1169	410	997	41 %	69 %
	TYR	461	3759	764	941	1176	412	1014	43 %	70 %
	VOR	468	2334	705	854	1046	342	905	30 %	58 %
	VIE	461	3650	708	876	1104	396	944	35 %	61 %
Summer '24	BUR	462	1305	537	604	685	148	637	4 %	11 %
	CAR	463	2069	592	710	859	267	762	13 %	34 %
	LOA	460	2401	517	584	697	181	639	4 %	13 %
	UPA	460	1533	523	605	719	196	641	3 %	14 %
	SAL	460	2084	555	654	799	244	694	7 %	25 %
	STY	460	2191	549	634	766	217	687	8 %	20 %
	TYR	460	1913	561	662	812	251	712	8 %	27 %
	VOR	464	1377	552	631	741	189	662	3 %	16 %
	VIE	460	1864	523	593	700	176	638	3 %	14 %
Year	BUR	460	3667	685	825	1171	486	975	36 %	53 %
	CAR	460	3505	903	1200	1562	658	1264	67 %	83 %
	LOA	460	4543	790	1096	1496	706	1191	57 %	74 %
	UPA	460	3954	834	1144	1485	650	1200	62 %	78 %
	SAL	460	3055	714	913	1193	479	988	41 %	64 %
	STY	460	3954	805	1066	1435	631	1161	56 %	75 %
	TYR	460	3759	812	1063	1389	577	1139	56 %	76 %
	VOR	460	3943	728	957	1330	603	1072	46 %	66 %
	VIE	460	4856	769	1006	1327	558	1096	51 %	72 %

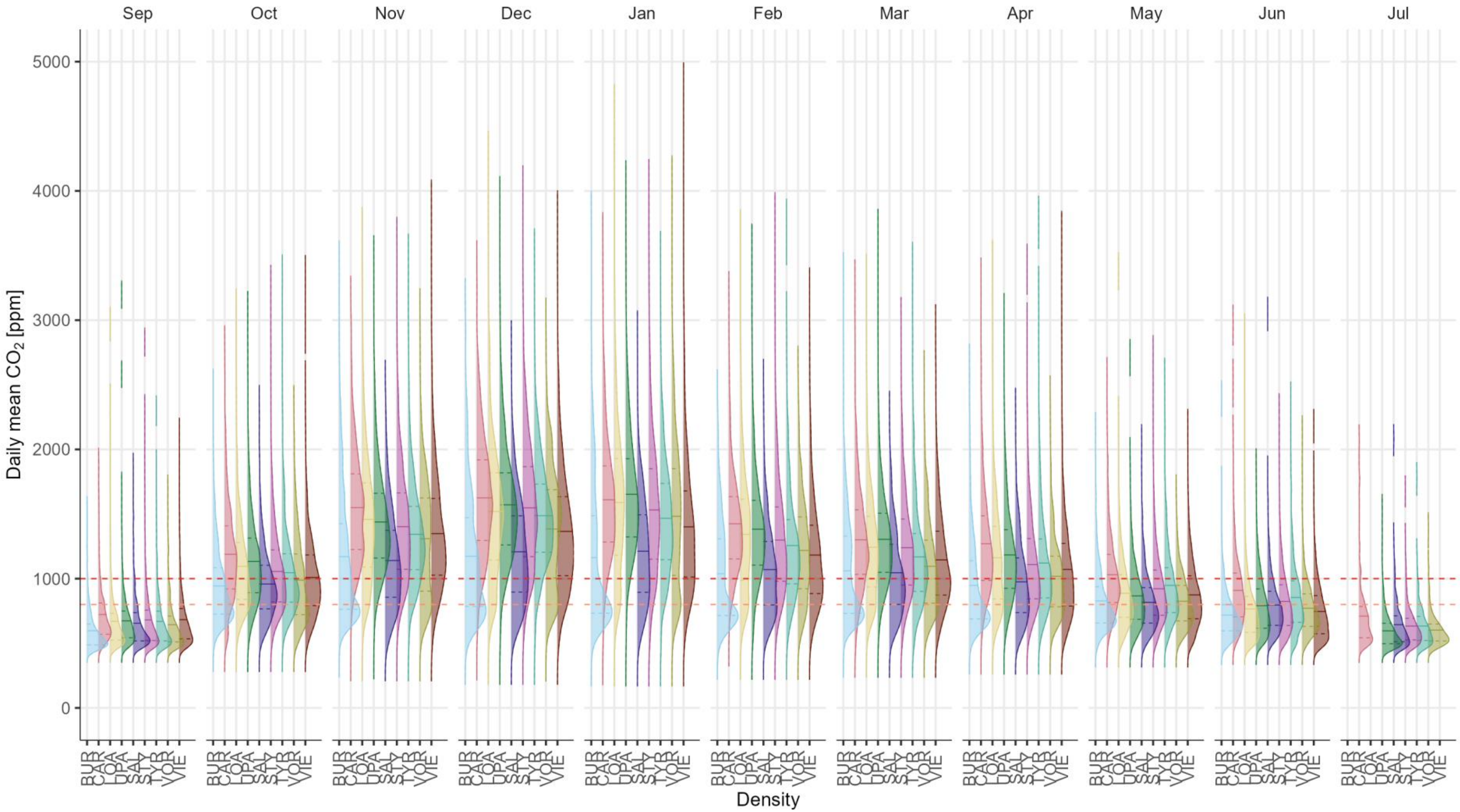


Figure A-31 Monthly distribution of daily mean CO_2 concentration in classrooms categorized by region, including CO_2 indoor compliance threshold (1000 ppm, dotted red line) and target threshold (800 ppm, dotted pink line). The solid line within each distribution indicates the mean, whereas the dashed lines mark the 25th and 75th percentiles.

Table A-13 Monthly statistics of daily mean CO_2 concentrations in classrooms categorized by area region and season, including frequency of CO_2 indoor threshold exceedances relative to 1000 ppm and 800 ppm thresholds. The frequencies in the last two columns refer to daily mean exceedances.

Month	Region	Min [ppm]	Max [ppm]	Percentile [ppm] 25.	50.	75.	IQR [ppm]	Mean [ppm]	Threshold exceedance >1000 ppm	>800 ppm
Sep	BUR	461	1512	487	545	648	161	597	3 %	10 %
	CAR	463	1886	570	660	811	241	723	9 %	27 %
	LOA	460	2992	524	607	732	208	670	7 %	17 %
	UPA	460	3197	543	629	749	206	674	6 %	19 %
	SAL	461	1850	518	588	737	219	655	6 %	18 %
	STY	461	2831	521	608	757	236	681	8 %	21 %
	TYR	461	2299	518	599	749	230	669	8 %	19 %
	VOR	460	1680	510	586	711	201	644	5 %	15 %
	VIE	460	2132	534	625	769	235	683	8 %	21 %
Oct	BUR	468	2420	726	868	1084	358	944	35 %	59 %
	CAR	475	2755	921	1149	1408	488	1188	67 %	87 %
	LOA	462	3061	840	1032	1280	440	1095	54 %	80 %
	UPA	464	3044	890	1082	1314	423	1133	61 %	85 %
	SAL	479	2299	766	912	1104	337	959	37 %	70 %
	STY	463	3245	820	997	1222	402	1056	50 %	78 %
	TYR	468	3326	818	970	1193	375	1046	46 %	77 %
	VOR	470	2294	722	922	1191	469	989	43 %	65 %
	VIE	464	3311	792	962	1183	392	1009	45 %	74 %
Nov	BUR	537	3326	763	1043	1426	663	1170	54 %	70 %
	CAR	484	3056	1225	1513	1811	586	1550	93 %	99 %
	LOA	469	3625	1091	1413	1741	650	1459	81 %	93 %
	UPA	502	3404	1160	1381	1660	501	1438	89 %	98 %
	SAL	487	2385	856	1089	1374	517	1140	60 %	80 %
	STY	479	3541	1073	1346	1663	590	1402	81 %	95 %
	TYR	478	3397	1070	1288	1559	489	1343	82 %	96 %
	VOR	471	2950	904	1295	1624	721	1309	70 %	85 %
	VIE	462	3833	1027	1278	1620	593	1349	77 %	92 %
Dec	BUR	490	2996	786	1068	1472	686	1174	55 %	72 %
	CAR	546	3303	1295	1595	1919	624	1625	93 %	98 %
	LOA	463	4184	1144	1485	1819	676	1520	83 %	93 %
	UPA	466	3831	1261	1523	1819	558	1571	93 %	98 %
	SAL	460	2680	897	1156	1487	590	1208	65 %	83 %
	STY	487	3907	1170	1496	1867	696	1548	86 %	96 %
	TYR	464	3400	1204	1449	1732	527	1487	90 %	98 %
	VOR	554	2845	1005	1408	1688	682	1384	75 %	88 %
	VIE	461	3721	1023	1305	1635	611	1366	77 %	92 %
Jan	BUR	510	3667	733	924	1487	754	1163	46 %	63 %
	CAR	527	3505	1283	1571	1872	589	1610	93 %	98 %
	LOA	466	4543	1182	1555	1929	747	1589	83 %	93 %
	UPA	480	3954	1323	1589	1928	605	1653	95 %	99 %
	SAL	472	2757	895	1181	1494	600	1212	65 %	83 %
	STY	463	3954	1151	1488	1850	699	1532	85 %	95 %
	TYR	464	3375	1147	1417	1737	590	1467	86 %	97 %
	VOR	492	3943	1025	1459	1851	826	1483	76 %	88 %
	VIE	469	4856	1013	1318	1679	666	1401	76 %	92 %

Continue in next page

Month	Region	Min [ppm]	Max [ppm]	Percentile [ppm]			IQR [ppm]	Mean [ppm]	Threshold exceedance	
	BUR	463	2338	715	929	1309	594	1038	45 %	58 %
	CAR	597	3104	1152	1373	1635	482	1425	90 %	98 %
	LOA	461	3621	987	1305	1614	627	1343	74 %	88 %
	UPA	464	3509	1105	1336	1606	501	1382	84 %	95 %
Feb	SAL	463	2422	797	1033	1288	491	1070	53 %	75 %
	STY	462	3748	980	1225	1555	575	1298	72 %	90 %
	TYR	474	3683	960	1190	1457	497	1256	72 %	89 %
	VOR	481	2523	922	1182	1478	556	1218	67 %	84 %
	VIE	461	3168	885	1112	1413	528	1183	62 %	84 %
	BUR	471	3266	732	941	1329	597	1060	47 %	62 %
	CAR	462	3215	1033	1248	1533	500	1301	77 %	92 %
	LOA	471	3284	936	1201	1484	548	1243	70 %	86 %
	UPA	468	3641	1049	1255	1507	458	1304	80 %	95 %
Mar	SAL	474	2204	801	986	1266	465	1046	48 %	75 %
	STY	461	2948	951	1183	1461	511	1240	69 %	89 %
	TYR	462	3364	901	1094	1349	448	1168	63 %	85 %
	VOR	468	2509	810	1031	1298	488	1096	54 %	77 %
	VIE	470	2896	873	1068	1368	494	1145	59 %	83 %
	BUR	489	2595	689	826	1139	451	948	35 %	53 %
	CAR	462	3259	986	1202	1486	500	1270	74 %	93 %
	LOA	462	3431	842	1102	1405	563	1162	59 %	79 %
	UPA	464	3015	925	1134	1379	454	1184	66 %	88 %
Apr	SAL	471	2256	737	921	1161	423	976	41 %	66 %
	STY	469	3394	844	1039	1310	466	1109	54 %	81 %
	TYR	478	3759	851	1038	1306	455	1121	56 %	81 %
	VOR	472	2334	783	971	1174	392	1018	46 %	73 %
	VIE	461	3650	788	998	1273	485	1071	50 %	73 %
	BUR	460	2123	656	755	937	281	828	20 %	42 %
	CAR	460	2556	815	975	1188	372	1031	46 %	77 %
	LOA	462	3379	701	836	1031	330	887	28 %	57 %
	UPA	460	2712	686	826	996	310	866	25 %	55 %
May	SAL	460	2033	656	772	931	275	817	18 %	44 %
	STY	462	2740	717	864	1067	350	922	32 %	61 %
	TYR	461	2554	738	884	1084	347	948	35 %	64 %
	VOR	468	1640	673	787	947	275	825	19 %	48 %
	VIE	461	2172	690	833	1023	333	875	27 %	56 %
	BUR	462	2394	596	674	798	202	718	8 %	24 %
	CAR	467	2984	705	851	1043	339	909	30 %	59 %
	LOA	460	2932	585	710	863	278	766	14 %	33 %
	UPA	460	1883	617	746	921	304	791	17 %	42 %
Jun	SAL	464	3055	639	753	902	263	796	15 %	40 %
	STY	460	2314	638	772	953	315	824	20 %	45 %
	TYR	461	2394	662	801	984	321	854	23 %	50 %
	VOR	465	2121	631	732	882	251	771	12 %	36 %
	VIE	460	2185	574	699	869	295	746	13 %	34 %
	BUR	-	-	-	-	-	-	-	-	-
	CAR	463	2069	543	651	785	242	711	10 %	21 %
	LOA	-	-	-	-	-	-	-	-	-
	UPA	460	1533	496	559	655	159	596	1 %	8 %
Jul	SAL	460	2084	512	590	713	200	644	6 %	16 %
	STY	460	1676	526	592	693	167	633	4 %	12 %
	TYR	460	1773	521	597	708	187	634	3 %	12 %
	VOR	464	1377	518	568	648	131	602	1 %	7 %
	VIE	-	-	-	-	-	-	-	-	-

C.1.3. Outdoor air pollutants

Table A-14 Ozone peak season analysis (6-month running mean by month)

Month	Min [μg/m³]	Max [μg/m³]	Percentile [μg/m³] 25.	50.	75.	IQR [μg/m³]	Mean [μg/m³]	Percentage of UBA stations above the WHO limit value for O_3 peak pollution of 60 μg/m³
Sep	85.1	103.2	92.9	96.4	99.5	6.6	95.7	100.0%
Oct	77.1	99.2	88.6	92.3	96.6	8.0	91.9	100.0%
Nov	68.0	93.6	81.4	86.3	90.8	9.4	85.3	100.0%
Dec	52.2	86.6	69.5	75.5	80.9	11.5	74.1	90.7%
Jan	43.6	83.0	61.6	66.5	73.1	11.5	66.6	81.4%
Feb	39.3	77.8	55.6	60.9	67.2	11.6	61.0	55.8%
Mar	37.8	74.1	52.2	57.4	63.5	11.3	58.4	46.5%
Apr	46.2	80.0	58.6	62.3	67.8	9.3	63.3	67.4%
May	56.2	90.0	67.4	71.3	75.2	7.8	71.2	95.2%
Jun	68.4	91.4	76.7	79.4	83.5	6.8	80.0	100.0%
Jul	77.3	94.9	84.0	87.5	91.7	7.7	87.6	100.0%

C.1.4. Analysis of matched pairs (C vs T)

To determine if the CTD and CTO values can undergo a parametric paired t-test, data normality must be checked first. At this aim the Shapiro-Wilk test is applied to the CTD and CTO values at the monthly, seasonal and yearly level. The Shapiro-Wilk test compares the study data to a perfectly normal distribution and returns the p-value as test output. A p-value smaller than 0.001 indicate that data are not normally distributed. As reported in Tbl. XX, there is enough statistical evidence that CTD and CTO values derived from daily mean CO_2 concentrations deviate from normality. The same conclusions apply to the CTD and CTO values obtained from hourly mean CO_2 levels, as all Shapiro-Wilk test p-values are smaller than 0.001.

Tbl. A-15. Results of the Shapiro-Wilk test for normality applied to values for the two metrics CTD and CTO, derived from daily mean CO_2 concentrations.

Table A-15 Result of Shapiro-Wilk test

Period	p-value CTD metric	p-value CTO metric
Sep	< 0.001	< 0.001
Oct	< 0.001	< 0.001
Nov	< 0.001	< 0.001
Dec	< 0.001	< 0.001
Jan	< 0.001	< 0.001
Feb	< 0.001	< 0.001
Mar	< 0.001	< 0.001
Apr	< 0.001	< 0.001
May	< 0.001	< 0.001
Jun	< 0.001	< 0.001
Jul	< 0.001	< 0.001
Summer '23	< 0.001	< 0.001
Autumn	< 0.001	< 0.001
Winter	< 0.001	< 0.001
Spring	< 0.001	< 0.001
Summer '24	< 0.001	< 0.001
Year	< 0.001	< 0.001

C.2. Survey results

C.2.1. School directors' survey

C.2.1.1. First survey results

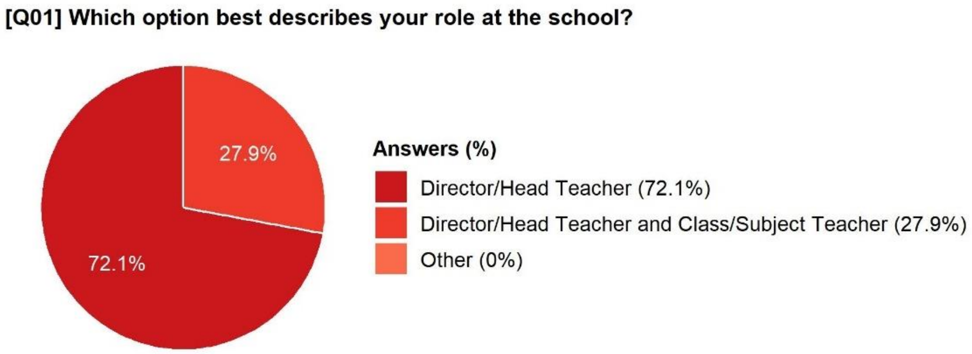


Figure A-32 Q1 Results from Question 1 in the first survey of school directors.

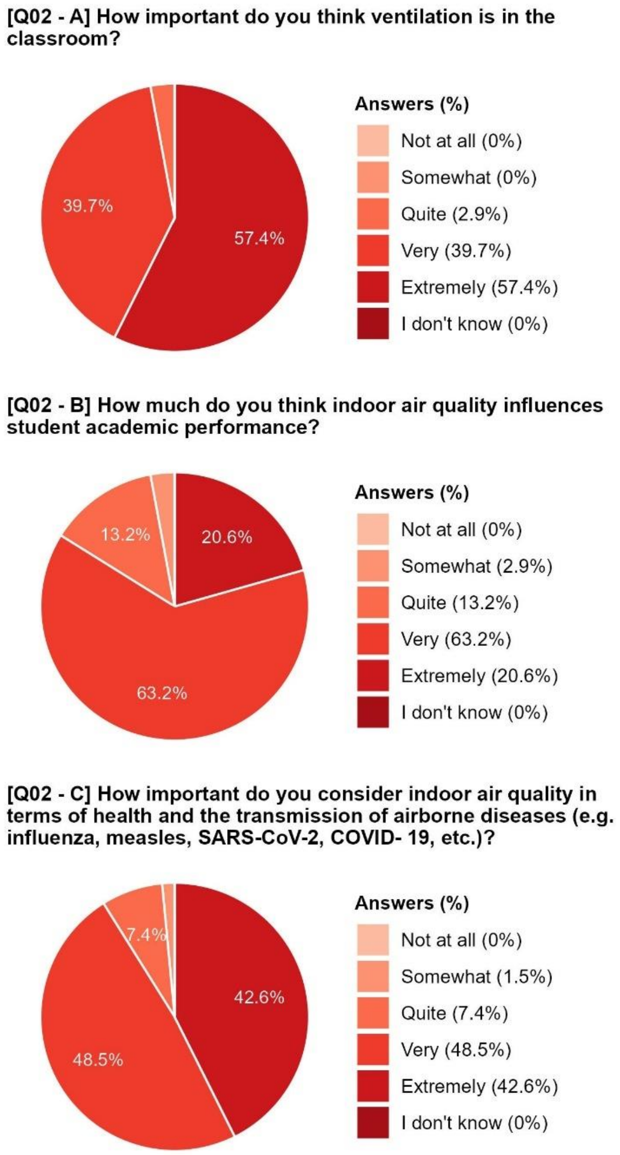


Figure A-33 Question 2, 2A, 2B, 2C results from the first school directors' survey.

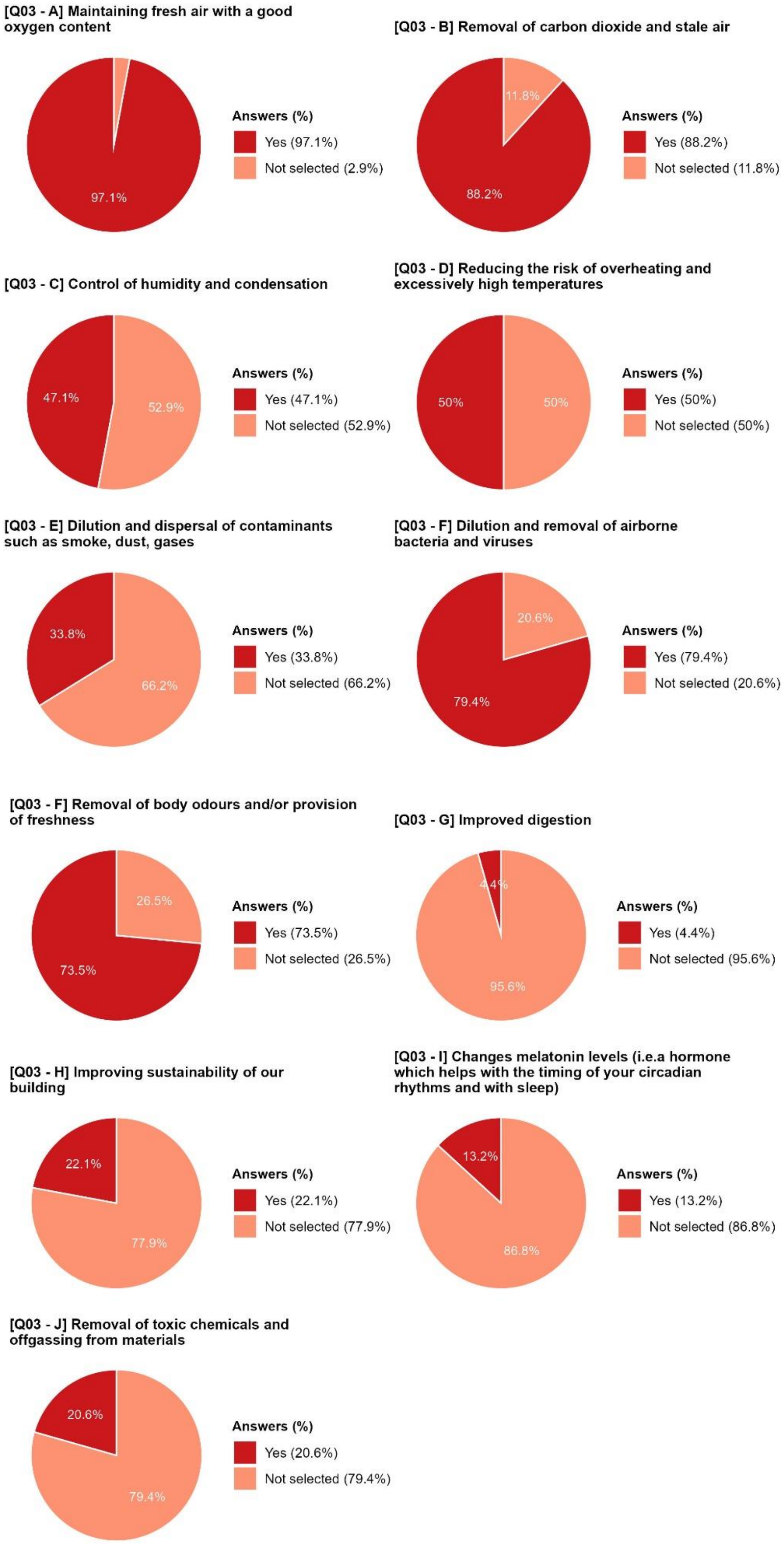
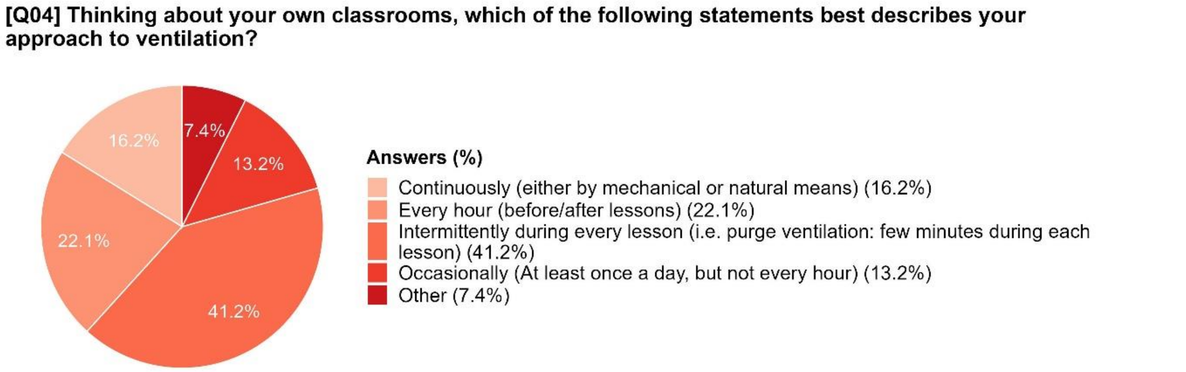
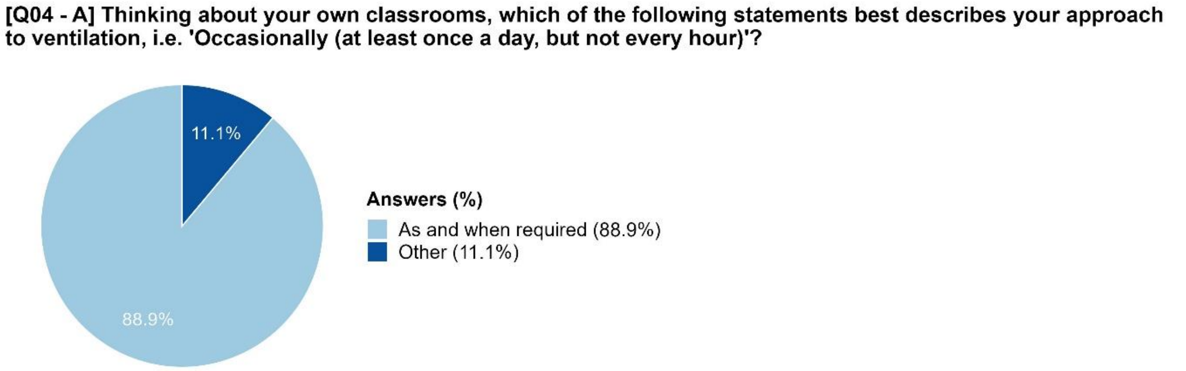


Figure A-34 Findings for Question 3 in the school directors' first survey.





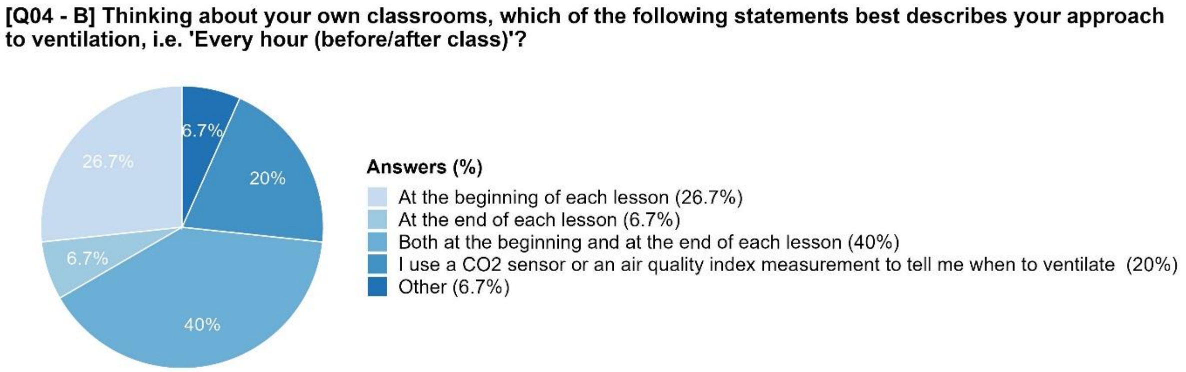


Figure A-35 Answers to question 4, 4A, and 4B in the school director's first survey.

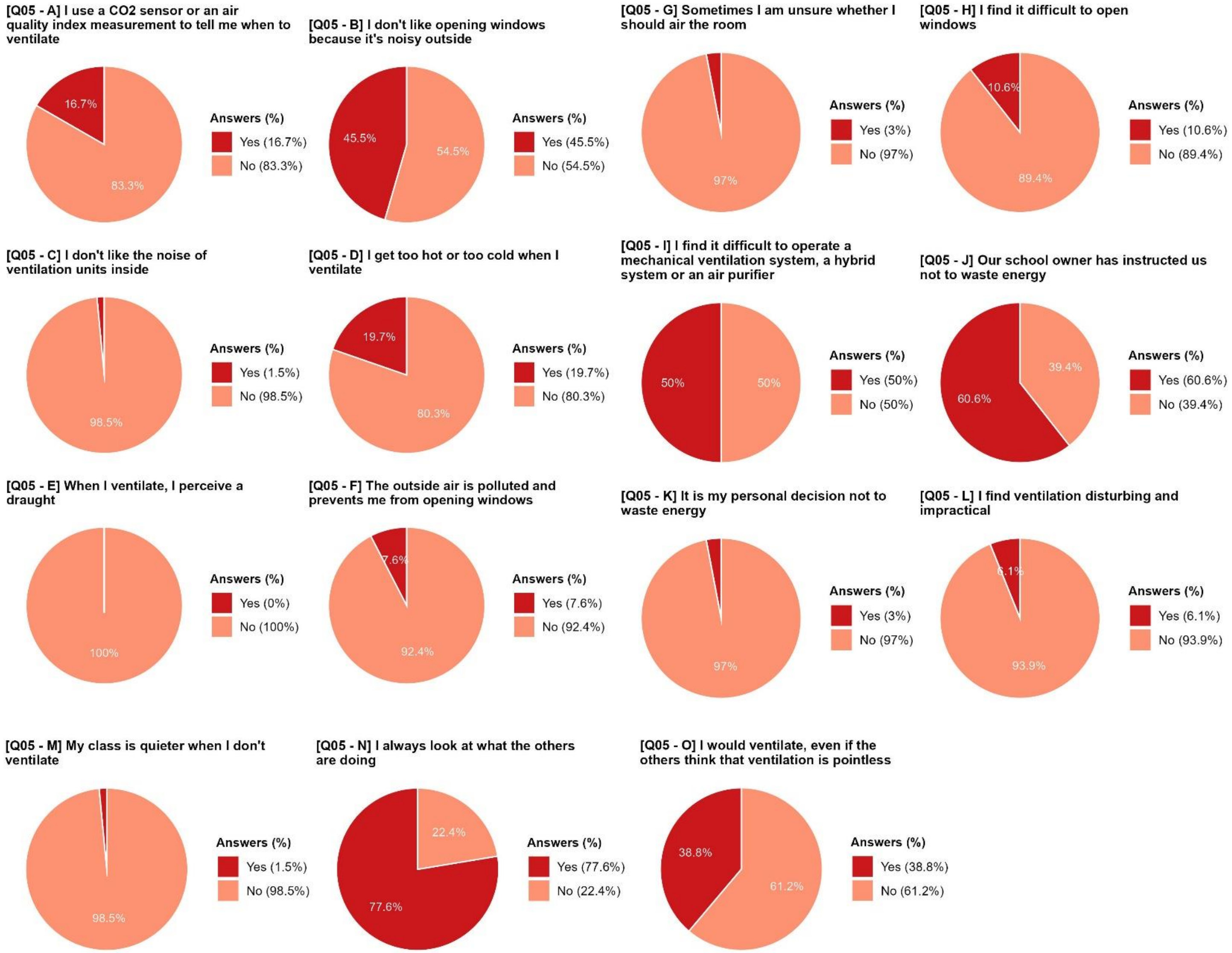


Figure A-36 Responses from the first school directors' survey, Question 5.

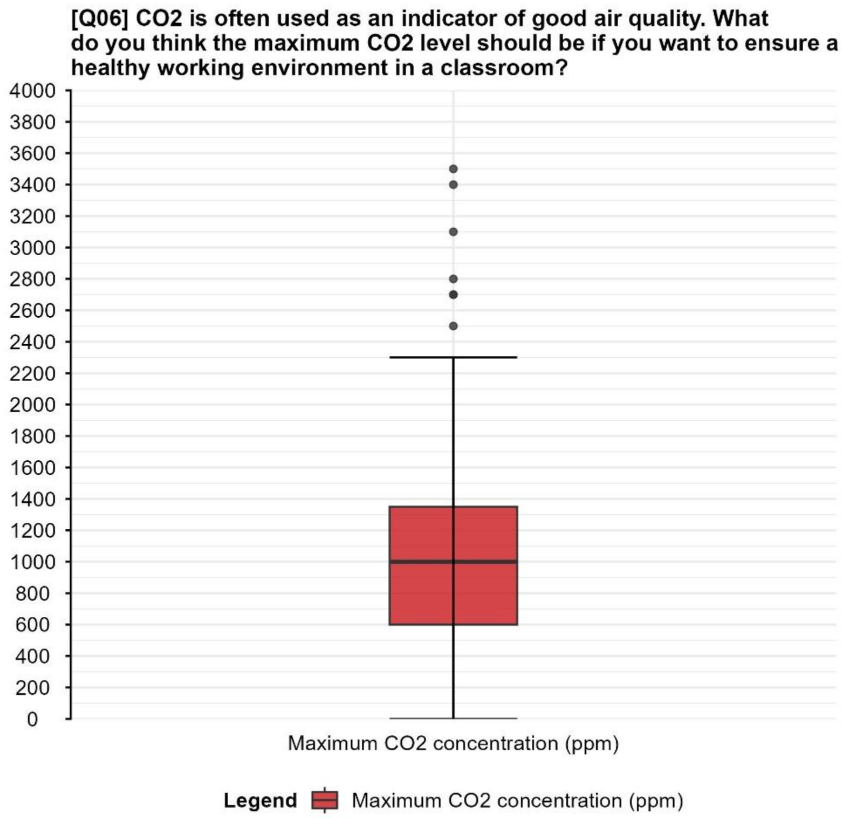
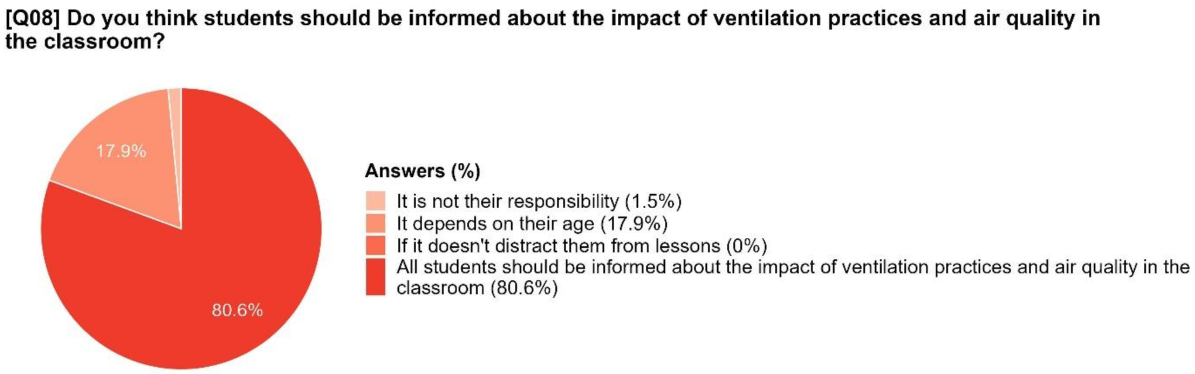


Figure A-44 Findings for Question 6 in the school directors' first survey.



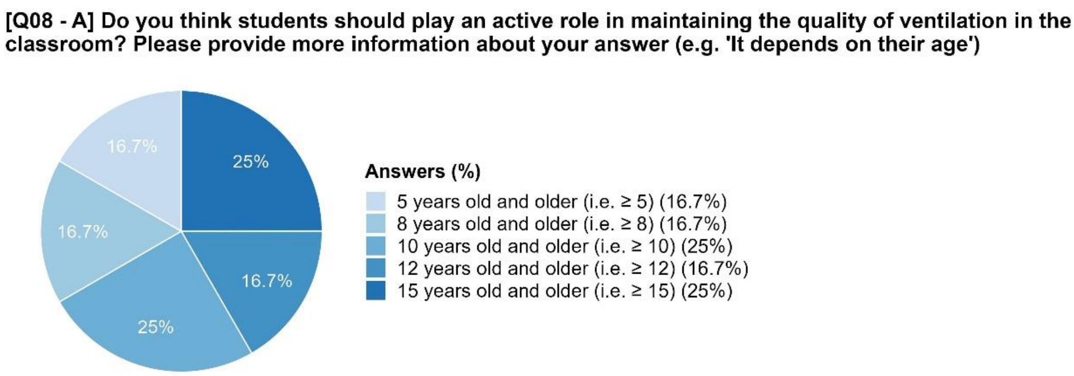


Figure A-37 Results from Question 8 and 8A in the first school directors' survey.

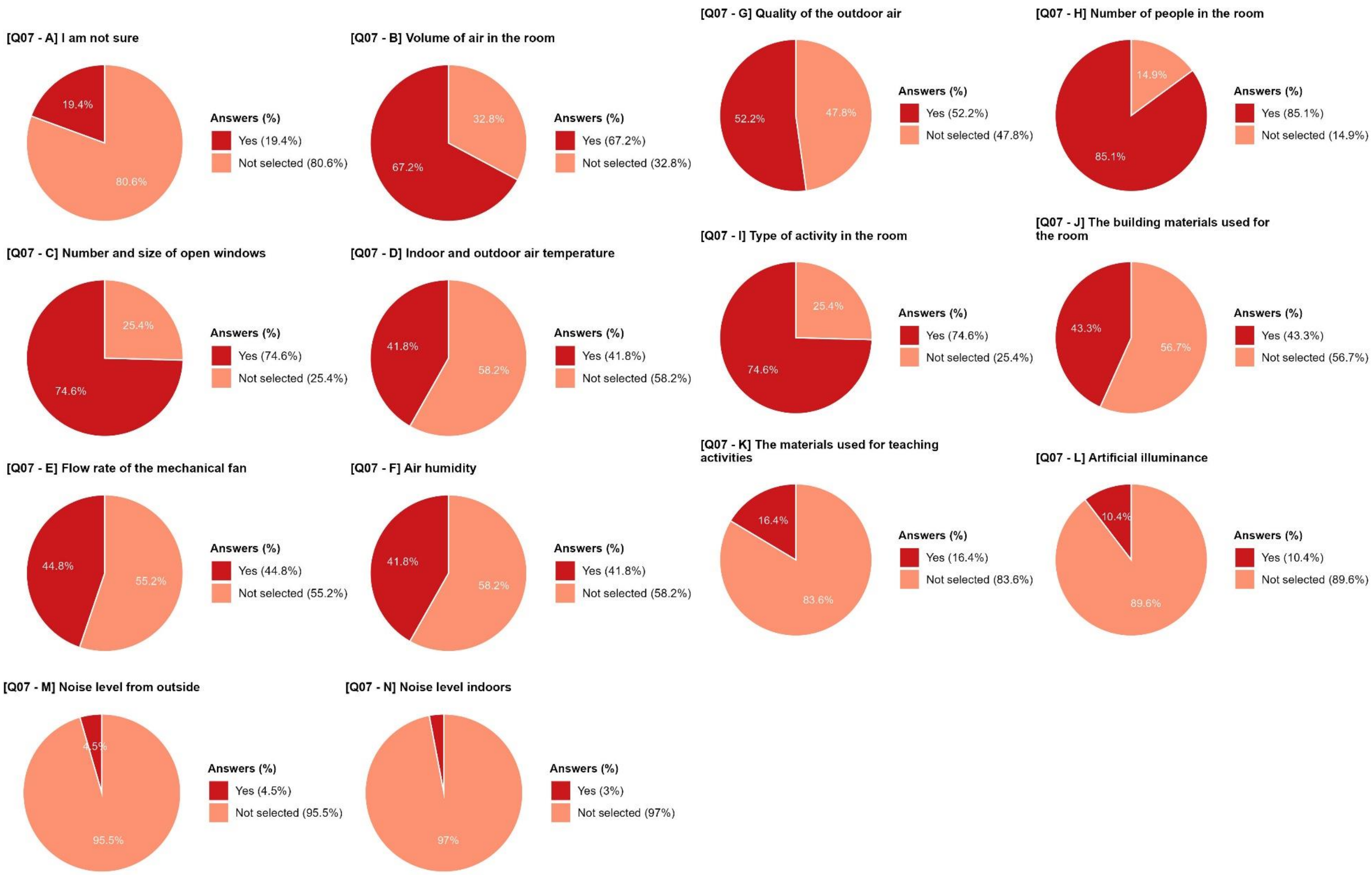
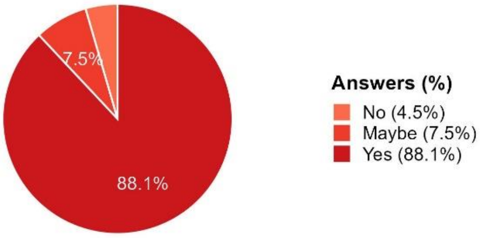
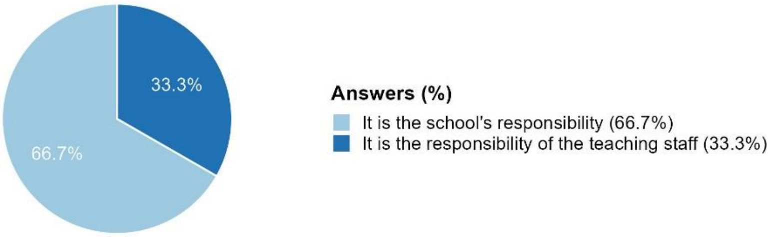


Figure A-38 Summary of responses to Question 7 from the first school directors' survey.

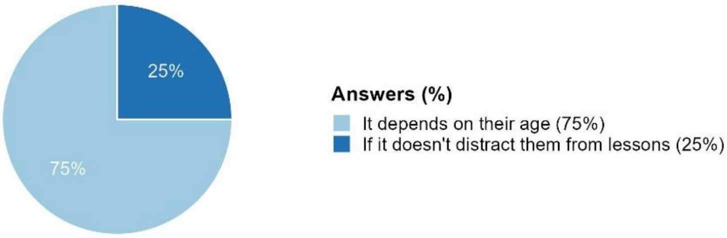
[Q09] Do you think students should play an active role in maintaining ventilation quality in the classroom?



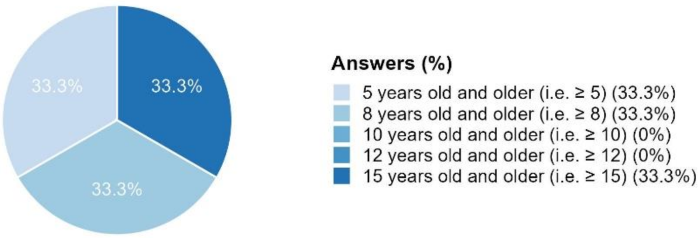
[Q09 - A] Please provide more information about your answer (e.g. 'No')



[Q09 - B] Please provide more information about your answer (e.g. 'Maybe')



[Q09 - B - 1] Please provide more information about your answer (e.g. 'Maybe, it depends on their age'):



[Q09 - C] Please provide more information about your answer (e.g. 'Yes')

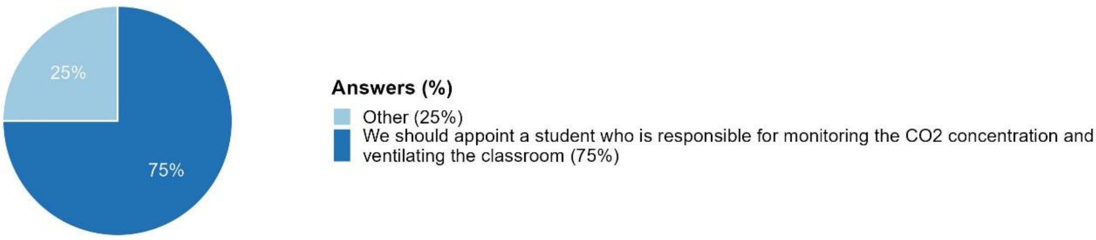


Figure A-39 Question 9, 9A, 9B, 9C results from the first school directors' survey.

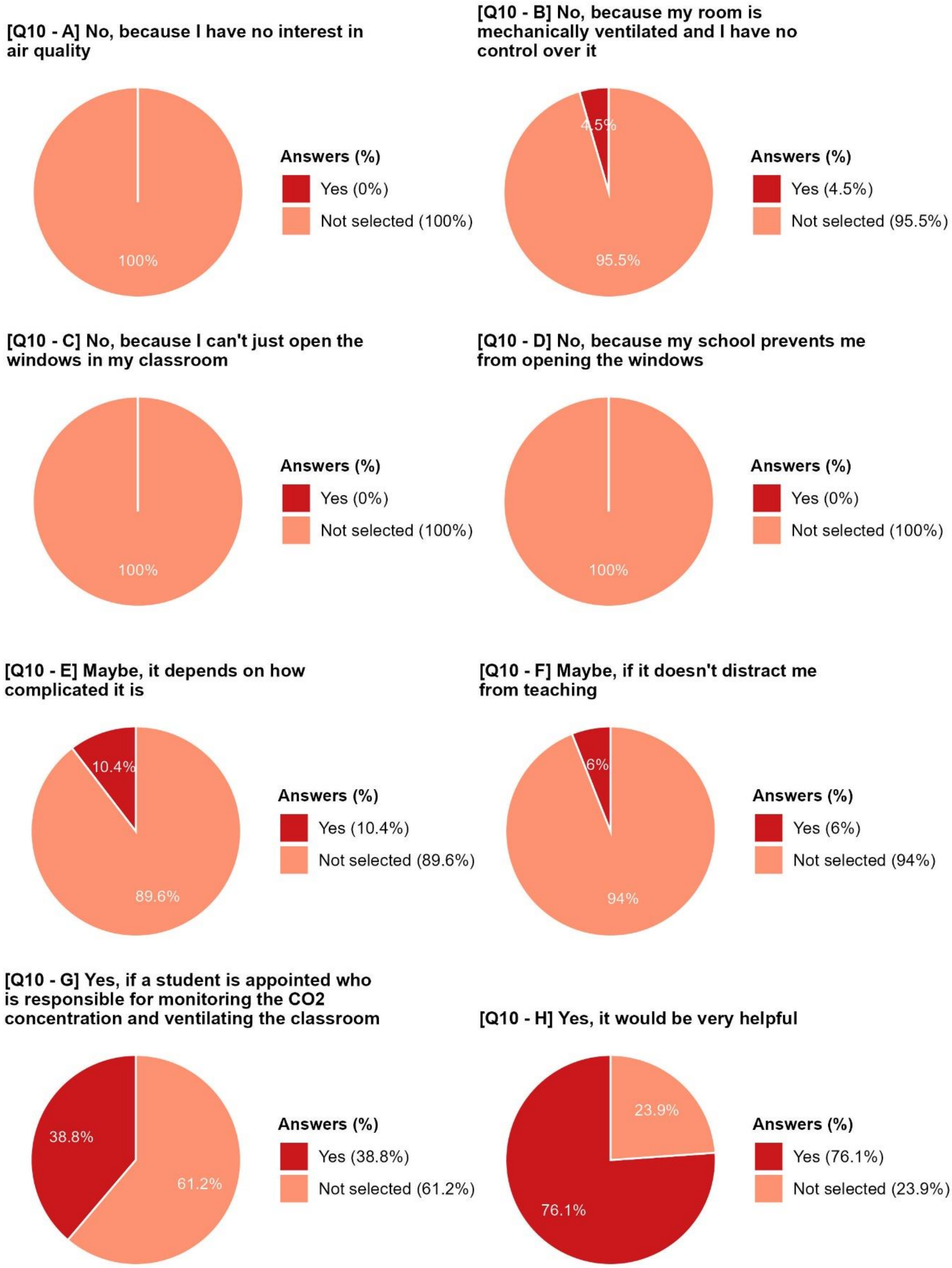


Figure A-40 Insights from Question 10 of the first survey conducted for the school directors.

C.2.1.2. Second survey results

The completed results of the survey are presented in Figure A-49 to Figure A-55.

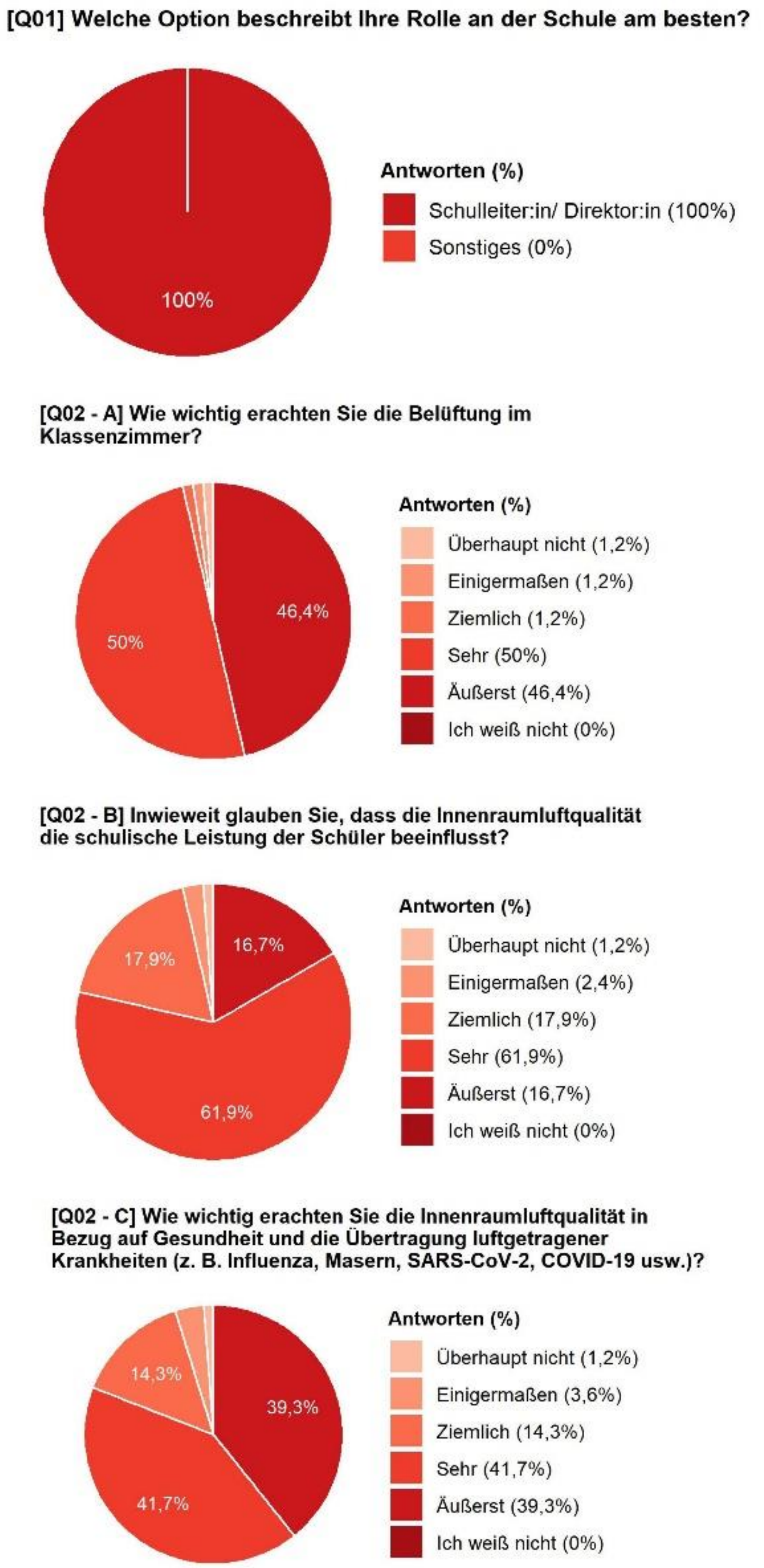


Figure A-41 Summary of responses to Question 1, 2, 2A, 2B, 2C from the second school directors' survey.

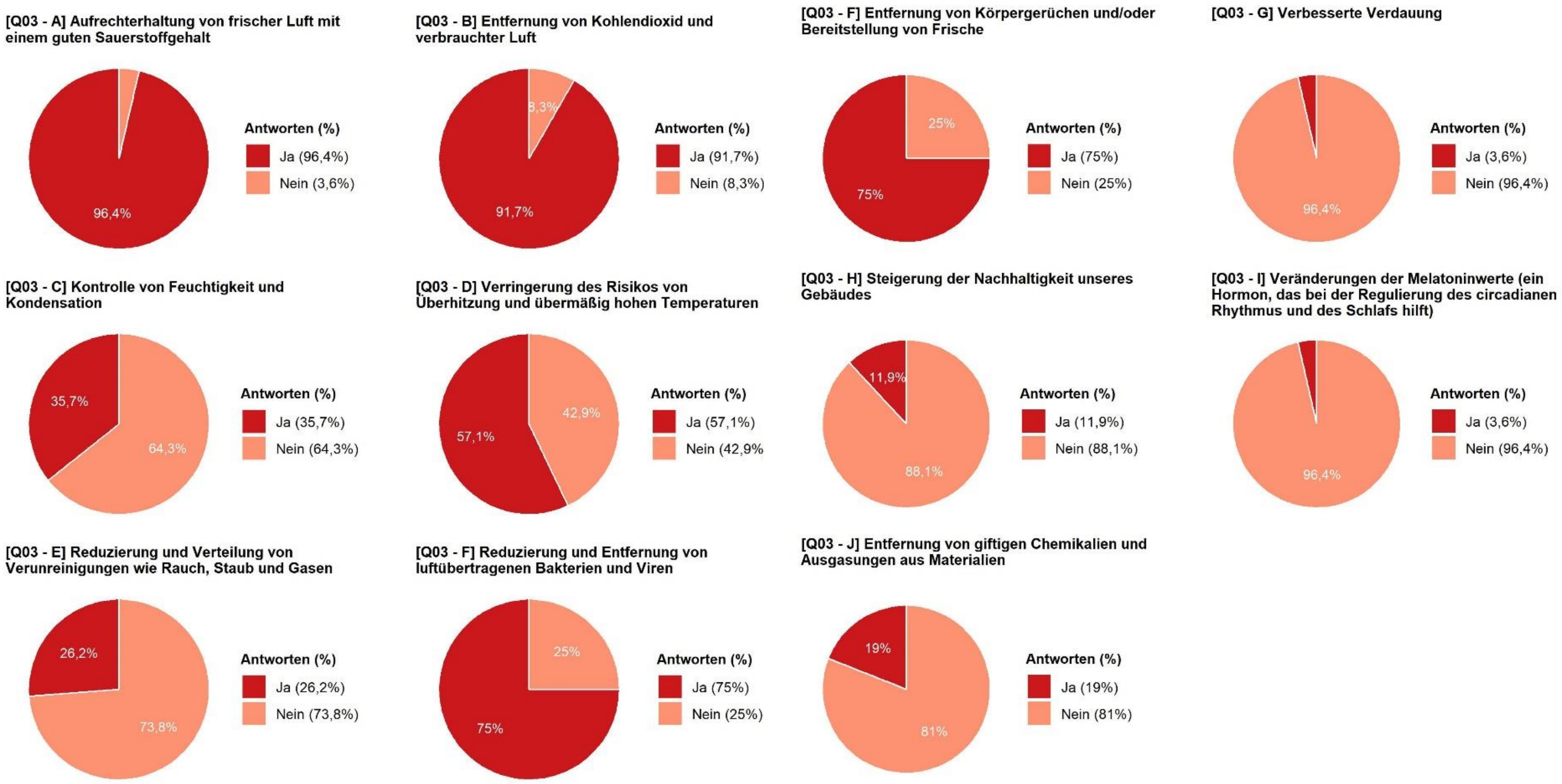
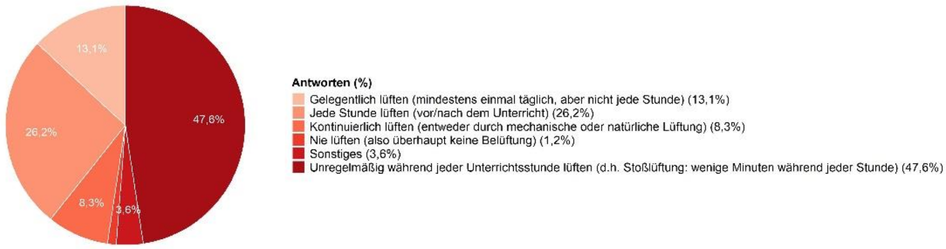
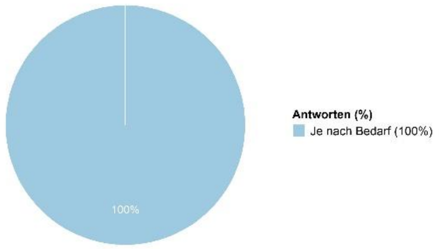


Figure A-42 Findings for Question 1 in the school directors' second survey.

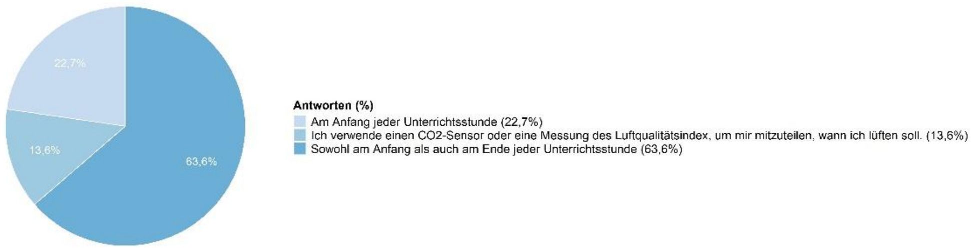
[Q04] Wenn Sie an Ihre eigenen Klassenzimmer denken, welche der folgenden Aussagen beschreibt Ihren Umgang mit dem Thema Belüftung am besten?



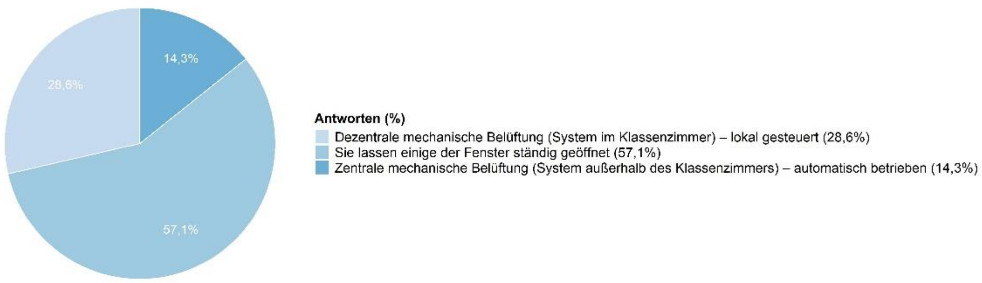
[Q04 - A] Wenn Sie an Ihre eigenen Klassenzimmer denken, welche der folgenden Aussagen beschreibt Ihren Umgang mit dem Thema Belüftung am besten, d.h. 'Gelegentlich (mindestens einmal täglich, aber nicht jede Stunde)'?



[Q04 - B] Wenn Sie an Ihre eigenen Klassenzimmer denken, welche der folgenden Aussagen beschreibt Ihren Umgang mit dem Thema Belüftung am besten, d.h. 'Jede Stunde (vor/nach dem Unterricht)'?



[Q04 - C] Wenn Sie an Ihre eigenen Klassenzimmer denken, welche der folgenden Aussagen beschreibt Ihren Umgang mit dem Thema Belüftung am besten, d.h. 'Kontinuierlich (entweder durch mechanische oder natürliche Mittel)'?



[Q04 - D] Wenn Sie an Ihre eigenen Klassenzimmer denken, welche der folgenden Aussagen beschreibt Ihren Umgang mit dem Thema Belüftung am besten, 'Andere Methode (z.B. tragbarer Filter oder Hybridmethode)'?

Figure A-43 Insights from Question 4, 4A, 4B, 4C, 4D of the second school directors' survey.

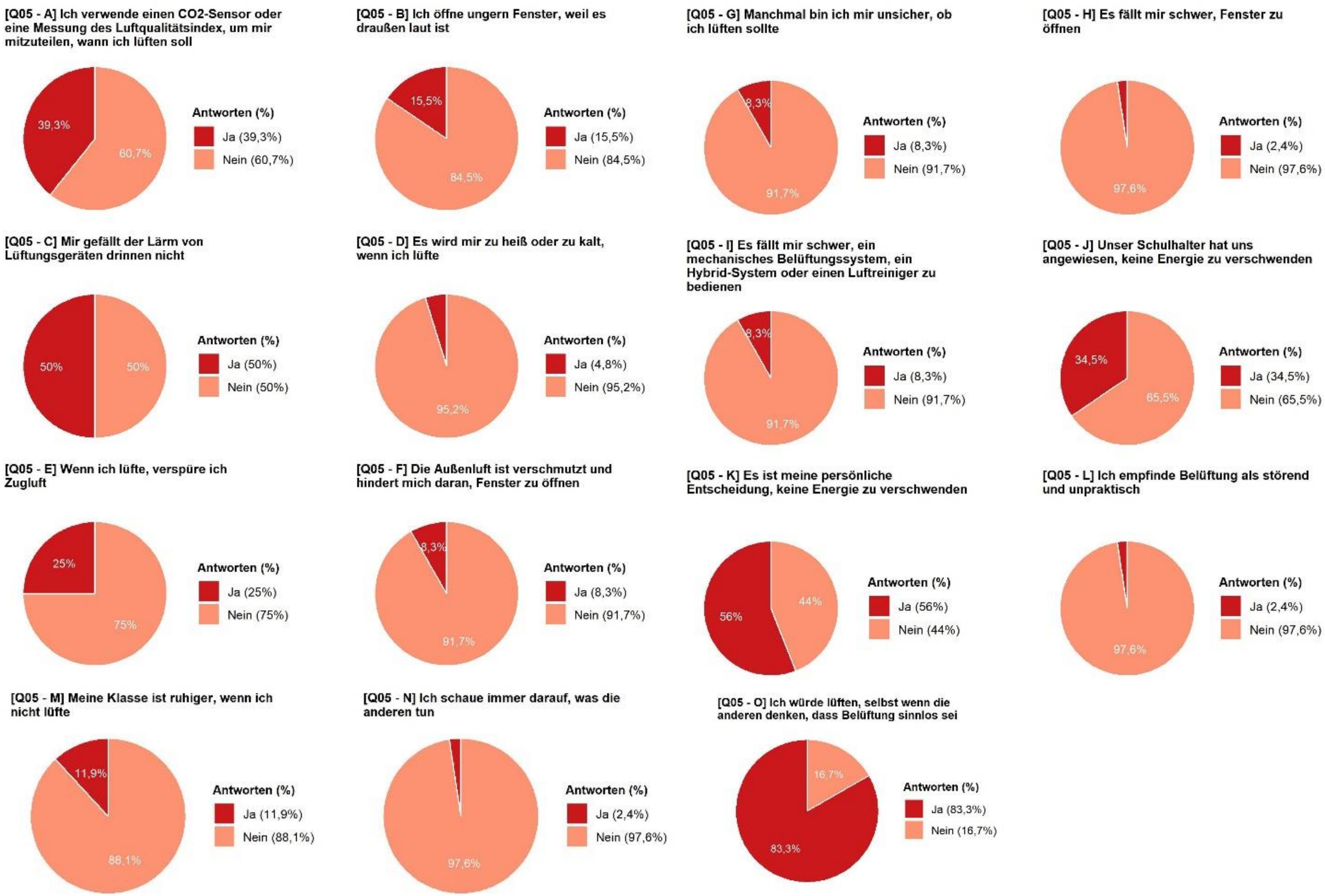


Figure A-44 Responses to the second school directors' survey, Question 5

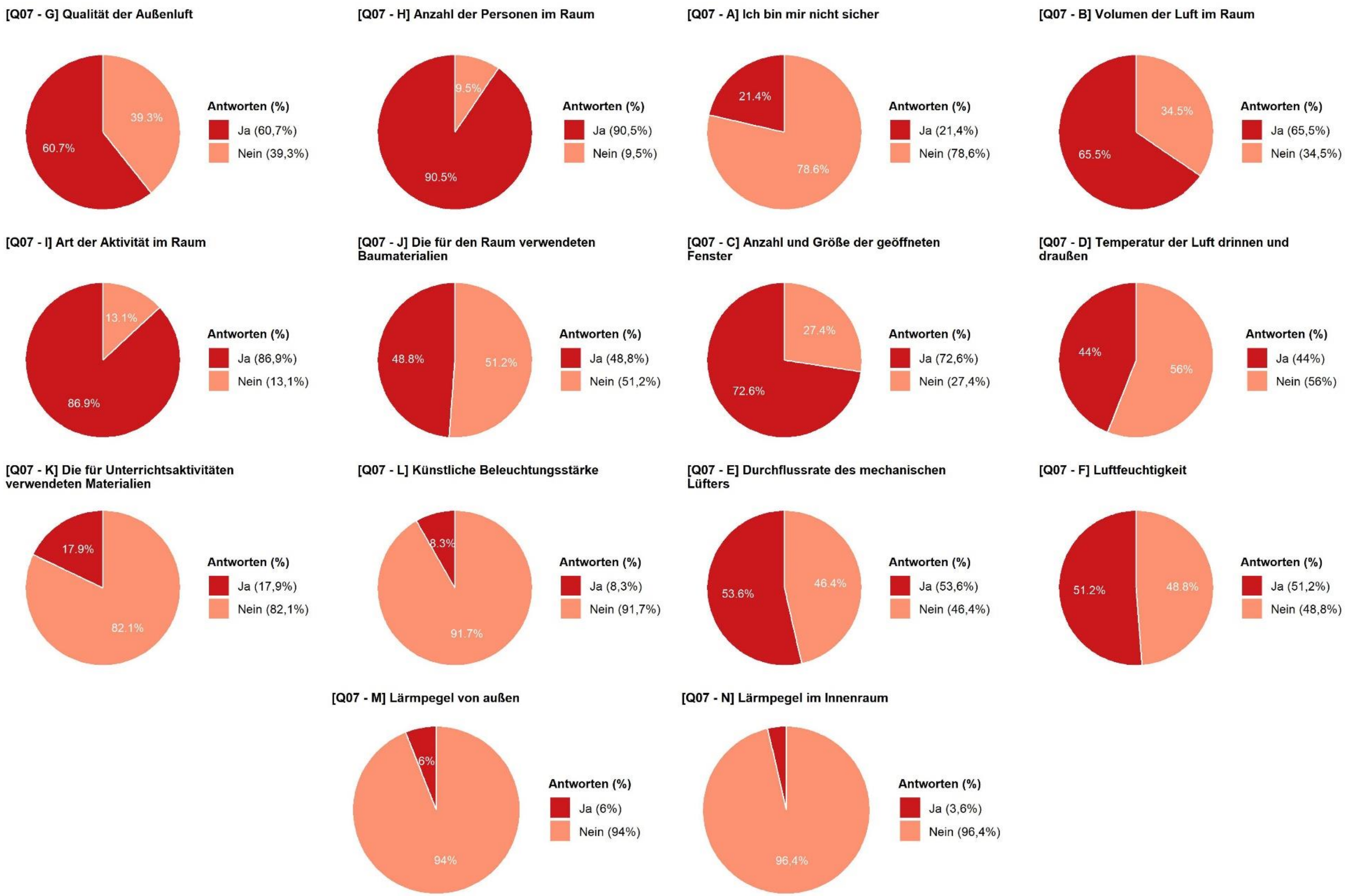
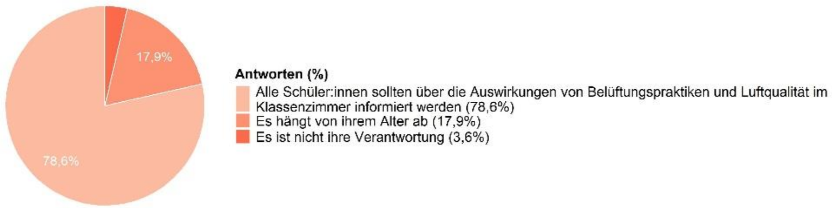
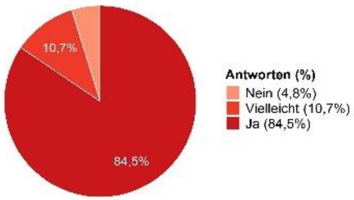


Figure A-45 Responses collected from school directors for Question 7 in the second survey.

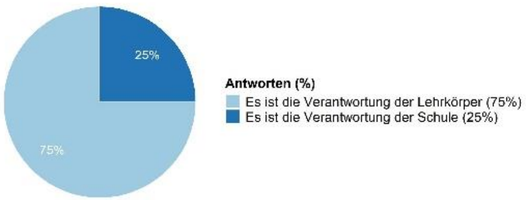
[Q08] Glauben Sie, dass Schüler:innen über die Auswirkungen von Belüftungspraktiken und Luftqualität im Klassenzimmer informiert werden sollten?



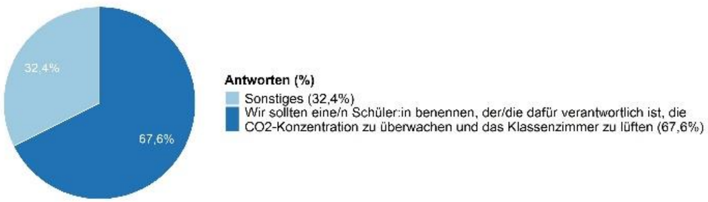
[Q09] Glauben Sie, dass Schüler:innen eine aktive Rolle bei der Aufrechterhaltung der Belüftungsqualität im Klassenzimmer spielen sollten?



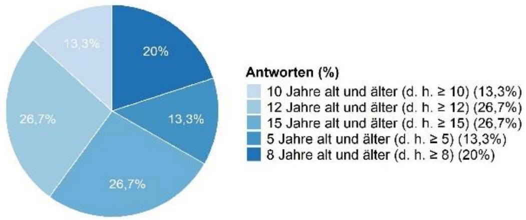
[Q09 - A] Bitte geben Sie mehr Informationen zu Ihrer Antwort an (z.B. 'Nein')



[Q09 - C] Bitte geben Sie mehr Informationen zu Ihrer Antwort an (z.B. ‚'Ja')



[Q08 - A] Bitte geben sie mehr Informationen zu Ihrer Antwort an (z.B. 'Es hängt von ihrem Alter ab')



[Q09 - B] Bitte geben Sie mehr Informationen zu Ihrer Antwort an (z.B. ‚'Vielleicht')

[Q09 - B - 1] Bitte geben Sie mehr Informationen zu Ihrer Antwort an (z.B. ‚'Vielleicht, es hängt von ihrem Alter ab'):

Figure A-46 Findings for Question 8, 8A, 9, 9A, 9B, and 9C in the school directors' second survey.

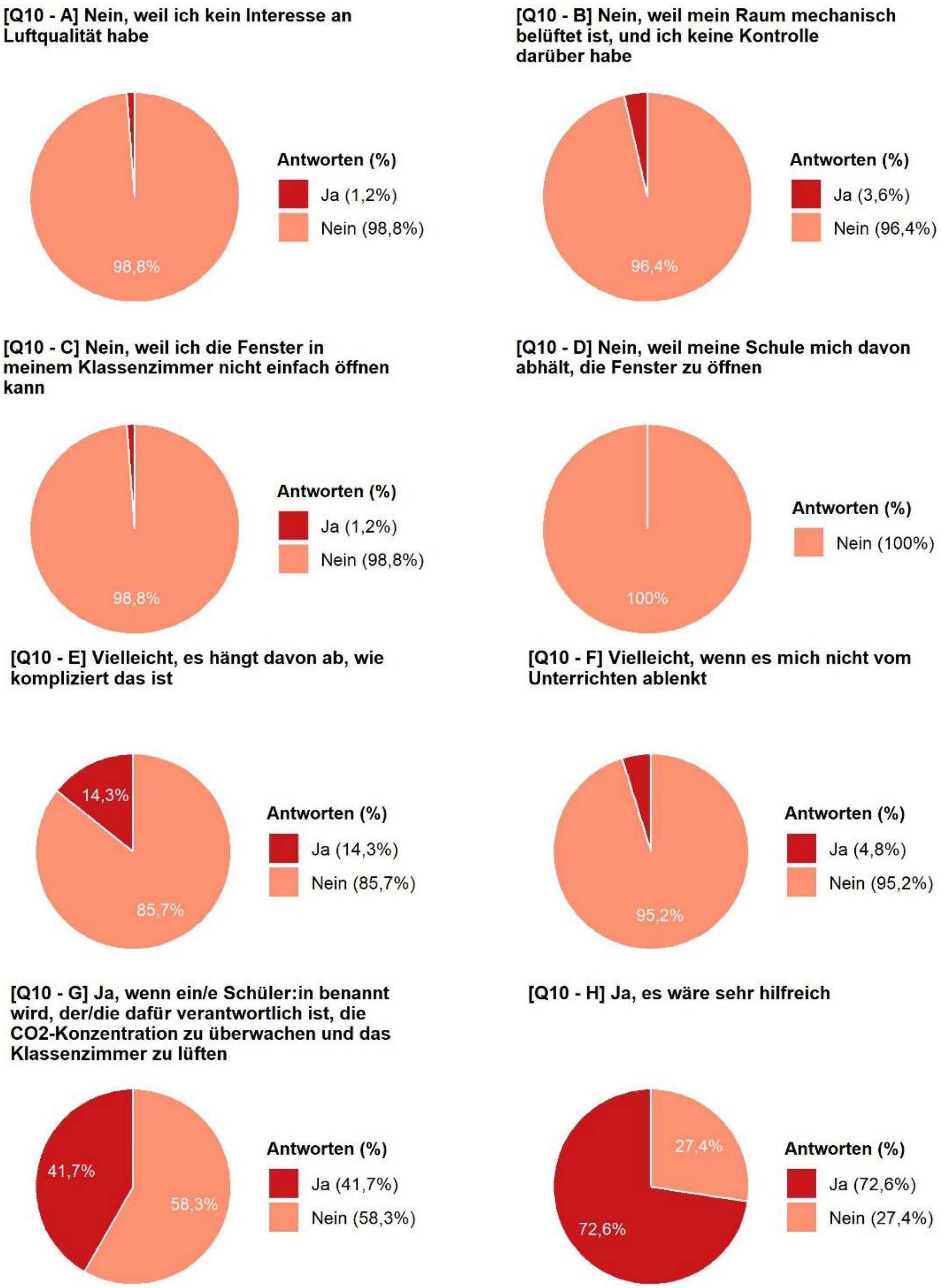


Figure A-47 Results from Question 10 in the second school directors' survey.

C.2.2. Teachers' survey result

C.2.2.1. First survey results

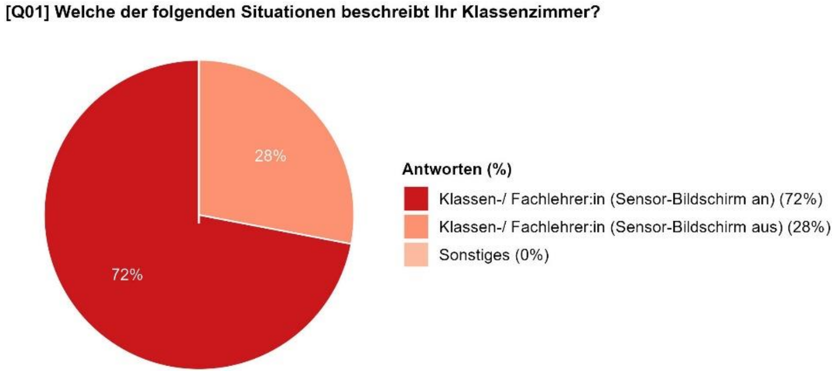


Figure A-48 Respondents from the first of the teacher survey (winter period)

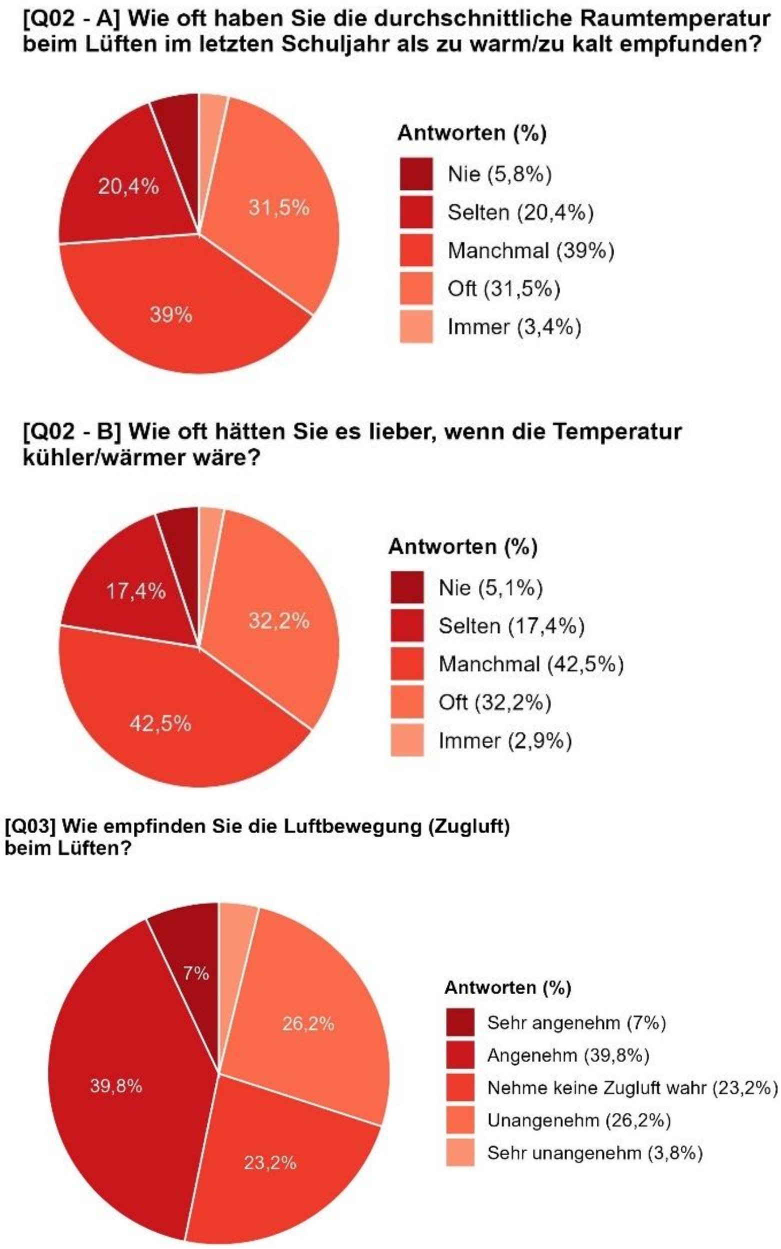
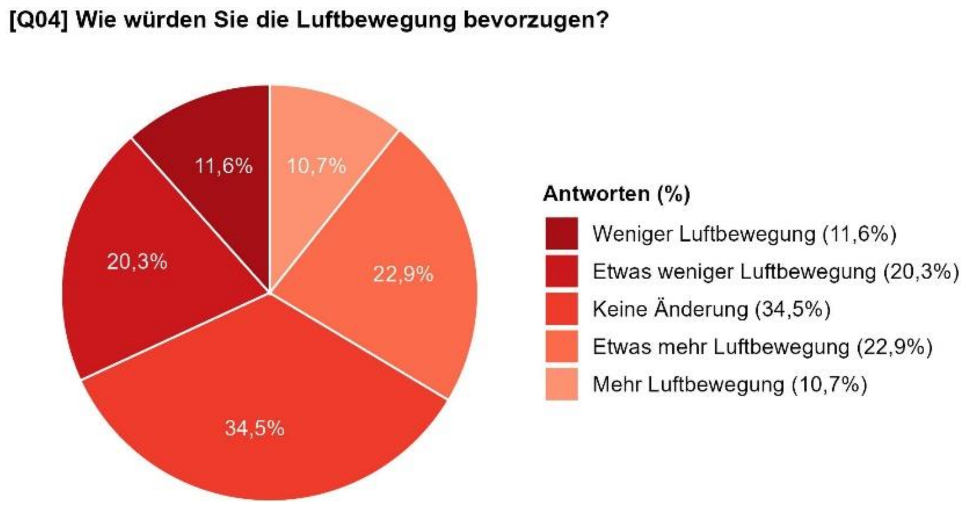
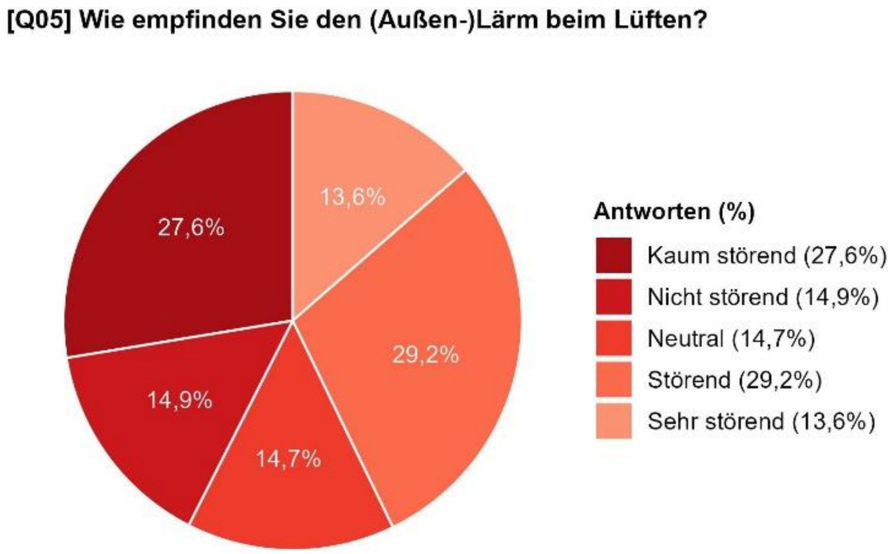


Figure A-49 Summary of Question 2 and 3 results from the first teacher survey conducted in winter.





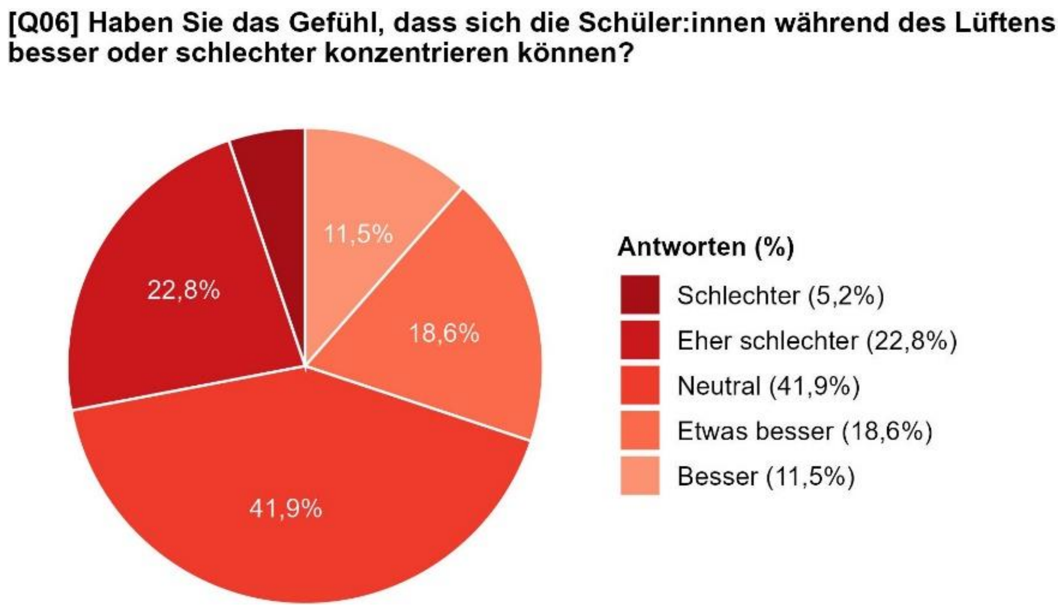


Figure A-50 Feedback on Question 4, 5, 6 from the first teacher survey in the winter.

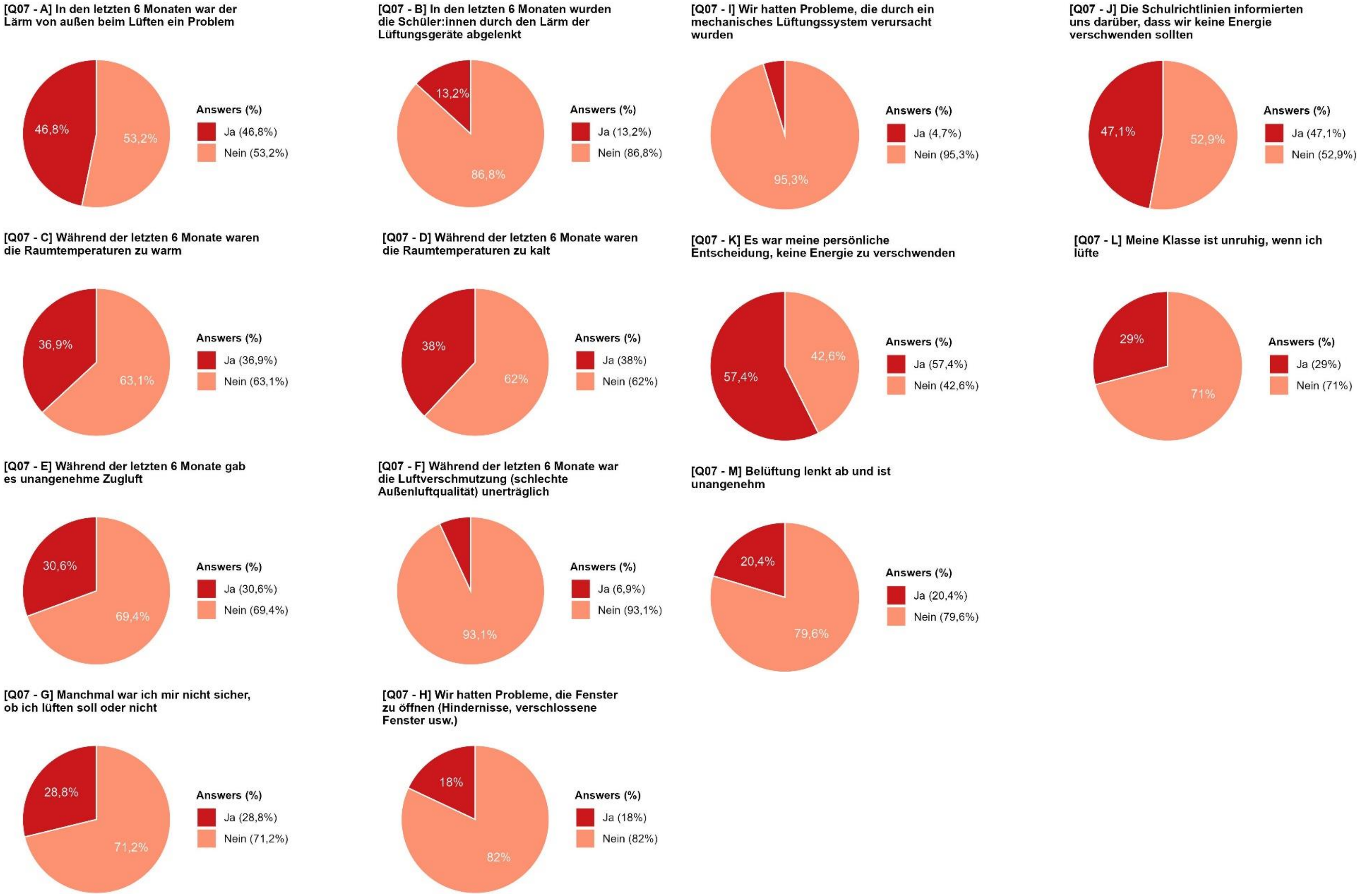


Figure A-59 Data from Question 7 in the first teacher survey held during winter.

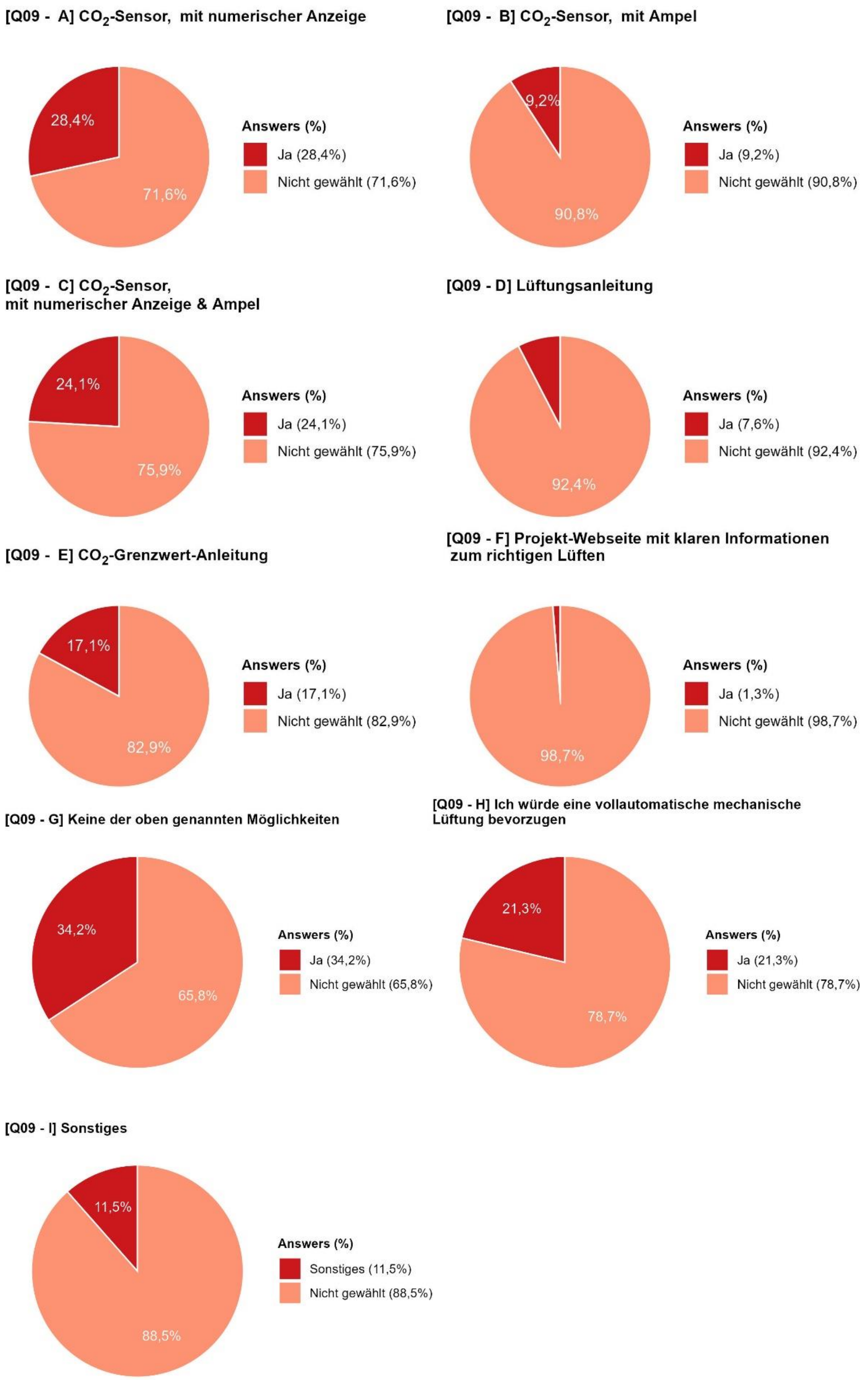


Figure A-60 Findings for Question 9 in the first teacher survey (winter period).

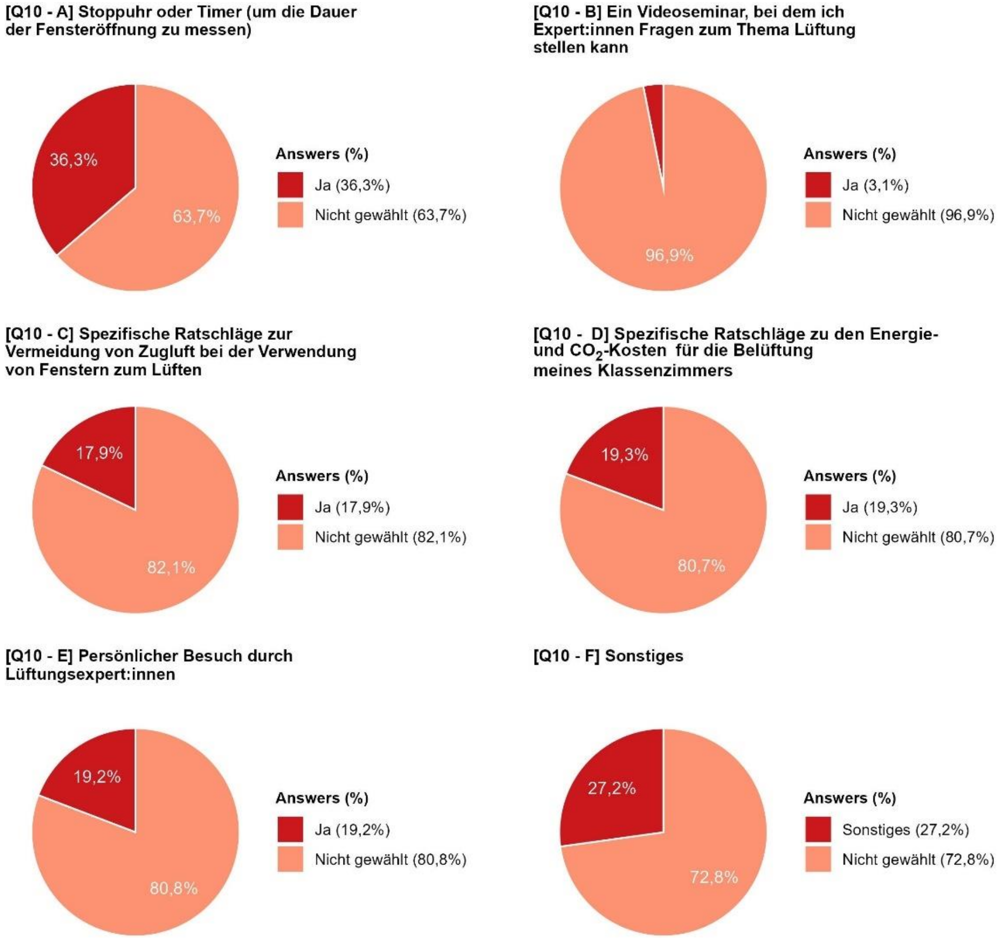


Figure A 51 Results from Question 10 in the first teacher survey conducted in winter.

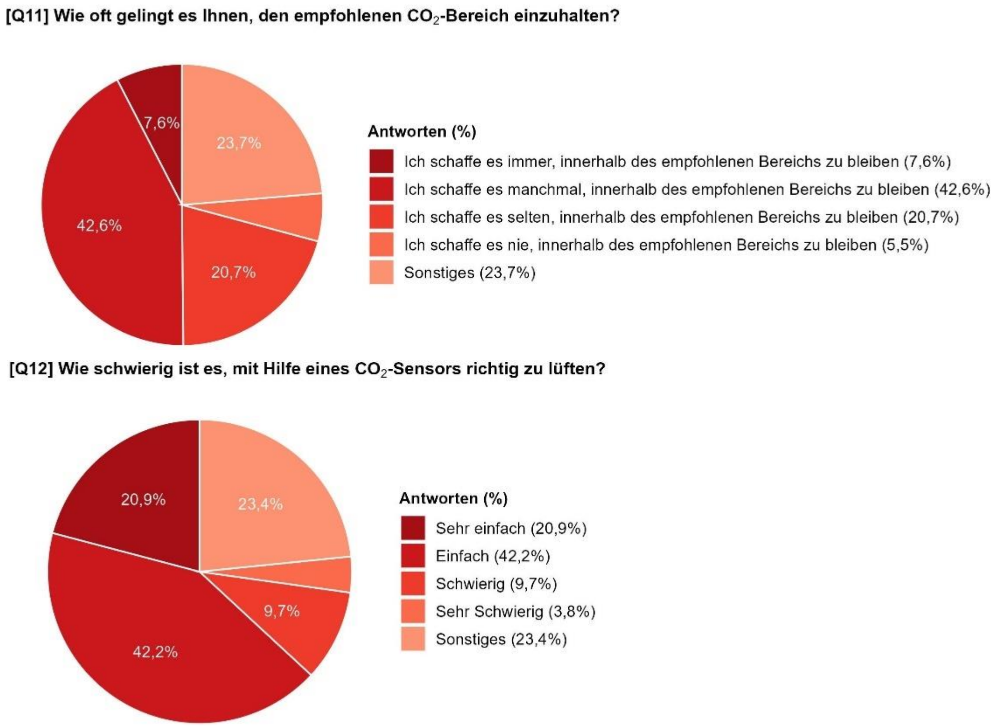


Figure A-52 Summary of Question 11 and 12 results from the first teacher survey conducted in winter.

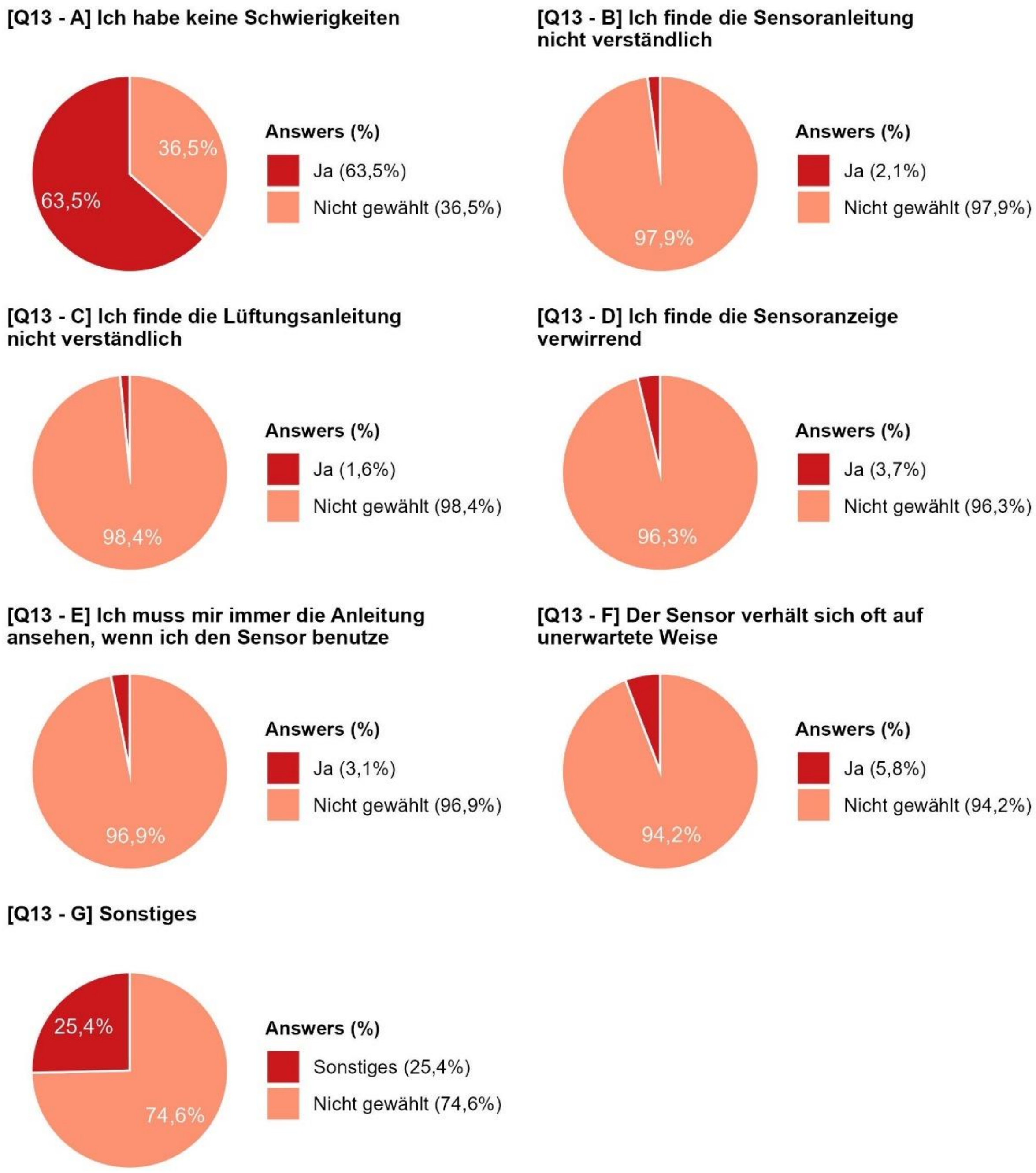


Figure A-53 Feedback on Question 13 from the first winter teacher survey.

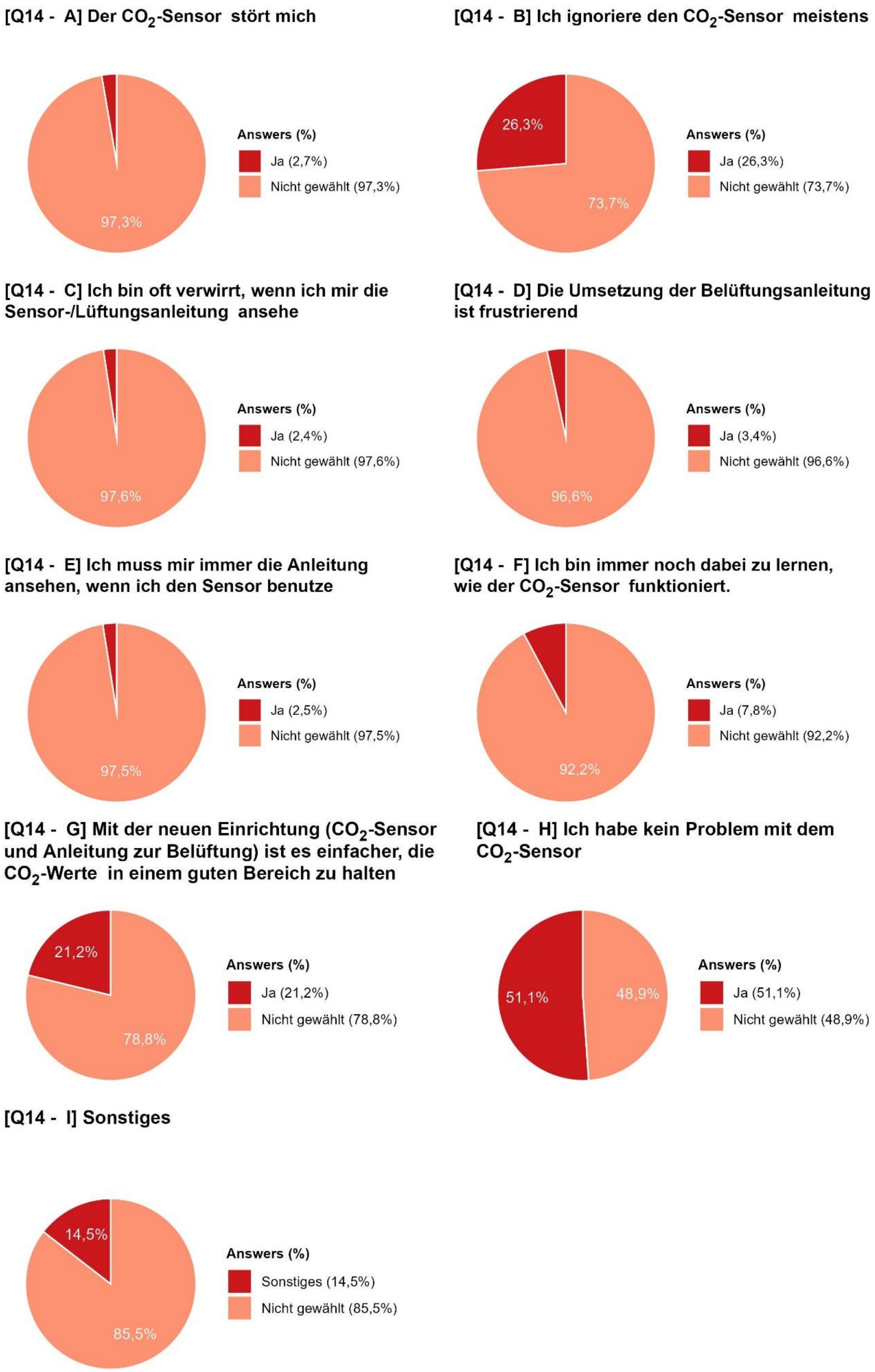


Figure A-54 Question 14 results from the first teacher survey in the winter.

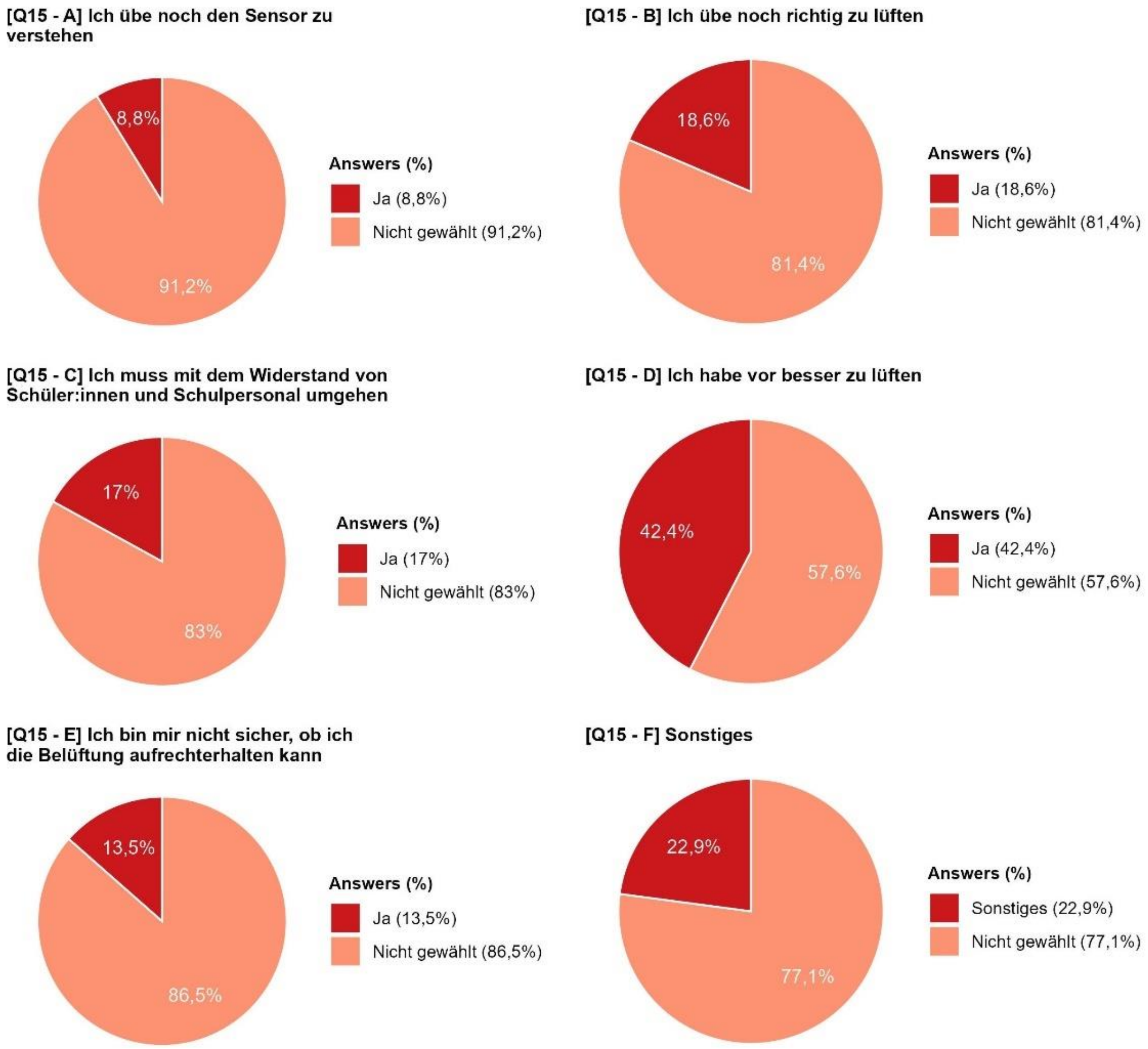


Figure A 55 Responses collected from teachers for Question 15 in the winter survey.

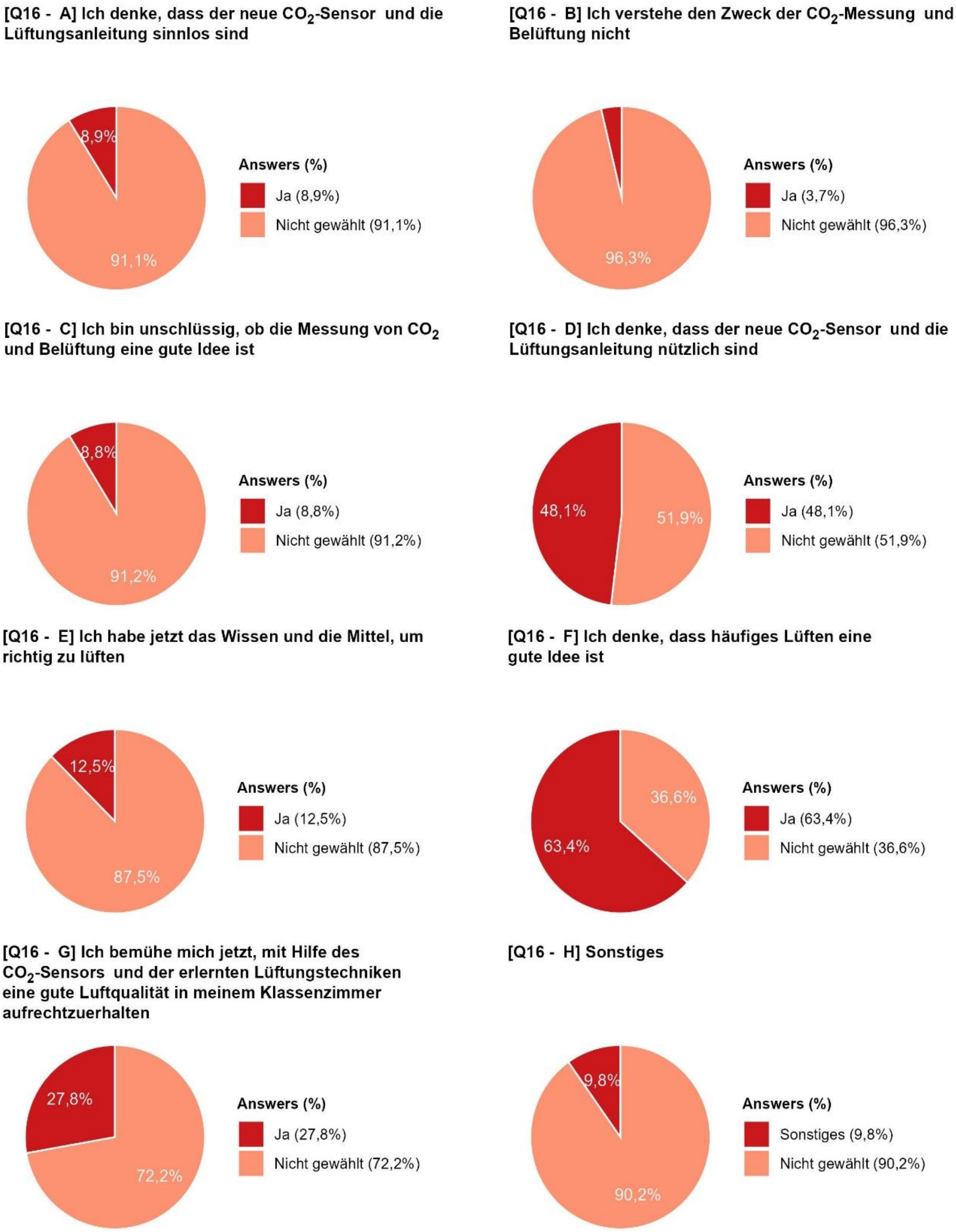
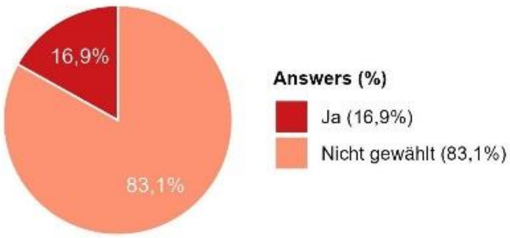
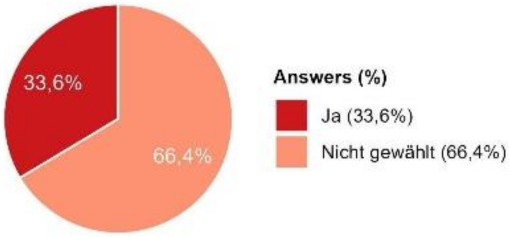


Figure A-56 Responses to question 16 for the first teacher survey (winter)

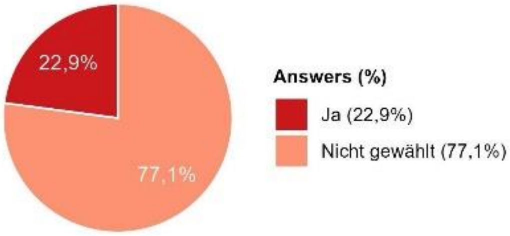
[Q17 - A] Ich schaue nie auf den CO_2-Sensor



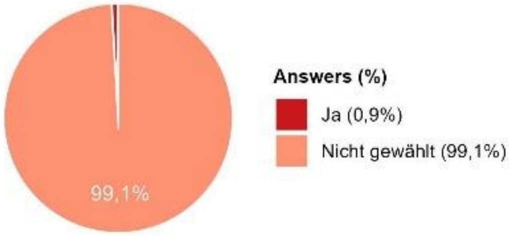
[Q17 - B] Ich schaue nur selten auf den CO_2-Sensor



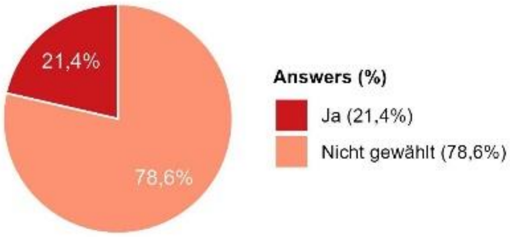
[Q17 - C] Ich schaue sehr häufig auf den CO_2-Sensor (mehrmals am Tag)



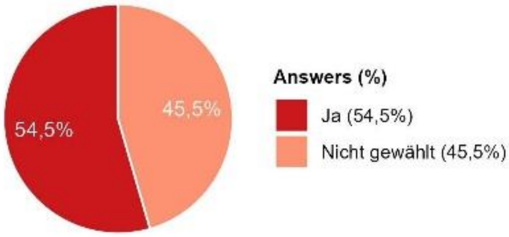
[Q17 - D] Ich schaue ständig auf den CO_2-Sensor



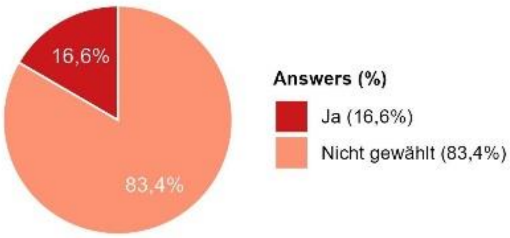
[Q17 - E] Ich tendiere dazu, den neuen CO_2-Sensor als Richtwert für meine Lüftungsgewohnheiten zu verwenden, anstatt die Fenster immer geschlossen zu halten



[Q17 - F] Ich öffne die Fenster häufig (mehrmals am Tag)



[Q17 - G] Ich beobachte den Sensor aufmerksam und lüfte dann (mehrmals täglich), um die bestmögliche Luftqualität zu erreichen



[Q17 - H] Sonstiges

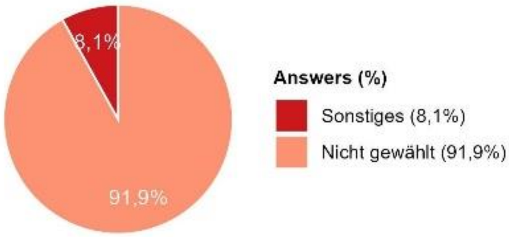


Figure A-67 Feedback on Question 17 from the teacher survey (winter period)

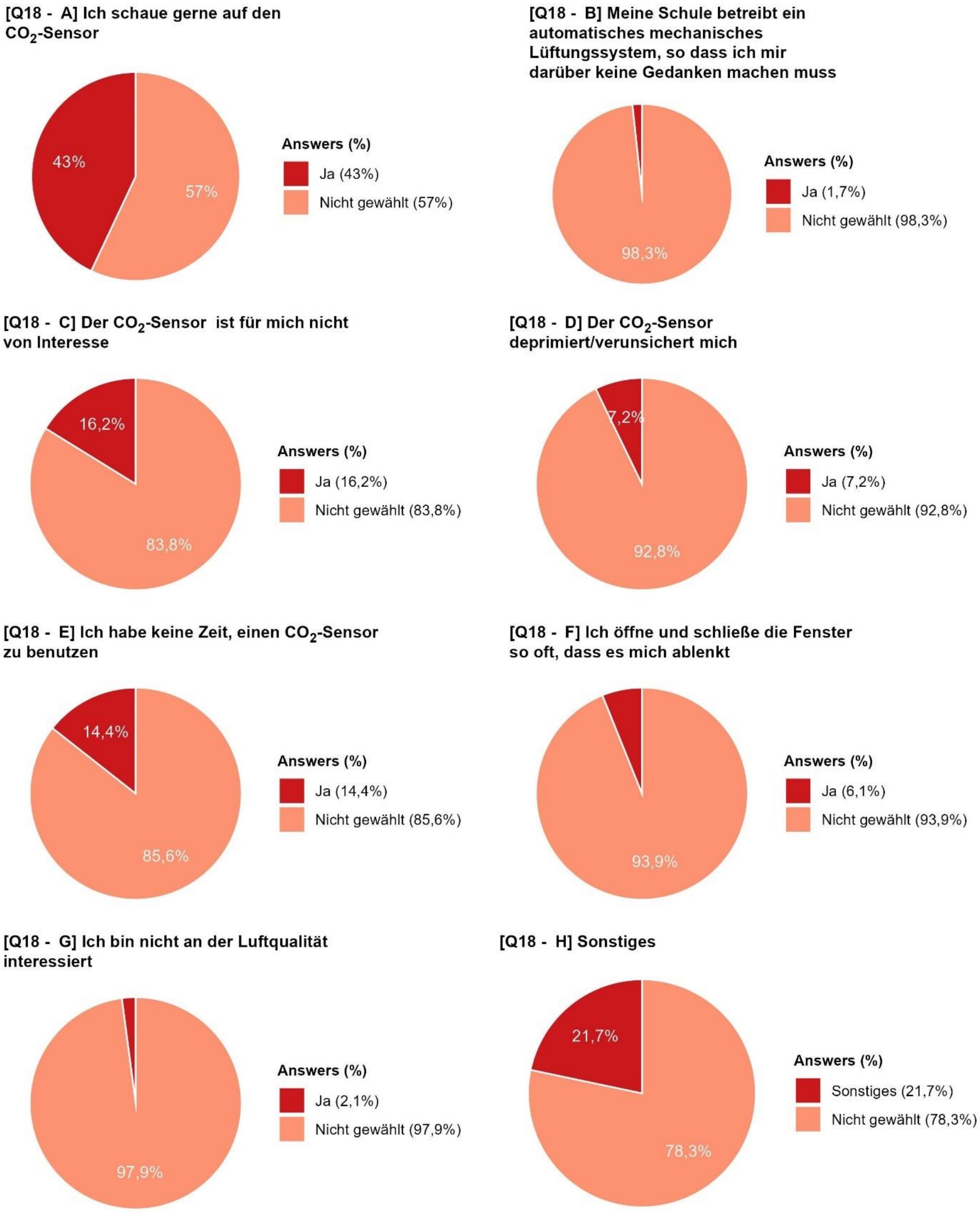


Figure A-57 Data from Question 18 in the first teacher survey held during winter.

C.2.2.2. Second survey results

Figure A-69 Respondents to the second teacher survey in the summer

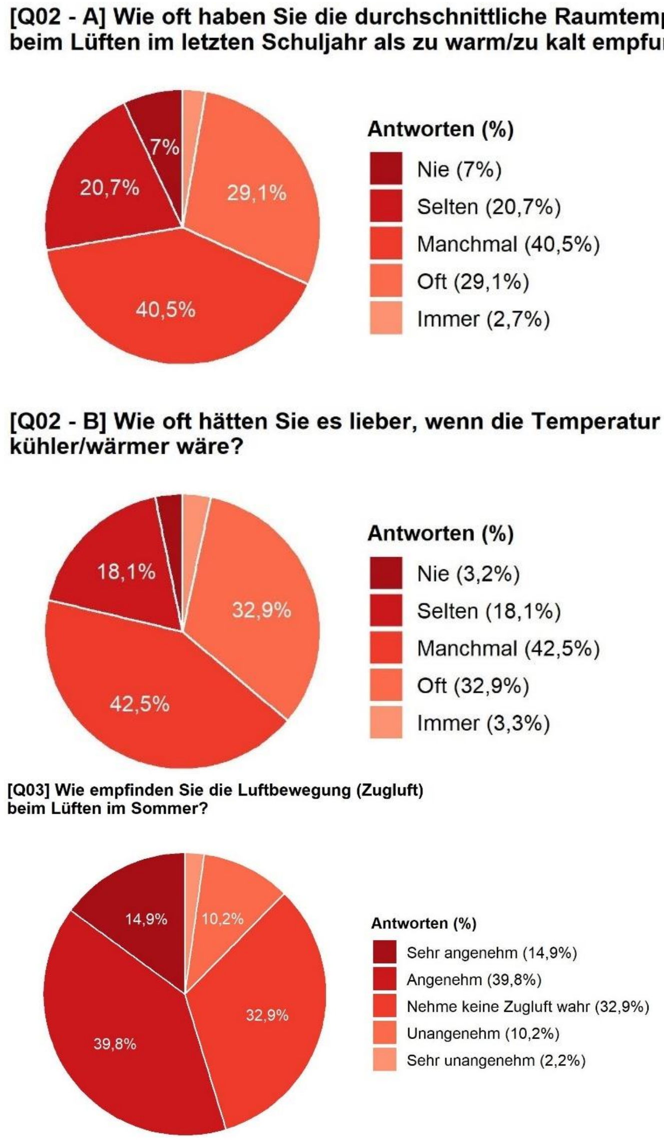


Figure A-58 Findings for Question 1 in the second teacher survey conducted in summer.

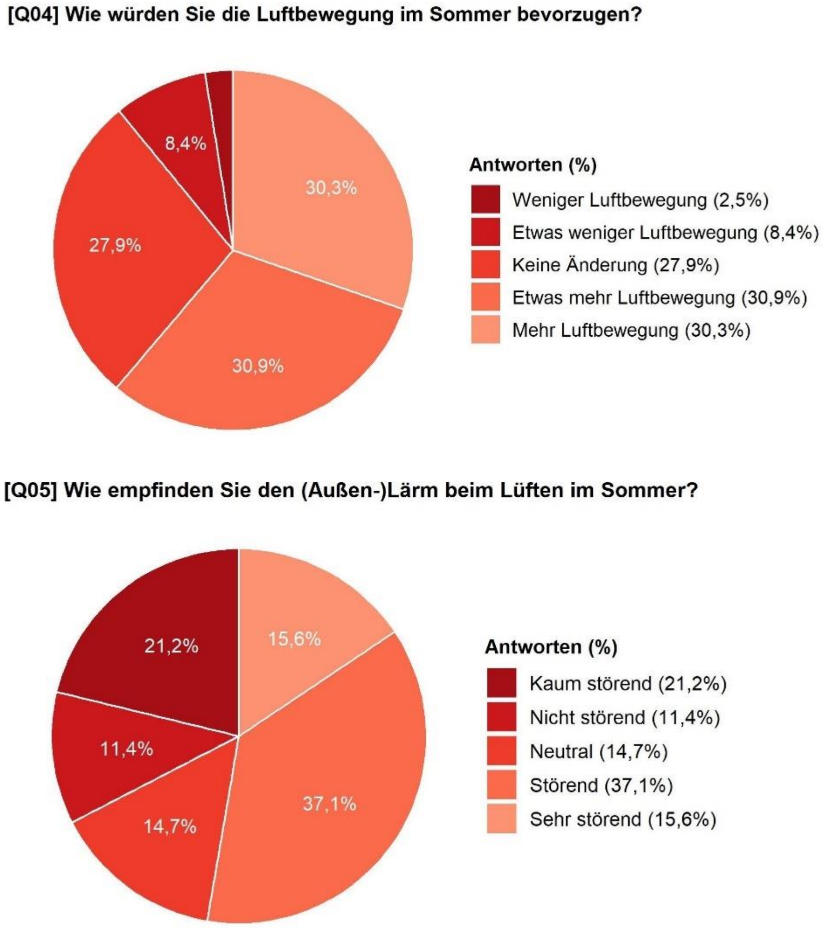


Figure A-59 Second teachers survey, responses to question 4 and 5

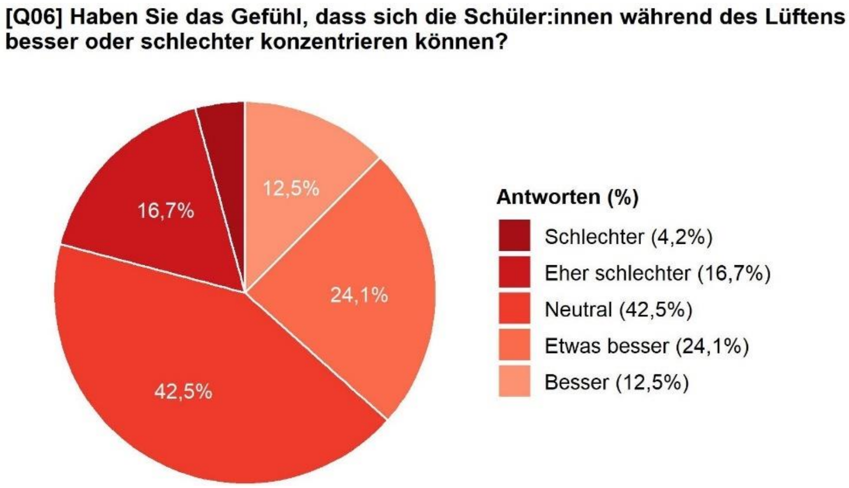


Figure A-60 Responses to Question 6 in the second teacher survey in the summer.

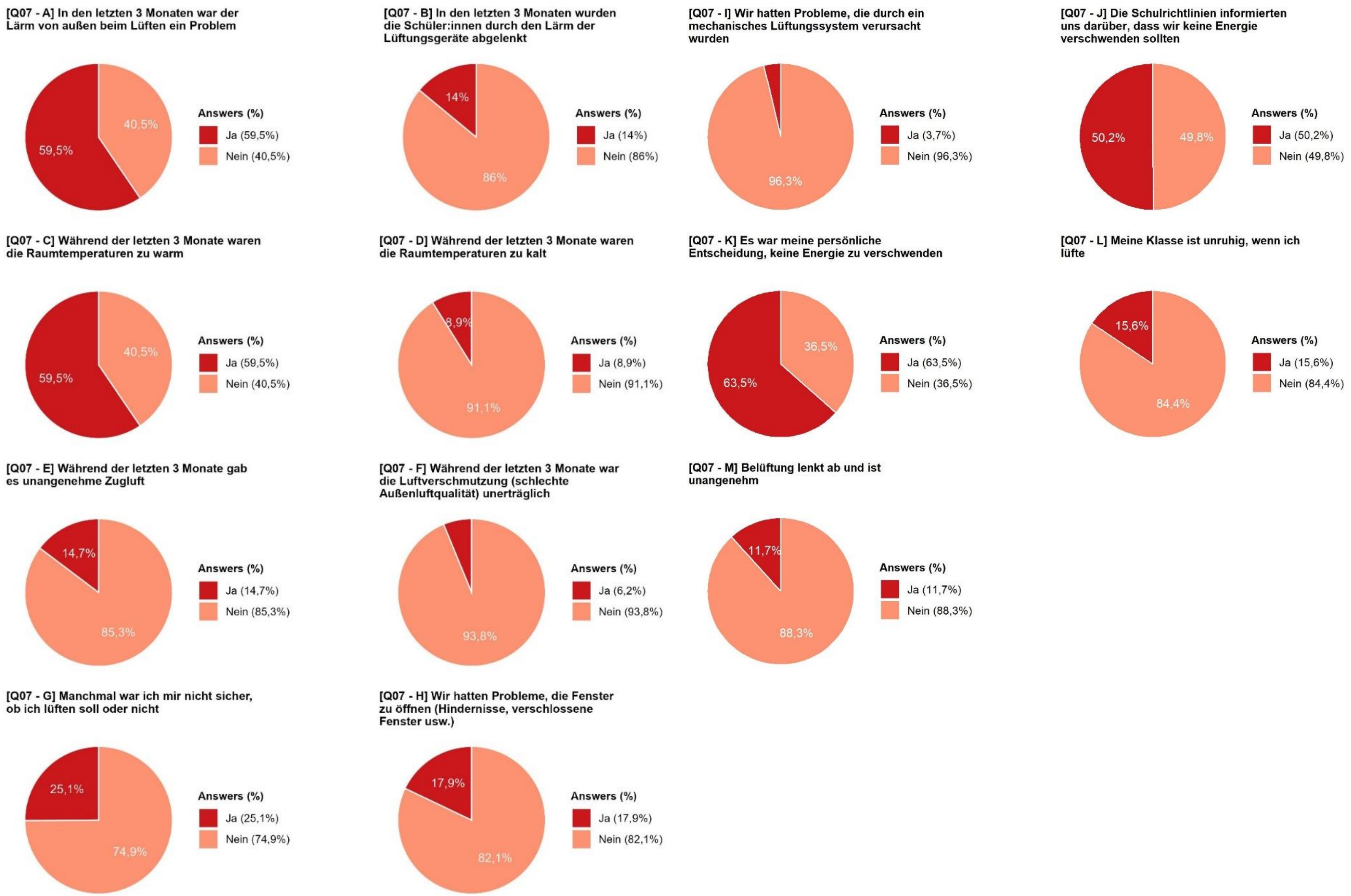


Figure A-61 Overview of responses to Question 7 in the second teacher survey conducted in the summer.

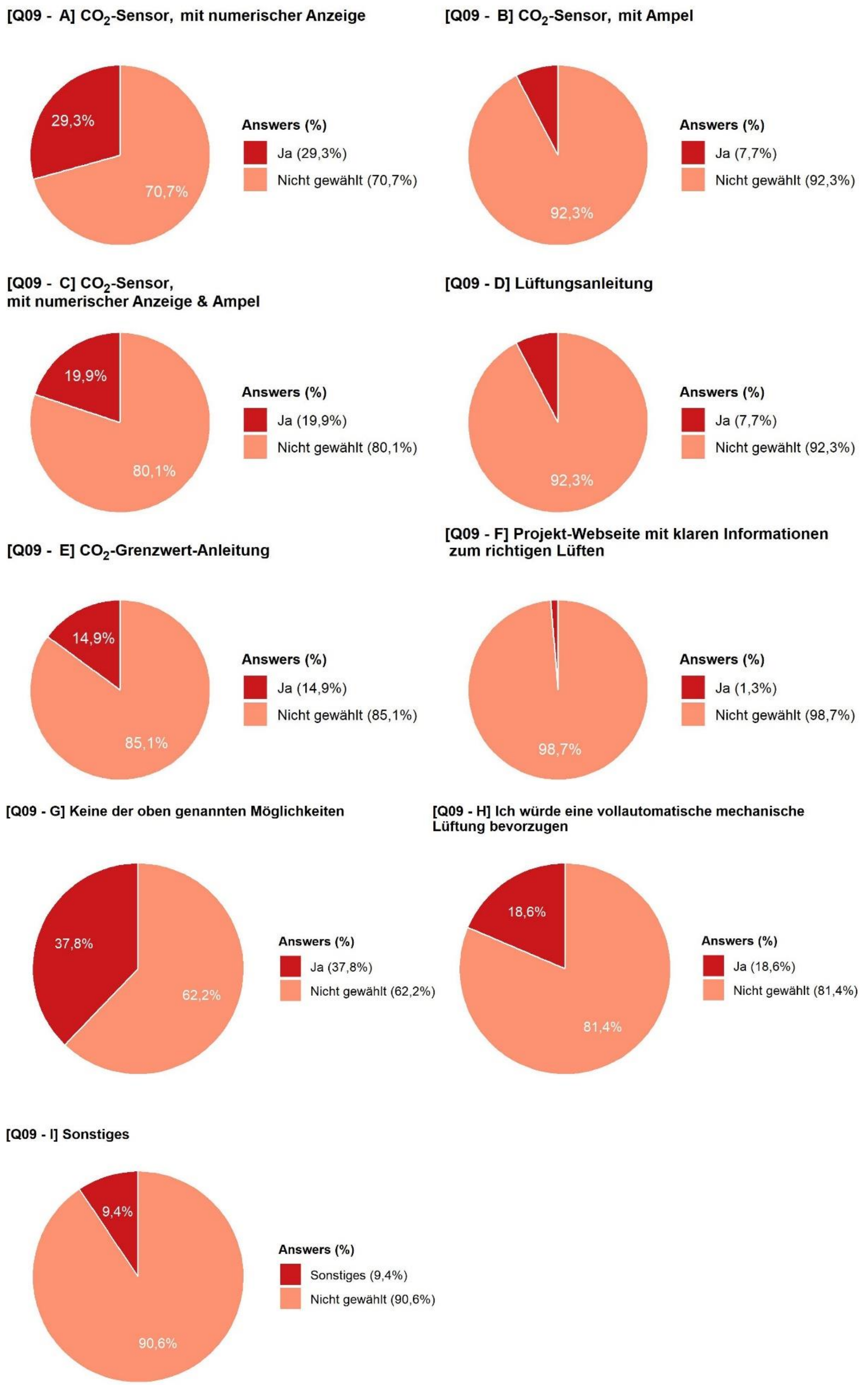


Figure A-62 Responses to Question 9 from the second teacher survey held in the summer.

Figure A-63 Responses to Question 10 in the second summer teacher survey.

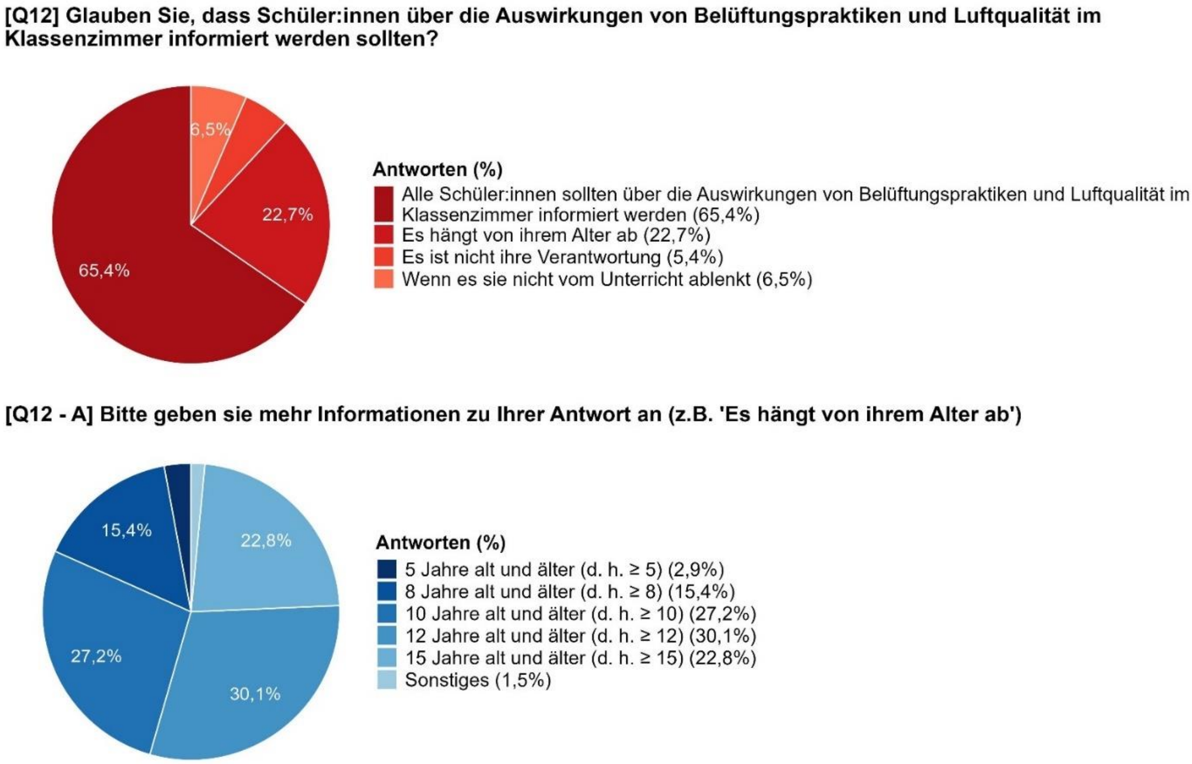
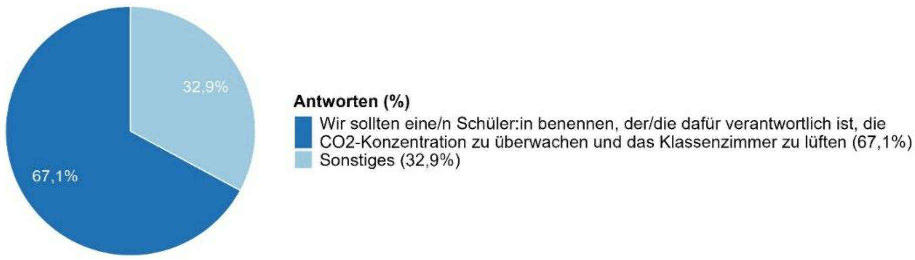


Figure A-64 Question 12 and 12A results from the second teacher survey held in summer.

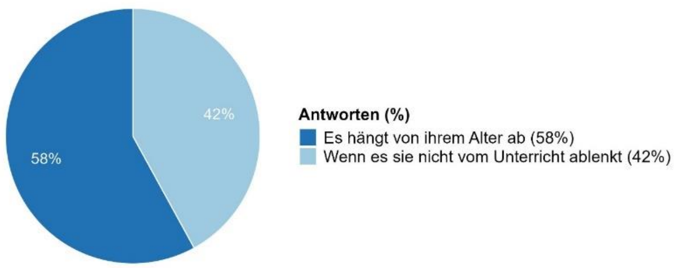
[Q13] Glauben Sie, dass Schüler:innen eine aktive Rolle bei der Aufrechterhaltung der Belüftungsqualität im Klassenzimmer spielen sollten?

[Q13 - A] Bitte geben Sie mehr Informationen zu Ihrer Antwort an (z.B. ,‘Ja‘)



[Q13 - C] Bitte geben Sie mehr Informationen zu Ihrer Antwort an (z.B. 'Nein')

[Q13 - B] Bitte geben Sie mehr Informationen zu Ihrer Antwort an (z.B. ,‘Vielleicht‘)



[Q13 - B - 1] Bitte geben Sie mehr Informationen zu Ihrer Antwort an (z.B. ,‘Vielleicht, es hängt von ihrem Alter ab‘):

Figure A-65 Responses to Question 13, 13A, 13B, and 13C from the second teacher survey, held in the summer.

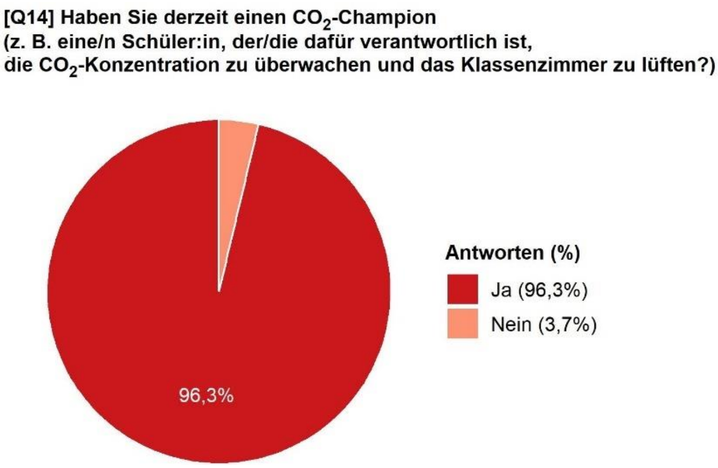


Figure A-66 Result from Question 14 in the second teacher survey held in the summer.

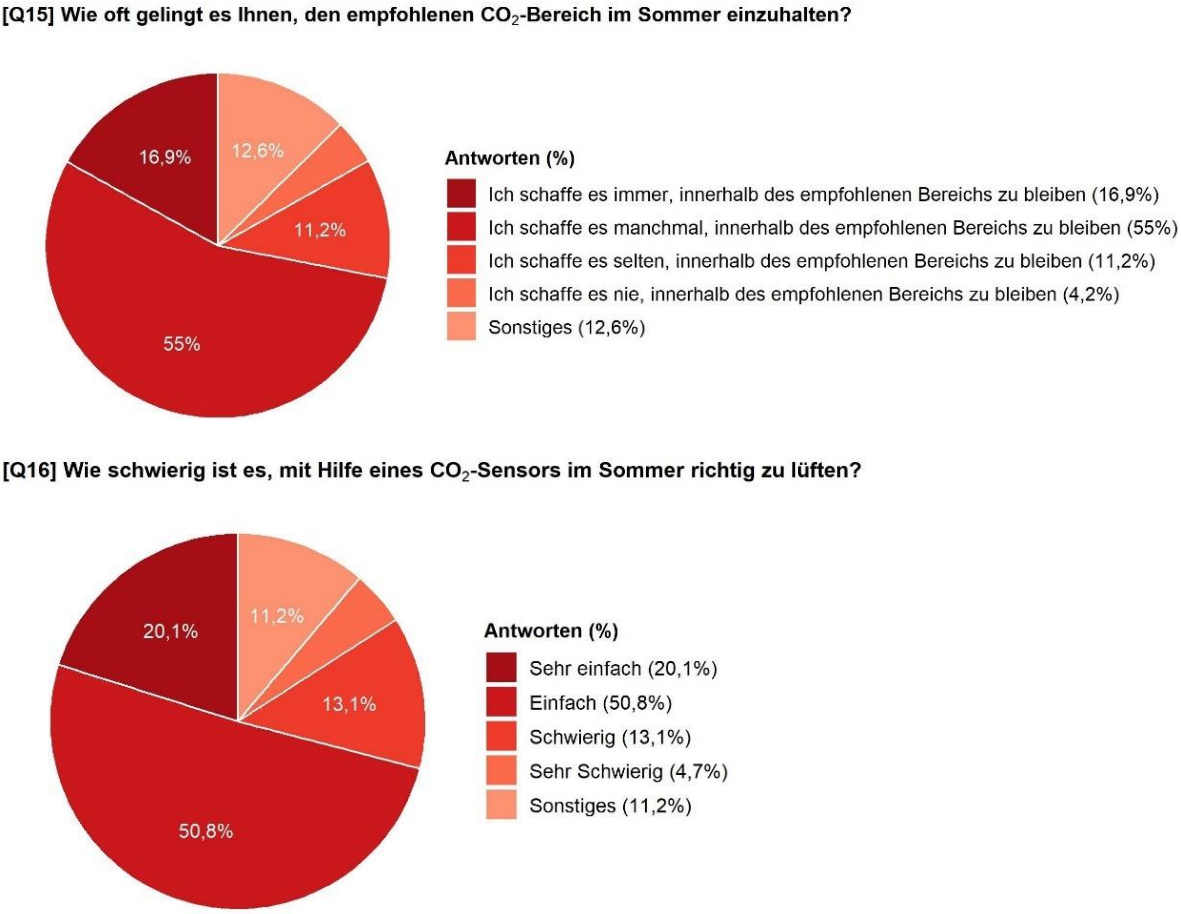


Figure A-67 Responses to Question 15 and 16 in the second teacher survey conducted in summer.

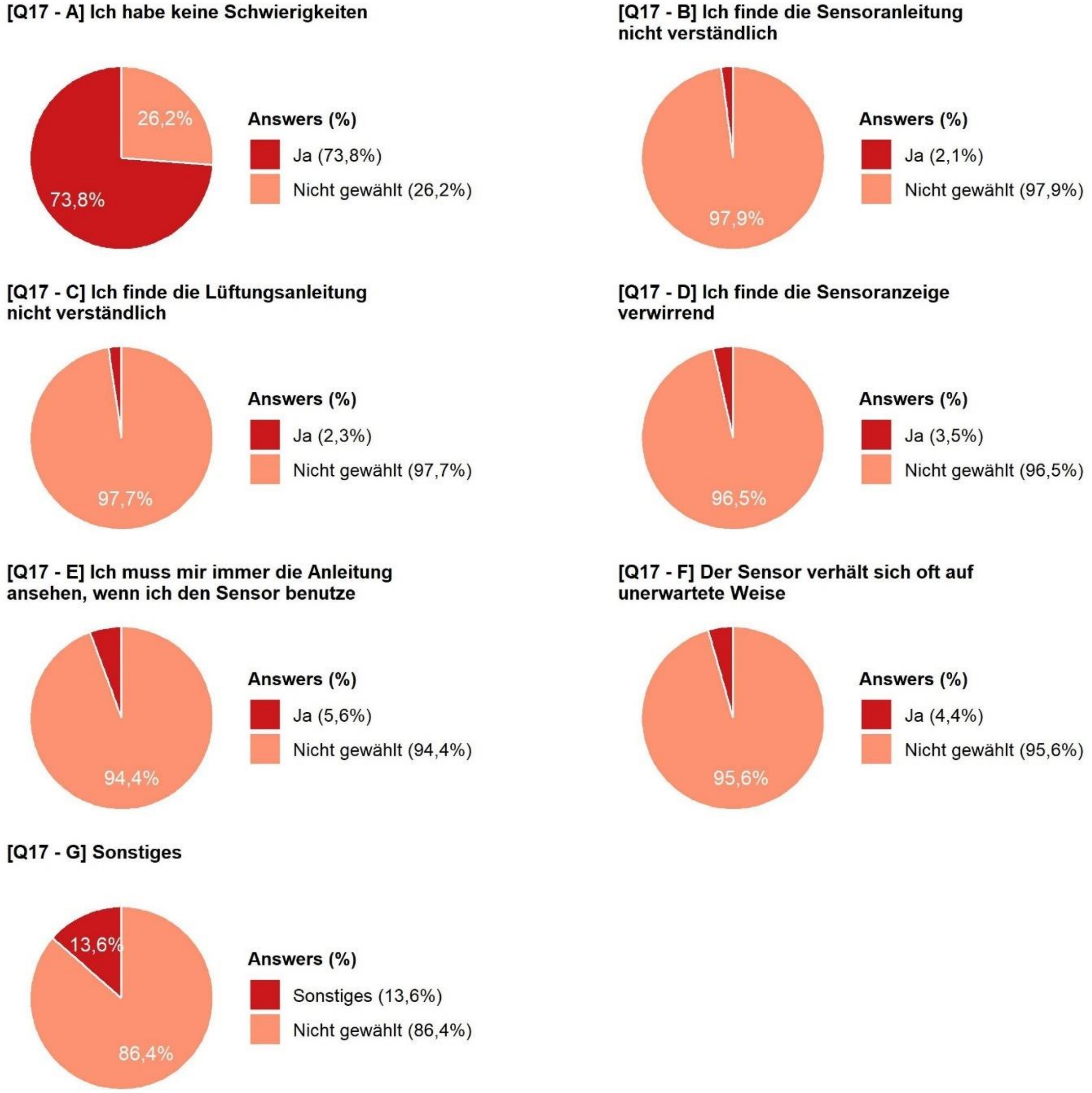


Figure A-68 Responses to Question 17 in the second teacher survey (summer period)

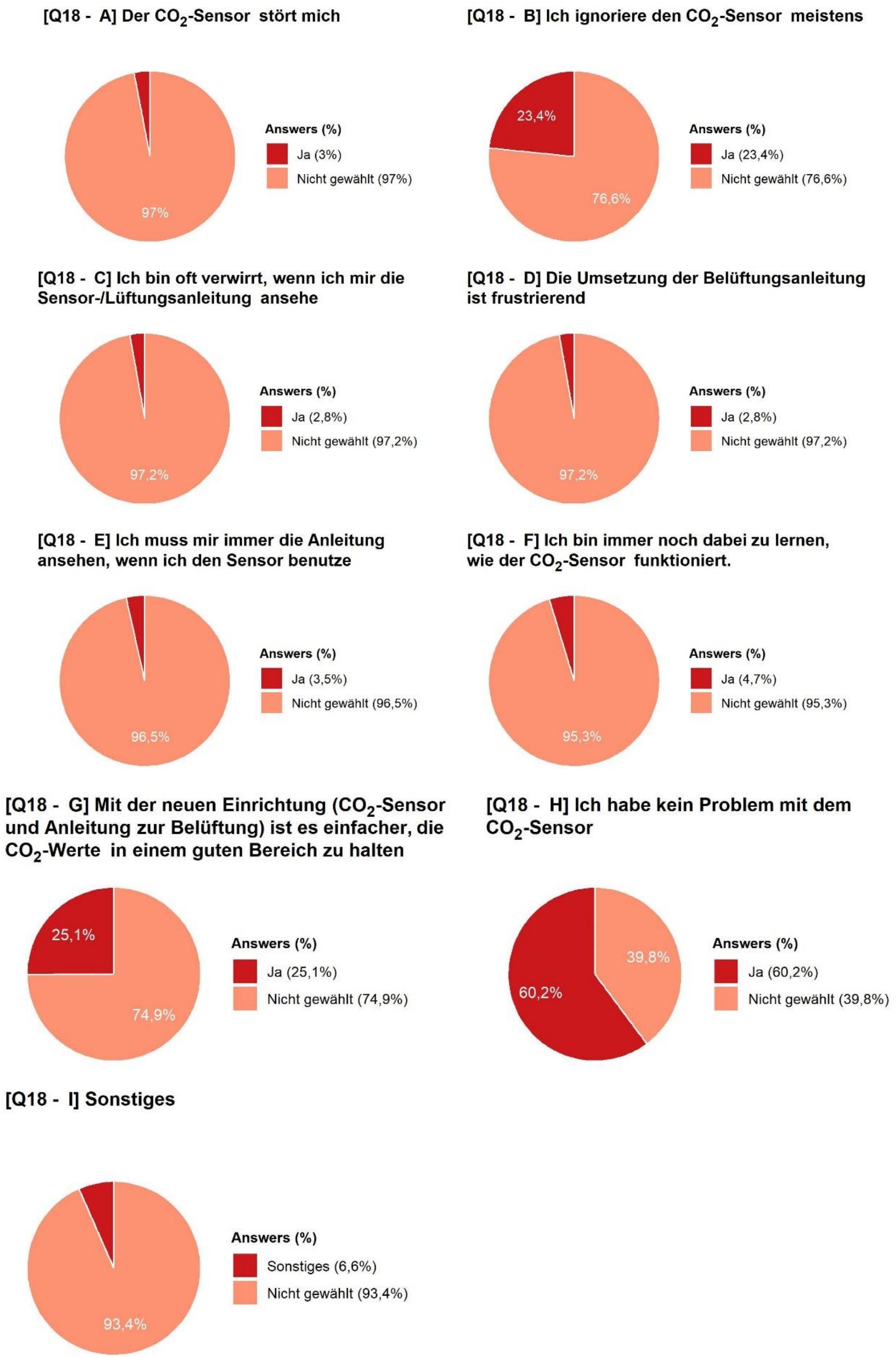


Figure A-69 Summary of responses to Question 18 from the summer teacher survey (second survey).

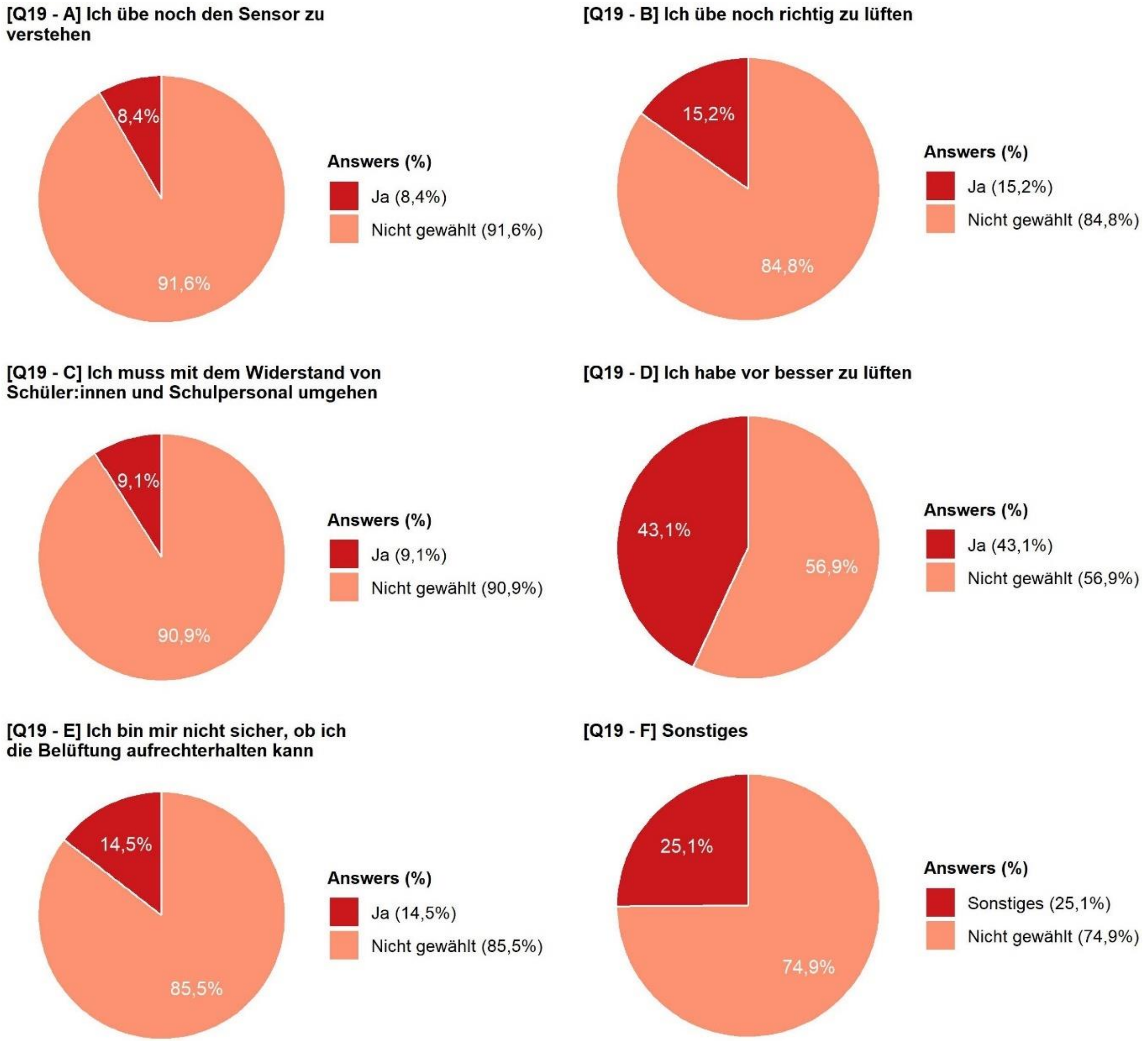


Figure A-70 Responses to Question 19 in the second teacher survey conducted in summer.

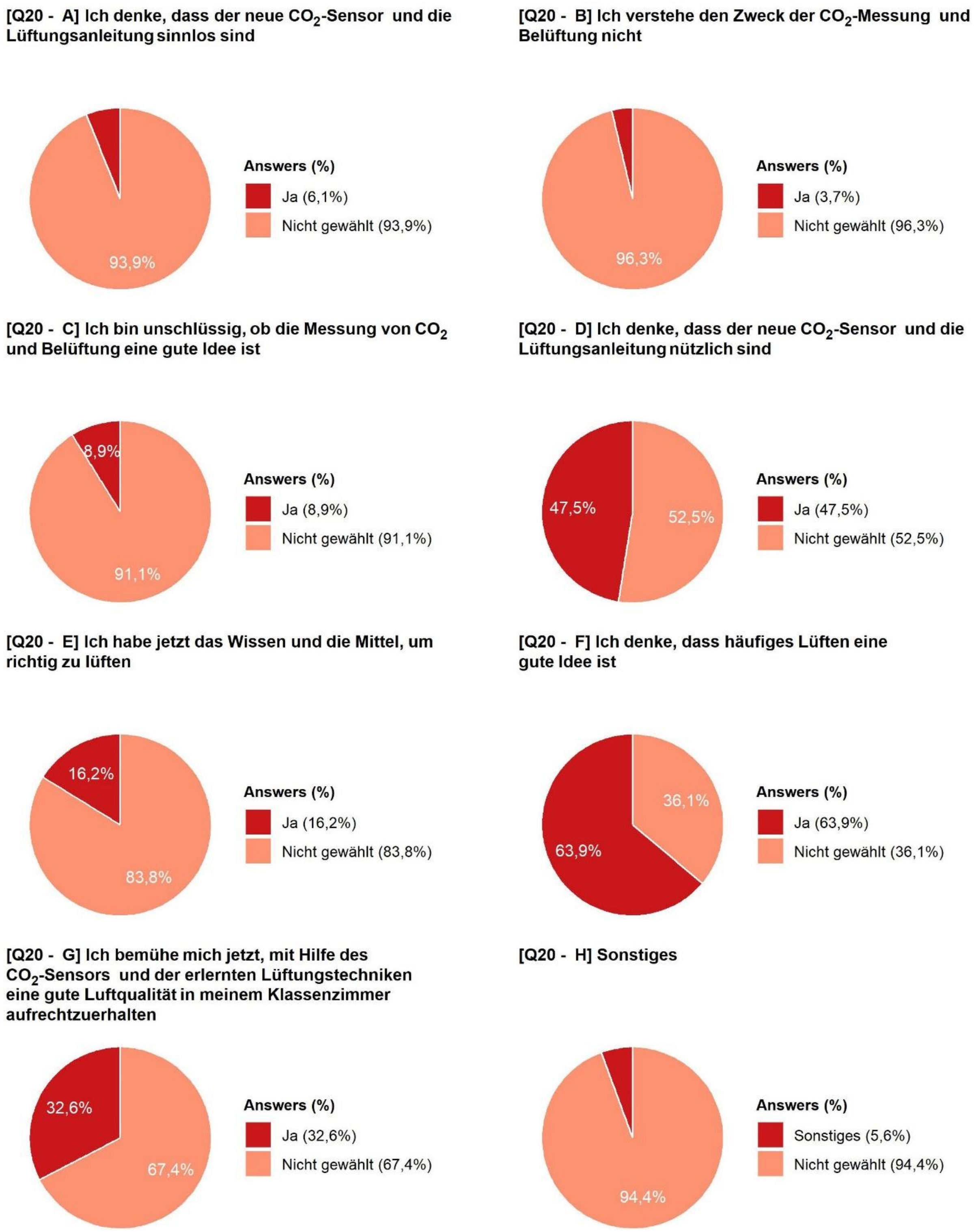


Figure A-71 Insights from Question 20 of the second teacher survey held during summer.

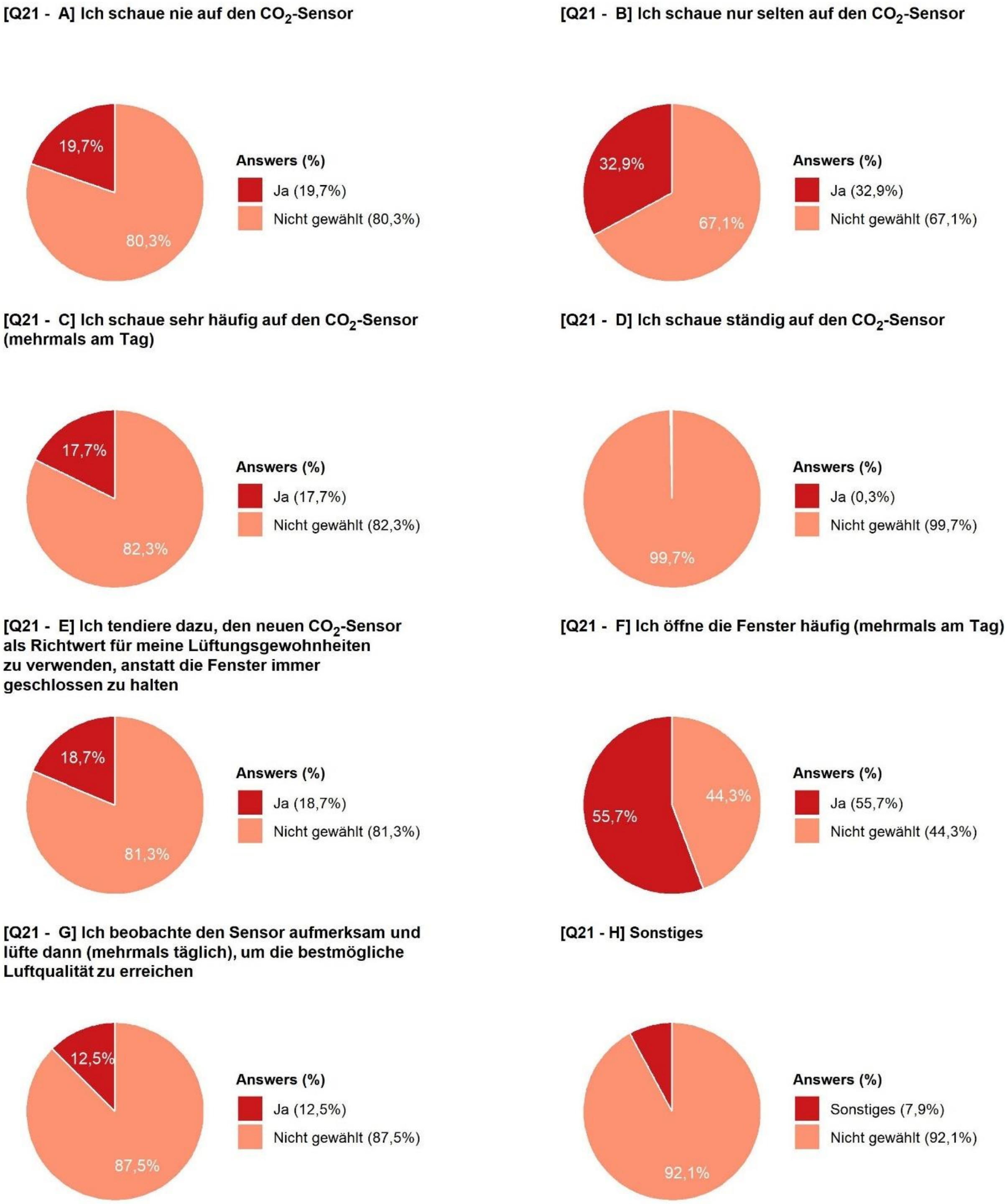


Figure A-72 Responses to Question 21 in the second summer teacher survey.

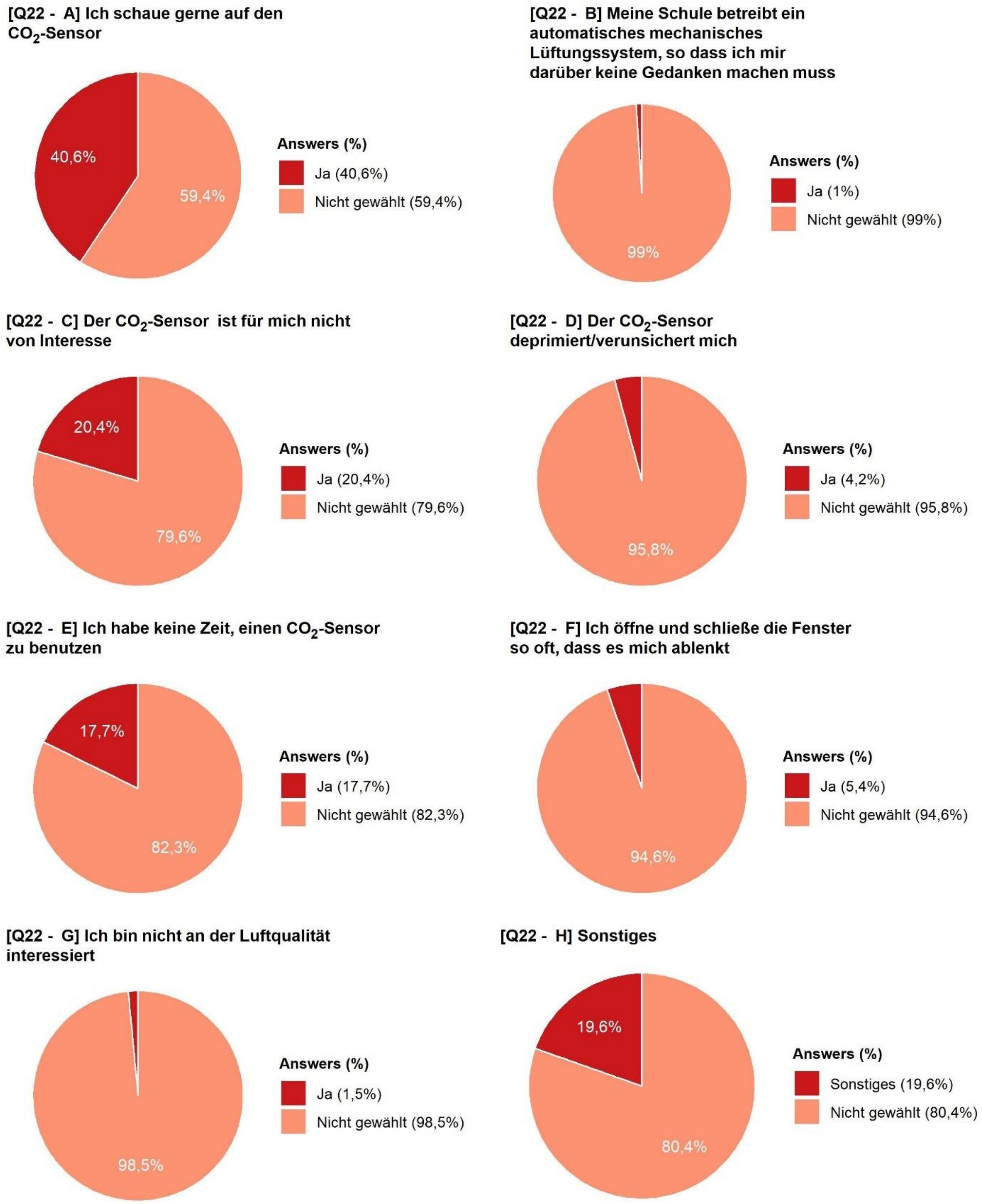


Figure A-73 Results from Question 22 in the second teacher survey held in the summer.