CO_2 monitoring to enhance digital and green competences in VET

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Abstract

This contribution presents the results obtained within the KA2 Erasmus Plus project CO_2 Monitoring in Schools for digital and green competences (CHANGE) [1]. The consortium, made up of an Italian Research Institute and four VET schools in Bulgaria, Italy, Romania and Spain, is developing, testing and optimizing a didactic pathway centered on Indoor Air Quality [2] in schools. The pathway combines digital skills, i.e. system integration, programming and data processing, with socially relevant topics such as IAQ monitoring, energy efficiency, greenhouse gases and climate change, raw materials and open data, in order to provide students with competences useful to meet the requirements of the labour market and to foster their critical thinking on scientific basis. The experimental section consists in the assembly of CO_2 monitoring stations controlled by a Raspberry PI microcomputer with open source code programmed in Python, and in its use for the continuous monitoring of the CO_2 concentration in the classroom. The acquired data, as well as the metadata needed for their interpretation, are collected in an open data repository [3] based on CKAN [4]. Mid-term monitoring (approx. 1 month) has been carried out in different indoor spaces and the results, analyzed by the students themselves, will be presented. The outcomes of the first project year (2022-23), testified by questionnaires and CO_2 monitoring reports, show a general satisfaction towards the pathway and the Erasmus Plus dissemination activities. As a drawback, the metadata annotation, needed to obtain reliable and reusable monitoring data, shows some weaknesses. The mitigation solutions that are going to be tested within the second year (2023-24) of the project include teachers' training on open data management, software interface simplification, and increase of the detail in the annotation and reporting guidelines provided to the students. This presentation will eventually discuss their effectiveness and ease of implementation. Indeed, the ultimate goal is the establishment of a reliable action chain connecting monitoring with open data in order to enhance further elaboration and citizen science initiatives involving schools.

Keywords: *indoor air quality, digital, sensors, open source, data, citizen science*

1. Introduction

Indoor air quality monitoring (IAQ) is expected to play a great role in the field wellbeing and green buildings in the next years. While societal issues such as the COVID-19 pandemics and the methane shortage, highlighted, on the one side, the importance of IAQ and, on the other side, the need for energy saving. However, the achievement of both objectives might be in contrast, since the fresh air supply required for the maintenance of good IAQ standards induces higher energy consumption in buildings [1], while the domestic heating sector is responsible for greenhouse gas emission and air pollution. Addressing these issues by providing adequate behavioural indications and innovative market solutions requires a comprehensive analysis of IAQ data obtained in different environments, including e.g. houses, schools, offices, hospitals, as well as the work of trained professionals. Commercial IAQ systems often incorporate carbon dioxide (CO_2) sensors, because, even if it cannot properly be defined as a pollutant, the CO_2 molecule is relatively easy to detect, and a high CO_2 concentration is indicative of poor room ventilation with respect to the number of occupants, which, in turn, might favour the presence of other potentially harmful pollutants [2].

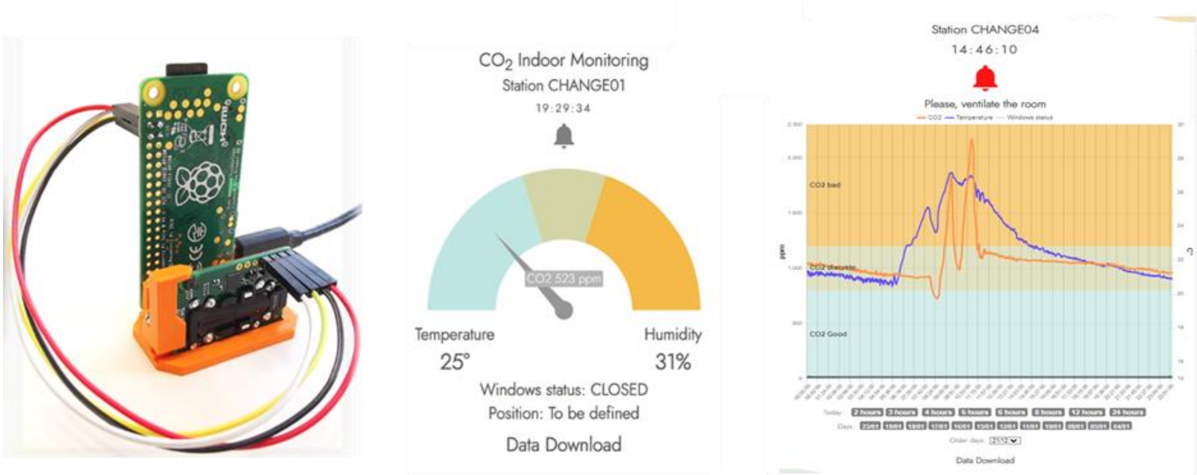
The project "CO_2 Monitoring in Schools for digital and green competences" (CHANGE) [3] has the scope to release a didactic pathway that introduces the growing IAQ market to VET students. The students involved in the pathway are expected to monitor the CO_2 concentration in selected school environments by making use of monitoring stations assembled by themselves, made up of commercial components, programmed with open-source software. The monitoring data are made open through the publication on a public repository [4,5]. The pathway includes theoretical sections that highlight connections of IAQ with themes such as environmental monitoring, climate change, assembly and software development for an electronic system, reuse of obsolete electronic devices, and open data, in order to generate digital and green competences and foster critical thinking on scientific basis. Having students familiar with digital skills and topics – software development, system installation and maintenance, programming, data processing – which are more and more required by the labour market ("90% of future jobs will require digital skills" – Digital Education Action Plan, 2021) provides solid credentials for a successful labour market entry.

The scientific content of the didactic pathway has been conceived and optimized by the National Research Council of Italy (CNR) and Proambiente S.c.r.l., a consortium of the CNR Technopole, in the framework of the self-financed Italian project CO2Lab (COOL), 2021-2022, and of the currently ongoing KA2 Erasmus Plus Project CO_2 Monitoring in Schools for digital and green competences (CHANGE), since 2022 November. In the latter, four Schools in Europe are adapting the pathway to their own specific curricular requirements, and testing it in selected classes, in order to provide suggestions for optimization.

This work presents the pathway and discusses the features that have been objective of optimization. The pathway has been proposed to 19 classes in different locations of Italy and 6 classes in Europe (Bulgaria, Romania and Spain). The presented optimization has been achieved by implementing the input acquired from the teachers by informal discussion since 2021, and by filling pathway evaluation questionnaires in 2023.

2. The Pathway

The didactic pathway has been developed by following a modular approach and consists of different materials (e.g. tutorial video and presentations, pdf manuals, report sheets and templates) available to be used and customized by the teachers. The core activities consist in: a theoretical section, covering the meaning of the CO_2 concentration in air, its relevance towards IAQ and climate change, the CO_2 measurement principle; a practical section dealing with the assembly and use of CO_2 monitoring stations based on low-cost commercial components and open-source software; CO_2 continuous monitoring; and evaluation of the acquired knowledge. Figure 1 shows the CO_2 monitoring station (a) and the two display modes of its WebApp interface (b,c).



(a) (b) (c)

Fig. 1. CO_2 monitoring Hardware and Software: assembled station (a), main WebApp page (b), chart WebApp page (c) with selectable timescale and date.

The main WebApp page (b) displays the actual CO_2 value (gauge) as well as the temperature and relative humidity values. In (c) is reported the trend of CO_2 - the orange line with the scale on the left axis – and the temperature - the blue line with the scale in the right axis.

2.1 CO_2 monitoring stations and WebApp

The monitoring station is made up of: a Sensirion SCD30 dual channel sensor, a single board computer Raspberry Pi Zero W equipped with supply and SD card with Python code on board, a 3D printed support, and accessories for the system assembly.
SCD30 detects the CO_2 concentration by the non-dispersive infrared absorption principle [6], and is equipped with temperature and relative humidity sensors. The measured values are acquired, every 5”, by a Raspberry Pi Zero mini-PC via an open source Python code that exploits a specific two-wire communication bus (I^2C). Finally, the acquired data are sent via wireless connection to a remote server, stored in a dedicated database and displayed through the project WebApp. Two visualization modes are possible: a three-colour CO_2 gauge with CO_2 level intervals below 800 sccm, between 800 and 1200 ppm, and above 1200 ppm; and a graph displaying the CO_2 concentration and the temperature vs time, with a selectable time interval between 1 and 12 hours. It is also possible to select previous measurement days and download the corresponding .txt files by clicking on the date buttons. Other information displayed are: temperature, relative humidity, window status, and position where the station is located. These parameters can be set via the administrator page.
The didactic material includes instructions and tutorials for station assembly, and a user manual for station usage and maintenance, data acquisition and visualization, in order to allow for an autonomous use of the stations by teachers and students.
In order to familiarize with the use of the stations, several experiments producing CO_2 concentration variations are performed in the classroom: 1) CO_2 increase in a closed box via a chemical reaction or the introduction of a glass containing sparkling water; 2) CO_2 decrease under a glass dome containing a plant or performing a mechanical ventilation (using a small electrical fan); 3) CO_2 increase induced due to people crowding near the monitoring station; 4) CO_2 decrease in consequence of window opening. These experiments are not intended to provide information on chemical reactions; nevertheless, the range of possible experiments was enriched thanks to the collaboration of teachers of chemistry. The analysed chemical reactions include acid/base reactions, such as the one between lemon juice or vinegar and sodium bicarbonate, fermentation, such as the reaction between yeast and sugar, and the visualization of the effect of CO_2 variations, i.e. balloon inflation or flame extinction. Coupling the CO_2 sensors with chemistry experiments is an added value for the pathway, because it provides connections with the chemistry curricular program. Nevertheless, the added value can be increased thanks to the multidisciplinary didactic material that fosters the connections with the computer science and mechanics teachers.

2.2 Thematic didactic modules

The choice of visualizing the data via a WebApp allows to avoid the use of a dedicated display and reduces the amount of electronic devices required for the activity. Data visualization can be achieved by using hardware that is already available, such as the classroom PC, the students’ mobile phones, or an old mobile phone that can be reused for the activity, in a circular economy perspective. This observation opens to the additional module “materials in electronic devices and planned obsolescence”, a specialist lecture on electronic fabrication technologies, material and chip shortage, and professional skills addressing the chip market. This is an example of digression from the main topic that can be added to the pathway modular structure. Other specialist lessons cover topics such as: the Intergovernmental Panel on Climate Change report; IAQ and health; IAQ and building materials; open source and open data. Practical activities are covered within the following modules include: python programming for system integration (sensors interface, data retrieval and storage, connection and data management); CSS and Javascript programming for WebApp development (data visualization and pages customization); mechanical CAD design for 3D-printing for system support or case realization.

2.3 CO_2 monitoring in classrooms

The modular structure allows to tailor the pathway to the school, class and expected outcome. The teachers who carry out the pathway in their class may be focusing on experiments involving CO_2 chemistry, Python coding, peer to peer education, outreach events promoting the school projects, while CO_2 monitoring in classrooms is the outcome recommended by the research institutions proposing the activities.

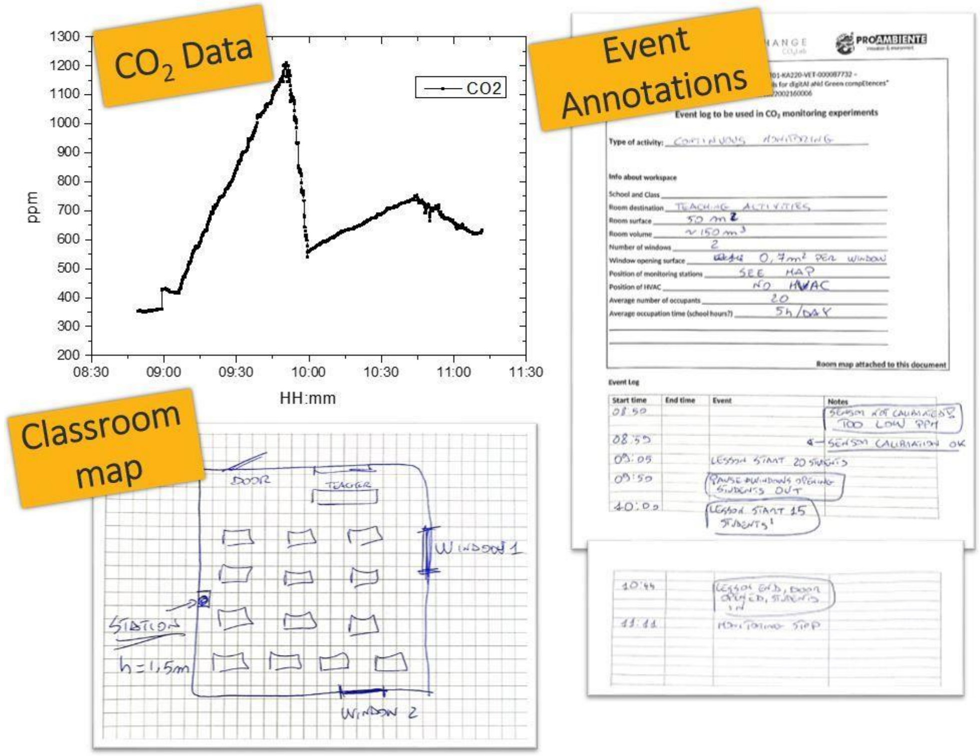
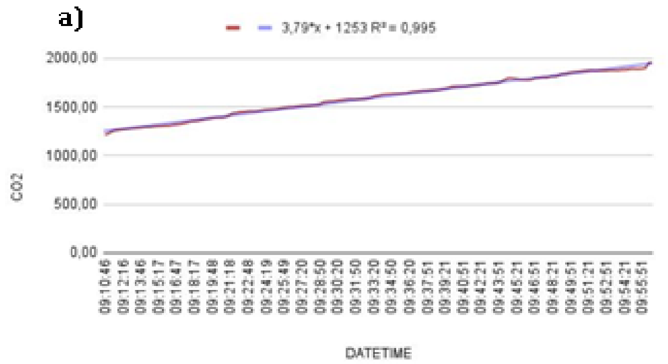


Fig. 2. Example of a daily CO_2 monitoring in a classroom: CO_2 graph (a), event log (b) and classroom map with info (c)

Fig. 2 shows an example of CO_2 monitoring report: the CO_2 concentration curve vs time (a); related data annotations (b,c): event log describing the situation and the events occurring at specific times (b); classroom map (c). It is apparent at a first glance that the CO_2 concentration curve (a) does not provide enough information for a successive interpretation. Data acquisition is carried out between 8:30 and 11:44. At the station start, the CO_2 concentration is < 400 ppm (section 1 of the curve). At TIME the CO_2 concentration undergoes an instant increase to about 420 ppm (instant 2 on the curve). At 9:00, the CO_2 concentration starts rising at 17 ppm/min rate (section 3 of the curve). At 9:50 the CO_2 undergoes a steep decrease (section 4), followed by an 8 ppm/min rise (section 5) until about 10:20. Finally, the CO_2 slowly decreases (section 6) till the end of the monitoring (instant 7 on the curve). These CO_2 trends can be related to the annotated events: during section 1, the measured CO_2 concentration is lower than the atmospheric one: it is necessary to calibrate the station, and this is done at 8:59, i.e. instant 2; after the lesson start, at 9:00, the CO_2 increases (section 3) until the break, that starts at 9:50; the window and door opening during the break induces the rapid decrease observed in section 4; the lessons begin at 10:00 with less students in the classroom: indeed, the slope of the CO_2 increase recorded in section 5 is lower than the one in section 3; also the door opening at 10:44 produces a smoother CO_2 decrease (section 7) then the one recorded during the pause, because in this case the students are in the classroom. At 11:00 data acquisition is stopped. Further analyses can be made to discuss a CO_2 concentration curve with respect to the classroom map (c). Examples are provided in Fig. 3:

- extract the CO_2 rise rate as a function of the unit area and unit volume occupied by each student (Figs. 3a and 3b);
- calculate the percentage of time spent by the students in a CO_2-rich environment with respect to the time spent in a healthy environment (Figs. 3c and 3d) having also the possibility to compare days with random (Fig. 3c) and scheduled (Fig. 3d) windows opening. The latter is approx. 10’ every hour;
- compare the obtained results as a function of the station location in the classroom, by changing, for example, its distance from the windows and from the students, or its height from the floor (Fig. 3c);
- find correlations between CO_2, temperature, and relative humidity trends, as a function of annotations and eventual Heating and Ventilation and Air Conditioning (HVAC) systems schedule.



b)

Number of students	Volume per student (m^3)	CO_2 rise rate (ppm/min)
22	15,7	3.97
22	15,7	3.79
20	17,2	3.48

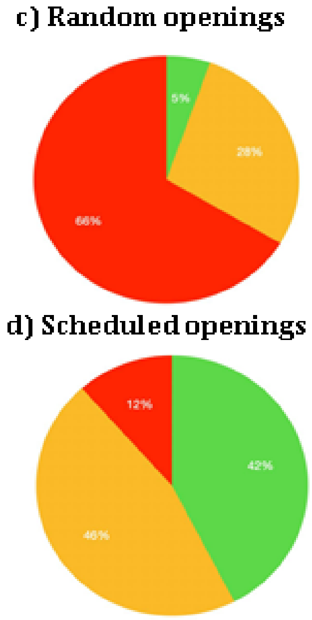


Fig. 3. Output examples by the students: graph mathematical analysis (a) and related info calculation (b), analysis of spent time vs CO_2 value having random (c) and scheduled windows opening

Such analyses might provide behavioral indications for the occupants of school spaces, thus increasing awareness towards measures that can be taken to improve IAQ. Furthermore, the calculations needed to extract the results represent an example of “authentic task” that improves the students’ digital competences, while changing the station location is an example of creation of an experimental setup, that opens to explain statistical errors and to identify proper working conditions for low cost sensors, in order to avoid measurement artifacts. The whole continuous monitoring activity, that includes decision on station location, data acquisition and metadata annotation, data analysis, and, eventually, reporting, increases the scientific literacy of the students.
Of course, the balance between the continuous monitoring activity and the use of the CO_2 sensors as a didactic tool in laboratory activities is a teacher’s choice. However, we noticed that the attention caught by the pathway is higher among the teachers of chemistry and biology, who, in turn, realize the connection between the pathway and the curricular program, and, consequently, emphasize the experiments involving CO_2 reactions also in the evaluation of the learning. For a complete exploitation of the CO_2 monitoring station potentialities both as a support for the experiments and as an IAQ data source, the class can rely on a document outlining CO_2 monitoring report guidelines.

2.4 CO_2 monitoring report

The CO_2 monitoring report is a written document. It must be made by the students and can be made either as a document or as a presentation. The function of the monitoring report is dual: it’s a learning evaluation tool and a data source. Much attention has to be dedicated to the data presentation and elaboration.
The CO_2 monitoring report must contain one plot of the CO_2 concentration as a function of time for each day of continuous monitoring in classroom. The plot can be drawn with a program (e.g. Excel, OpenOffice Calc) or can be a screenshot of the WebApp. The suitable XY scale must be chosen in order to highlight the reported phenomena.
The information that must be correlated to the graphs in order to appropriately validate the data are:

- classroom size: surface (m^2), volume (m^3).
- CO_2 monitoring station position: it can be accompanied by a photo or by a map of the classroom. The height and the distance from the closest CO_2 source, usually a person, are useful information.
- Useful information can be also the activities carried out in the room (e.g. sport, lunch, cleaning), mainly in case the monitoring is carried out in a place other than a classroom.
- Each datum, i.e. each point, should be correlated to the number of people in classroom (students + teachers) and to the window status (open/closed).
- Correlation between the window status and temperature.

This report can be verified by researchers or a peer to peer verification system can be setup in the class, by using this checklist as a guide. Verified data can be published on the project data open portal according to the Findable, Accessible, Interoperable, and Reusable (FAIR) data principle.

3. Discussion on the optimization

This section deals with the issues encountered in the achievement of the set objectives and presents the refinements made to conform to the expectations of the researchers who first outlined the learning pathway. The core need addressed by the pathway is to provide VET students with up-to-date making (electronics and system integration) and digital (programming, WebApp development, data visualization) competences that can be useful in future green professions. As stated in section 1, IAQ represents a growing market and is then suitable for competence development, starting from an easy-to-understand marker as CO_2.

Moreover, the public release of the data from CO_2 monitoring in different schools carried out within the CHANGE project, is expected to contribute to the generation of knowledge about IAQ in schools, directly connected with pupils' wellbeing [7] and attention [8] and which is also sensitive to site-specific features [9].

The advantage from the collection of such data increases by increasing the number of involved classrooms. However, a tradeoff is required, since the numerical impact of this action would be modest if the researchers were meant to be directly involved all along the pathway, and on the other hand, the contact between with researchers might stimulate pupils' interest towards advanced electronic devices and their use in innovative applications. The tradeoff might be offered by establishing a close collaboration with researchers in the data acquisition, in order to allow students to act "as researchers", while having the teachers lead the pathway in their classes, using the CO_2 monitoring stations as a didactic tool for the provision of both knowledge and competences. Besides, supporting the teachers to autonomously use the CO_2 monitoring stations lays the foundations of the project durability: trained teachers might keep on using the stations as didactic instruments also after the end of the project. To this purpose, some teacher training actions have been held or scheduled along the CHANGE project duration. The training consists in an overview of the teaching material and a session of station assembly and use to get familiar with these tools. Trained teachers have access to the modular teaching material, free for reuse and adaptation; additionally, the CO_2 monitoring stations have been equipped with a detailed user manual, that allows for problem solving during operation. This supporting document has been appreciated by the teachers attending the training course. It is worth noting that this supporting document is not necessary if the pathway is implemented having the researchers give the lessons.

Besides the impact on pathway spread and durability, teacher involvement has been recognized as a positive element for the effectiveness of the continuous monitoring. In our experience, punctual metadata annotation and high-quality reports were achieved by the classes where teachers were directly involved in analysing the monitoring data. Similarly, A. Di Gilio *et al*., who carried out a study on CO_2 concentration in schools upon random window opening or after the establishment of a ventilation protocol, observed that an overall improvement of CO_2 levels was indeed registered for all classrooms where teachers were compliant and helpful in the management of the air ventilation strategy and that the real-time visualization and monitoring of CO_2 concentrations allowed for effective air exchanges to be implemented [10].

It is worth to remark that though the interest in CO_2 concentration in schools raised after the COVID-19 pandemics, the interest in indoor air quality is high in the scientific community, and the collection of data from schools across Europe can contribute to outline behavioural protocols [9]. For this reason, effective event annotation correlating monitoring data is mandatory. A first step that was implemented to obtain complete data reports was the release of monitoring report guidelines. This document proposes a scheme for the reports on the CO_2 monitoring experiments carried out in school environment. As a second step, the pathway didactic material was completed with the addition of a seminar on the FAIR data concepts [11], in order to raise awareness on the importance of metadata for the successive use of the produced monitoring data. As a third improvement, the WebApp can be implemented with the possibility to set the metadata, i.e. location, number of people, window status, in the moment of the data analysis. This trick allows to just write down the window opening/closing instants during the lesson in order not to interrupt it, while maintaining the possibility of saving annotated data.

4. Conclusions

The availability of low-cost sensors for indoor pollutants enables widespread measurement campaigns that are carried out in several research projects, also involving citizen science. In particular, CO_2 is relatively easy to detect, and, even if it is not a pollutant, it can be indicative of poor room ventilation with respect to the number of occupants, which, in turn, might favour the presence of other potentially harmful air pollutants. For this reason, CO_2 sensors are often employed in commercial indoor air monitoring systems, whose use was recommended also in schools after the COVID-19 pandemics. This work presented a didactic pathway which uses CO_2 monitoring stations made up of commercial and open source material that can be used both for CO_2 monitoring, according to the citizen science concept, and as a didactic tool for monitoring chemical reactions involving CO_2, or as an informatics lab. Coupling CO_2 monitoring with green and digital competences allows for maintaining the durability of this topic beyond the interest raised by the COVID-19 pandemics.
The pathway was developed by two research institutions in Italy, and optimized thanks to the contribution of teachers of different disciplines in Italy and Europe. The pathway optimization concerned the contents, the supporting material, and the management method of the pathway. From this experience, we believe that the key elements for a successful implementation of the pathway are the contribution of teachers from different disciplines leading the pathway, and the direct contact between students and researchers in the data collection and evaluation stage.
Further developments might involve the use of multi-sensors IAQ monitoring systems, adding for instance Particulate Matter (PM) and Volatile Organic Compounds (VOCs). These can be simply seen as an enrichment of the proposed CO_2 monitoring system while providing a more comprehensive picture of IAQ in schools.

References

[1] Moghadam, T.T., *et al.*, “Energy efficient ventilation and indoor air quality in the context of COVID-19 - A systematic review”, Renewable and Sustainable Energy Reviews, 182, 2023, p. 113356. DOI: 10.1016/j.rser.2023.113356
[2] Prill, R. et al., “Why Measure Carbon Dioxide Inside Buildings?”, Washington State University Extension Energy Program (2000). https://www.energy.wsu.edu/documents/co2inbuildings.pdf last consulted on January 29th, 2024.
[3] https://www.co2lab.it/change-erasmus/
[4] https://dalia-bo.cnr.it/organization/change.
[5] https://ckan.org/
[6] https://en.wikipedia.org/wiki/Nondispersive_infrared_sensor
[7] Peng, Z., and Jimenez, J., "Exhaled CO2 as COVID-19 infection risk proxy for different indoor enironments and activities", Environ. Sci. Technol. Lett. vol 8, 2021, pp. 392–397. DOI: 10.1021/acs.estlett.1c00183
[8] Daisey, J.M., *et al.*, “Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information”,Indoor Air, 13, 2003, pp.53-64. DOI: 10.1034/j.1600-0668.2003.00153.x
[9] Sadrizadeh, S., et al., “Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment”, Journal of Building Engineering, 57, 2022, 104908. DOI: 10.1016/j.jobe.2022.104908
[10] Di Gilio,A., et al., “CO2 concentration monitoring inside educational buildings as a strategic tool to reduce the risk of Sars-CoV-2 airborne transmission”, Environmental Research, 202, 2021, 111560.
[11] https://en.wikipedia.org/wiki/FAIR_data