Indoor air quality in Austrian classrooms – Assessing different ventilation strategies with a citizen science approach

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ABSTRACT

With many existing Austrian school buildings to be renovated in the coming years, there are debates between stakeholders, about which ventilation strategy to pursue in existing schools. Therefore, different intervention strategies such as retrofitting ventilation systems, installing CO_2-monitoring signals, or raising awareness among teachers and students should be evaluated. This paper presents the preliminary results of the project "DIGIdat" on air quality measurements in the first quarter of 2023. The "as-is" indoor air quality situation in 36 classrooms in western Austria is assessed by comparing results between different classrooms and ventilation types. To gather information on indoor air quality, data is collected using multiple low-cost air sensors per classroom that are programmed and maintained by the students under scientific supervision. The citizen science approach helps to overcome the spatial barrier between the scientists and the measurement sites, with students being "responsible" for the continuous operation of their sensor kit. Altogether 15 sensor kits, distributed over three to four classrooms, are installed in each of the ten participating schools. The sensors measure CO_2-, fine particulate matter (PM), and volatile organic compounds (VOC) concentration as well as temperature and humidity. The sensor kits were positioned and started recording after finishing programming workshops, i.e., in January and February 2023 for most schools. Statistical analysis of the measured data (with varying sample size of approx. 10 to 20 thousand five-minute averages per category) was carried out utilizing the Welch t-Test and Mann-Whitney-U-Test for differences between window airing and ventilation systems. Significantly higher CO_2 and $PM_{2.5}$ values were found with window airing compared to ventilation systems. Somewhat less significantly, humidity was also higher in classes with natural ventilation than with mechanical ventilation. In addition to that, a correlation analysis showed a dependency between average CO_2-levels in window-ventilated classrooms and average outside temperature, whereas this was not the case with classrooms equipped with ventilation systems. The same analysis comparing inside and outside $PM_{2.5}$ concentrations showed also the mechanically ventilated classrooms have, probably due to fine particulate filters, lower ratios of fine particulate matter between inside and outside. Boxplots and correlation regression lines confirm graphically the data analysis results and highlight the conclusions.

KEYWORDS

Indoor Air Quality, Schools, Carbon Dioxide, Ventilation, Data Analysis

1 INTRODUCTION

In densely occupied rooms ensuring adequate indoor air quality, particularly in classrooms, can prove challenging. To address this issue and quantify its effects, the project "DIGIdat" was initiated. Currently, the authors are not aware of monitoring studies that investigated long-term air quality surveys in Tyrolean (Austria) schools. Therefore, it is crucial to determine the status quo and the effects of various interventions on indoor climate and air quality, especially considering that many schools are due for renovation and adaptation to meet new legal standards. This paper presents preliminary results from the first three months of data collection in participating schools.

"DIGIdat" is a citizen science project, with different stakeholders supporting the procedures and pupils from the investigated schools participating in the data collection and maintenance of sensors. The pupils are actively taking part in the scientific process as they help work out solutions and collect data. As it is difficult to maintain good information exchange with all of the children, the discussions and project contents are carried out in two workshops per year, containing an introduction to the topic, programming the sensor-kits, exploring their school building in a rally, and analysing the measured data (see Figure 1). In between the workshops, they take ownership of the sensor kits, meaning each team is responsible for the maintenance and takes regular records of the condition and function of their sensor kit. The second pillar of the citizen science approach is discussing results and possible intervention strategies in a stakeholder workshop including building owners, architects, HVAC designers, health experts, and public authorities.

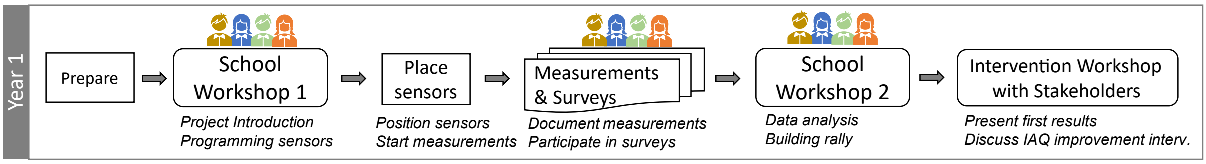

Figure 1: Citizen Science phases during the first year

The measuring instruments, supplied by "senseBox" (senseBox, 2023a), comprise a microcontroller, various air-quality sensors, and a Wi-Fi module. A total of 150 measuring devices gather air-quality data in scheduled one-minute intervals, which are then transmitted live to OpenSenseMap, a platform for publishing and visualizing open environmental sensor data (OpenSenseLab, 2023). Following the as-is situation assessment, the project aims to implement different intervention strategies such as raising awareness, providing CO_2-based warning signals, automatic window openers, and retrofitting mechanical ventilation systems. Comparisons will be drawn between air quality before and after interventions as well as across different classrooms with varying ventilation modes.

2 METHODS

2.1 Collection of data

About 137 of 150 sensor kits were programmed and positioned to measure temperature, humidity, volatile organic compounds (VOC), fine particulate matter (PM), and CO_2-levels. After sensor programming workshops with the pupils, mainly between November 2022 and February 2023, the sensor kits were positioned by the scientific project team in the different classrooms, mainly between December 2022 and March 2023. Therefore, different measurement durations (sample periods) are available for the different schools. The time intervals between measurements were set to one minute to achieve sufficient accuracy without generating unnecessarily large amounts of data. Due to data-transfer problems, the sample interval had to be increased temporarily to four minutes in several schools. With the one-minute time grid, the opening of doors or windows can be recorded well and a steep increase of e.g., the CO_2-levels, can be mapped reasonably accurately. The programming language used for the "senseBox" is a device-associated language based on "Blockly" (Wikipedia, 2019), which then is converted to "Arduino-Code" for compiling (senseBox, 2023b). As long as power supply is given, the devices save the measured data on a built-in memory card as well as load it onto the OpenSenseMap database using the matching API.

2.2 Positioning

About three to four measuring devices were placed in each of the 36 surveyed classrooms. Some schools were partially equipped with ventilation systems. In these cases, an attempt was made to select the classrooms in such a way that an equal number of classrooms with and without mechanical ventilation are represented. An outdoor measuring device was also installed in each participating school. Additional sensors were placed in other rooms, such as teacher conference rooms, computer science rooms, pupil's workshops, and also hallways which are connected to the surveyed classrooms. At least one of the devices in the classrooms and every outdoor device is equipped with a sensor for fine particulate matter.
Measurements are taken at a height of approximately 110 cm, where the main activity is seated work, and at a height of 150 cm, where the main activity is walking or standing. This also meets the recommendations of ISO16000-1 (2004), although the sensors could not be placed off the wall (as also recommended by standards) as they should not interfere with school activity and need to be securely mounted in order to be "child-proof". A highly air-permeable housing for the sensors was developed and 3D-printed as the standard mounting solution. The housings were attached to the wall with double-sided adhesive tape (see Figure 2). No effects on the VOC measurements by possibly outgasing tape glue were observed during respective tests. 110 cm for seated work was chosen to match the head height of seated students. The outdoor sensors were mounted to the exterior wall in a weatherproof place with good exposure to natural air flow while avoiding the direct vicinity of windows and doors, where indoor air could influence the measurement when opened.

Figure 2: Example of mounted measurement device (in 3D-printed housing)

Inside the classrooms, the first measurement device is usually placed on the side of the blackboard, the second on the opposite side of the blackboard, and the third on the inner wall opposite the wall with the most windows. As most of the surveyed classrooms are built in a similar way, the positioning described could be achieved in almost all classrooms. In general, measuring devices were kept as far away as possible from windows, doors, sinks, and other point sources of pollutants. The particulate matter sensor was placed inside the housing according to manufacturer specifications (Sensirion, 2019).

2.3 Sensors

In this study, a set of low-cost sensors is utilized to monitor environmental conditions. The selected sensors include the Bosch BME680, which is capable of measuring temperature, humidity, and air pressure, as well as gas resistance, which is converted into breath-VOC equivalent (b-VOC_{eq}) and a so-called Air Quality Index (not within the scope of this analysis). Additionally, the Sensirion SCD30 sensor was employed, which primarily measures CO_2-levels but can also record temperature and humidity within the sensor. Lastly, the Sensirion SPS30 sensor was used to measure fine particulate matter in the size categories of $PM_{1.0}$, $PM_{2.5}$, and $PM_{4.0}$. This sensor automatically extrapolates the PM_{10} values from the other size categories. The sensor properties for b-VOC_{eq}, CO_2, and $PM_{2.5}$ are listed in Table 1.

Table 1: Properties of sensors for b-VOC_{eq}, CO_2, and PM

Sensor	Measurement	Method	Range	Accuracy	Source
BME680	b-VOC_{eq}*	Metal Oxide Semiconductor	0.5 – 1000 ppm**	-	(Bosch Sensortec, 2022)
SCD30	CO_2	Nondispersive Infrared	400 – 10000 ppm	± 30 ppm	(Sensirion, 2020a)
SPS30	$PM_{2.5}$	Optical (light scattering)	0 – 1000 μg/m³	± 10 %	(Sensirion, 2020b)

*calculated from correlation of typical VOCs to gas sensor resistance
**min- and max-output (tested range not available)

2.4 Underlying conditions

The microcontroller and sensors take the measurements inside a 3D-printed housing with an acrylic glass lid (see Figure 2), which both were designed in the scope of this project. Since especially the microcontroller and the Wi-Fi module emit a non-negligible amount of heat, they are placed in a separate compartment of the housing. In addition, the sensors themselves generate a small amount of heat, which offsets the BME680's temperature readings by about 0.5 - 1.5 °C above the "actual" temperature. This offset could not yet be quantified exactly, which is why the data was not adjusted in the following analysis.
The selected classrooms are all of a similar height of approximately 2.7 - 3.5 meters and provide space for 15 - 25 students. Like in most Austrian schools, the students of the participating classes spend most of the school day in "their" assigned classroom, with the exception of e.g., sports, arts, crafts, or physics lessons.

3 RESULTS AND DISCUSSION

In order to combine the multiple sensor datapoints in a classroom into a common room average, the readings are resampled into 5-minute intervals based on their time stamp. As sufficient information on classroom occupancy was not available, only the time period between 9:00 and 12:00 in the morning was analysed for the results presented herein. Within this timeframe, a full classroom occupation is very likely. In this sense, the results do not necessarily represent the average exposure concentration of the pupils.
For evaluation, measured values are then averaged within their 5-minute interval. This means that regardless of how many sensors take measurements in this 5-minute period, the mean value is always taken from the available measured values of this particular room. This makes it easy to handle rough failures and bring the data into a meaningful grid to be statistically analysed. The following data analyses and graphics were calculated and created using Python 3.0 scripts, mainly with the libraries Pandas, NumPy, and Matplotlib.

3.1 Significance

In order to analyse the existing 5-minute averages of the individual rooms, they are presented statistically in the form of a boxplot. The following boxplots show the median, the 25th respectively 75th percentile, and the whiskers, which end at the largest and smallest measurement within 1.5 times of the interquartile range.

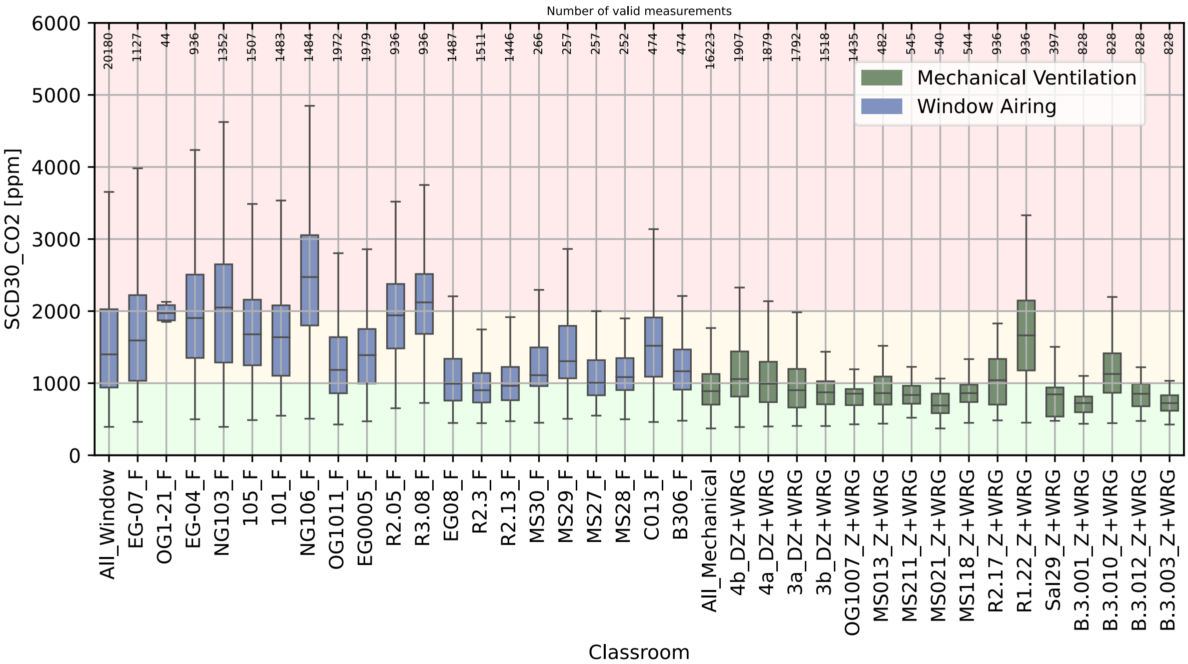

Figure 3: Boxplots of CO_2 concentration measured between 9:00 and 12:00 during schooldays

Figure 3 displays the boxplots of the CO_2 measurements for each classroom, sorted by 'mechanical ventilation' (green) and 'window airing' (blue). The first bars of the categories show the analyses of all classrooms combined for each category. It is visible that classrooms with window airing show mostly a wider range concerning the CO_2 content than those with mechanical ventilation.

The means of the underlying data are then checked for a statistically significant difference between window airing and mechanical ventilation. At first, it has to be examined, if the classroom averages are normally distributed. This is done using the Shapiro-Wilk-Test (Hedderich & Sachs, 2020). If the means are then confirmed to be normally distributed, the Welch t-Test (Hedderich & Sachs, 2020) can be a good choice for testing a significant difference, if not, the Mann-Whitney-U-Test (Spiegel & Stephens, 2018) can be more suitable. As it is not certain which is the better approach (Fay & Proschan, 2010) for the given measurement averages, the results of both tests are calculated and presented in Table 2. According to this statistical analysis, the CO_2-value is significantly higher with window airing than with mechanical ventilation (for details see Table 2). The chosen significance level for all tests is 5%.

Figure 4 displays the fine particulate matter measurements ($PM_{2.5}$) for each classroom. All classrooms, with one exception (see Figure 4, EG-04_F), are within an acceptable range, respectively below 10 µg/m³. The exception however consists of a classroom where only 20 five-minute interval data points could be evaluated due to data transmission problems, and should therefore be interpreted with care. With the same approach as with the CO_2-values, a statistically significant difference was tested with $PM_{2.5}$. Welch's t-Test and Mann-Whitney-U-Test show, $PM_{2.5}$ levels are significantly higher in window-ventilated classrooms than in mechanically ventilated classrooms.

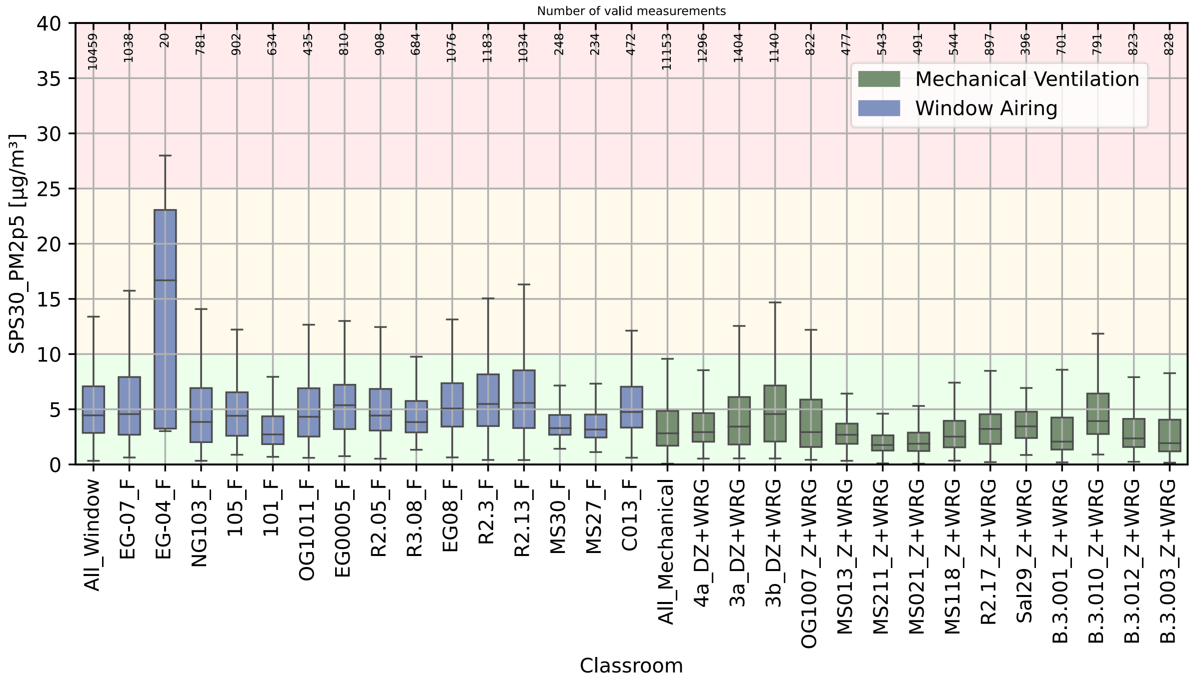

Figure 4: Boxplots of $PM_{2.5}$ concentration measured between 9:00 and 12:00 during schooldays

In terms of relative humidity in classrooms, measurements in window-ventilated classrooms are slightly higher than in mechanically ventilated classrooms and show a slightly wider spread towards higher values (see Figure 5). The analysis of the classroom averages results that this difference is statistically significant. All classrooms examined are inside the recommended range or have at least acceptable relative humidity, with some of the lower whiskers considerably in the range of unrecommended humidity.

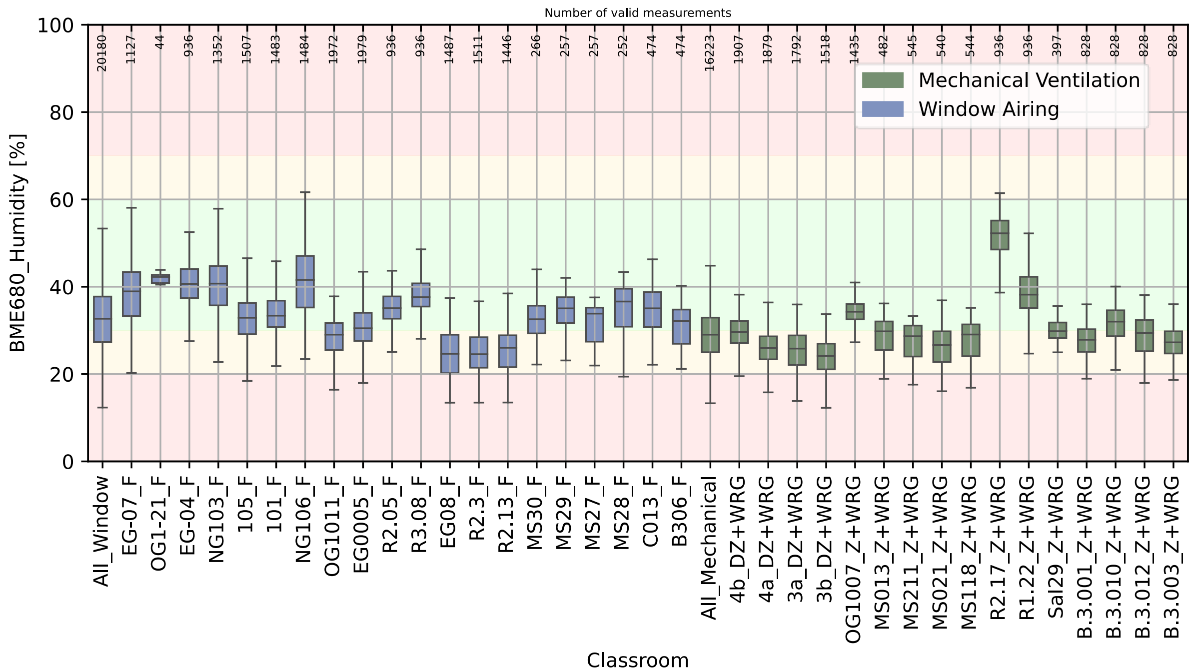

Figure 5: Boxplots of humidity levels measured between 9:00 and 12:00 during schooldays

In addition to that, also the calculated b-VOC_{eq} levels were analysed and support that there is a statistically significant higher concentration of volatile organic compounds in classrooms with mechanical ventilation compared to those with window airing. This has not yet been investigated in sufficient detail, which is why the results cannot be presented or verified here. However, to complete the picture, the values are included in Table 2.

Table 2: Significance of differences: window airing vs. mechanical ventilation (significance level 5%)

Classroom Avg.	Test-Variant	p-Value Wt*	p-Value MWU**	Result
CO_2	window airing > mechanical vent	0.0004 %	0.001 %	very significant
$PM_{2.5}$	window airing > mechanical vent	0.21 %	0.02 %	very significant
b-VOC_{eq}	window airing < mechanical vent	3.74 %	2.51 %	significant
Humidity	window airing > mechanical vent	4.53 %	1.14 %	significant

*Wt … Welch's t-Test
**MWU … Mann-Whitney-U-Test

3.2 Correlations

A further investigation concerns the correlation between indoor and outdoor measurements. For this purpose, data pairs are generated that represent the average of the measurements over the time period from 9:00 to 12:00. Figure 6 displays these data pairs for fine particulate matter ($PM_{2.5}$) and a regression line was created to show the trend of the highly variable data points for separate classrooms with and without mechanical ventilation. The band around the regression line represents the range within the root-mean-square deviation (short RMS, Spiegel and Stephens, 2018). This relatively small sample of data indicates a correlation between inside and outside $PM_{2.5}$ values with a correlation coefficient for mechanical ventilation of 51.2% and for window airing of 65.3%. Both regression lines have a relatively high RMS. It can be said that this data seems to indicate the effectiveness of the particulate filters in ventilation systems.

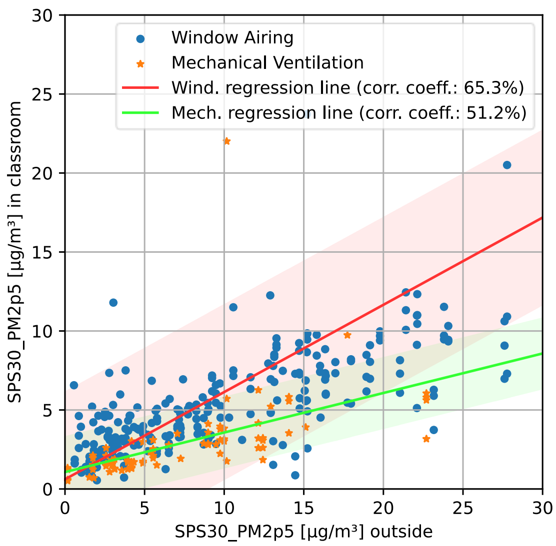

Figure 6: Correlation between avg. $PM_{2.5}$ in classroom and avg. $PM_{2.5}$ outside

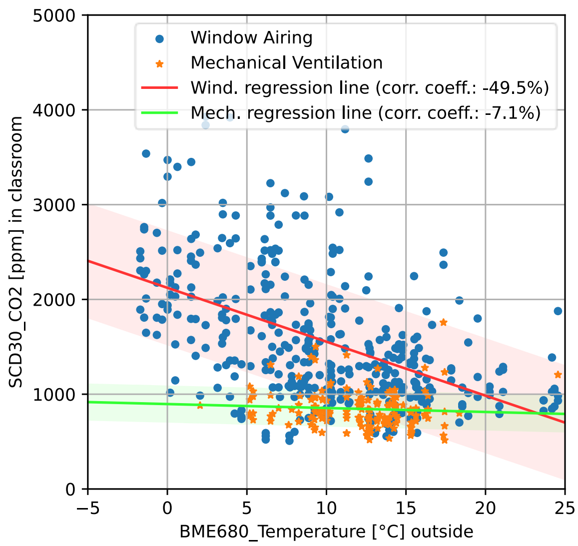

Figure 7: Correlation between avg. temperature outside and avg. CO_2-level in classroom

Figure 7 shows data pairs of the average outside temperature compared to the corresponding average CO_2-level. This correlation analysis shows a high dependency of the inside CO_2-level from the outside temperature in window-ventilated classrooms and almost no correlation in mechanically ventilated classrooms. This suggests that the colder it is outside, the less likely it is that occupants will adequately ventilate the classrooms if done by window airing. On the other hand, since most mechanical ventilation systems have heat recovery implemented the outside temperature plays a minor role given such a system. The parameters of the correlation, the regression line, and the root-mean-square deviation are listed in Table 3.

Table 3: Parameters of correlation and the regression line

Case	Ventilation	Interception*	Slope*	Correlation Coeff.	RMS
$PM_{2.5}$ inside / $PM_{2.5}$ outside	Window Airing	0.61 µg/m³	0.55	65.3 %	5.57 µg/m³
	Mechanical Ventilation	1.07 µg/m³	0.25	51.2 %	2.28 µg/m³
CO_2 inside / Temperature outside	Window Airing	2123 ppm	-56.9 ppm/°C	-49.5 %	608 ppm
	Mechanical Ventilation	896 ppm	-4.2 ppm/°C	-7.1%	196 ppm

*regression line in style of $value_{inside}$ = slope × $value_{outside}$ + interception

4 CONCLUSIONS

This work, which is based on the preliminary measurement data of the project DIGIdat, examines various air quality parameters by means of statistical data analysis. The low-cost sensor kits used have been placed in 36 classes so far and measure temperature and humidity, as well as CO_2-levels, fine particulate matter (PM), and volatile organic compounds (here as b-VOC_{eq}). Measurements were carried out at one-minute intervals, although due to problems with the database infrastructure, some classrooms had to temporarily be measured in four-minute intervals. The aim of this study was to find statistical differences between classes with and without mechanical ventilation and to investigate correlations between outdoor air and classroom air. Higher concentrations of CO_2 and $PM_{2.5}$ were found in classes with window airing confirmed by statistical significance. There also was a statistically significant lower level of humidity in mechanically ventilated classrooms. Statistical differences were tested with the Welch t-test and Mann-Whitney-U-test at 5% significance level. The correlation for mechanically ventilated classrooms showed that fine particulate filtering is statistically visible. However, $PM_{2.5}$ concentration is low for all classes with median values well below 10 µg/m³. For window airing, a dependence of the CO_2-levels on the outside temperature can be found. In general, the colder the outside temperature the higher the CO_2 measurements, with CO_2 concentrations above 2000 ppm in several of the window-ventilated classrooms. The preliminary analysis indicates that mechanical ventilation as installed and operated in Austrian schools reduces CO_2 concentration significantly. The goal for further analysis is to expand the data set and generate clean data for further analysis, including temperature and b-VOC_{eq}. Furthermore, the data failures are to be quantified and correlations to underlying conditions in the individual classes, such as class size, window orientation, etc., are to be established.

5 ACKNOWLEDGEMENTS

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