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Evaluation of the impact of ventilation system daily operation on air quality, comfort and well-being in primary schools

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Abstract. The Scol'air-FR project is issued from the need to establish an inventory of indoor air quality conditions in primary schools of the canton of Fribourg, Switzerland. In Fribourg, the official trend is to promote mechanical ventilation systems in schools to ensure a good air quality. A properly designed, built, commissioned, and operated mechanical ventilation system should be able to deliver the anticipated flow rate, regardless of who uses it - the only person involved being the person responsible for ventilation system operation. In some cases, however, the expected objectives are not achieved. This similar observation applies to natural ventilation. A good ventilation concept, properly implemented and operated, should also achieve the same objective if the outdoor air quality is good. The aim of this article is to identify differences, in terms of indoor air quality and well-being, between naturally and mechanically ventilated schools. Moreover, we expect to identify if trends are attributable to the operation of ventilation systems or to occupant behaviours. We observed lower carbonic gas levels in building equipped with mechanical ventilation systems. This finding can be extended to VOCs and relative humidity. We also identified different and recurrent issues among the different mechanical ventilation systems. Our results highlight issues measured in buildings equipped by mechanical ventilation systems are mostly related to the balance of the system, while in natural ventilation systems, IAQ related issues are mainly due to the present context and its influences on occupants' behaviour.

1. Introduction

Indoor air quality (IAQ) in educational facilities is a major concern for children's health and development and, consequently, for the authorities in charge of the school buildings. For instance, it has been shown that children's cognitive performances are affected at high levels of CO_2 in classrooms [1,2]. The Scol'air-FR project is issued from the need to establish an inventory of indoor air quality conditions in primary schools of the canton of Fribourg in Switzerland. It is the first project undertaken by the recently formed association ORTQAI (www.ortqai.ch), which aims to aggregate and spread IAQ-related knowledge. In this project, we measured and studied the indoor air quality in different schools selected within the canton of Fribourg between 2021 and 2023. Due to various circumstances, Fall 2021 campaign was marked by strict SARS-CoV-2 pandemic restrictions, Winter 2022 by more flexible SARS-CoV-2 pandemic restrictions and Winter 2023 campaign by energy savings measures.

The main research question addressed by the Scol'air-FR project is the following: Can IAQ and well-being differences be identified among naturally and mechanically ventilated schools? Moreover, are these trends attributable to the operation of the ventilation systems or to the occupant's behaviors? Moreover, are the expected results of the pandemic restrictions, in terms of aeration and disinfection, measurable in our data? Besides, did these effects last on the long term? In other words, was IAQ similar during SARS-CoV-2 pandemic restrictions and the energy saving period in the investigated classrooms? This paper is the first of publications to come that will be based on the data acquired during this leading and innovative project in West Switzerland.

2. Methods

Over an 18-month period, four different measurement campaigns were carried out in three different seasons: Fall 2021, Winter 2022, Summer 2022, and finally Winter 2023. In total, 24 schools were monitored over one full week periods during each of the campaign. The selected schools were chosen to be representative of the linguistic context, the ventilation system's type, and area's type (rural, suburban, urban). The sample comprises 13 naturally ventilated schools (passive ventilation), and 11 with mechanical ventilation systems (mostly double flux systems). In each school, two classrooms and one outdoor nearby location were systematically investigated. Indoor CO_2, particulate matter (PM), VOCs, radon, air temperature and relative humidity were monitored as well as outdoor apart for CO_2. Qualitative surveys were addressed to teachers to assess users' comfort and activities in their classrooms. In schools equipped with a mechanical ventilation system, more in-depth analyses were carried out to assess the quality of the latter.

3. Results

The available results considering Fall 2021, Winter and Summer 2022 and Winter 2023 campaigns are presented below.

3.1 Carbon dioxide

The carbon dioxide concentration was measured, along with temperature and humidity, during four campaigns. In Table 1 are reported the results of basic descriptive statistic tools, based on data measured only during the teaching periods for all classes, grouped by season and ventilation systems. The concentration range recommended by the Swiss standard SIA 180 is 1000-2000 ppm for occupied spaces. The standard SIA 382-1 recommends to size and use the mechanical ventilation systems so that 1400 ppm is not overpassed.

Table 1. CO_2 concentrations (ppm) in mechanically and naturally ventilated classrooms.

Season	**Fall 21**		**Winter 22**		**Summer 22**		**Winter 23**	
Conditions / Restrictions	Strict SARS-CoV-2		Flexible SARS-CoV-2		Normal		Energy saving	
Heating	On		On		Off		On	
Ventilation system	Mec	Nat	Mec	Nat	Mec	Nat	Mec	Nat
Average CO_2 concentration	706	809	675	816	576	594	705	962
Maximum CO_2 concentration	2042	2644	1580	3129	1498	2318	2812	3274
% of time above 800 ppm	30%	42%	25%	44%	11%	14%	30%	57%
1000 ppm	11%	24%	6%	24%	2%	6%	12%	38%
1400 ppm	1%	5%	0%	7%	0%	1%	1%	15%

On average, naturally ventilated classrooms' number of students were higher by two more students and in terms of surface, $5.5m^2$ smaller than mechanical ventilation classrooms. However, the average classrooms' volumes were not significantly different (X^2 test, $P < 5$ %).

The CO2 concentration during teaching time above a given concentration limit were larger in naturally ventilated classes than in mechanical ventilated ones. The difference is statistically very significant during the heating season (X^2 test, P(d=0) <0.01%), but less significant in June or September (e.g. (P(d=0) =18% for the average CO_2 concentration). The seasonal effect exists with both ventilation systems. The CO_2 concentrations were larger in winter than in summer. The differences were however much larger (about the double) in naturally ventilated classrooms than in mechanically ventilated ones. Hygienic airing measures to reduce the SARS-CoV-2 contamination were mandatory during Fall 2021 and winter 2022 but no more in 2023, when energy saving measures were recommended. In naturally ventilated classrooms only, the average CO_2 concentration increased by 19%, and the part of the teaching time above 1000 ppm increased from 24% to 38%.

3.2 Air humidity

Increasing the ventilation rate per person reduces the concentration of any human-produced contaminant, including water vapour. Therefore, an exess of ventilation rate dries the indoor air, especially in the cold season.

Table 2. Relative humidity in mechanically and naturally ventilated classrooms.

Season	**Fall 21**		**Winter 22**		**Summer 22**		**Winter 23**	
Conditions / Restrictions	Strict SARS-CoV-2		Flexible SARS-CoV-2		Normal		Energy saving	
Heating	On		On		Off		On	
Ventilation system	Mec	Nat	Mec	Nat	Mec	Nat	Mec	Nat
Average humidity (%)	28,1	31,2	23,8	27,9	43,0	47,3	28,8	28,5
% of time below 30%	78%	44%	92%	67%	5%	2%	59%	59%
% of time below 40%	92%	93%	100%	97%	34%	13%	98%	96%

In winter, air humidity was very low in most classrooms, and below 30% most of the time in mechanically ventilated ones. It was slightly higher in naturally ventilated classrooms, but still always lower than the minimum recommended 40% [3].

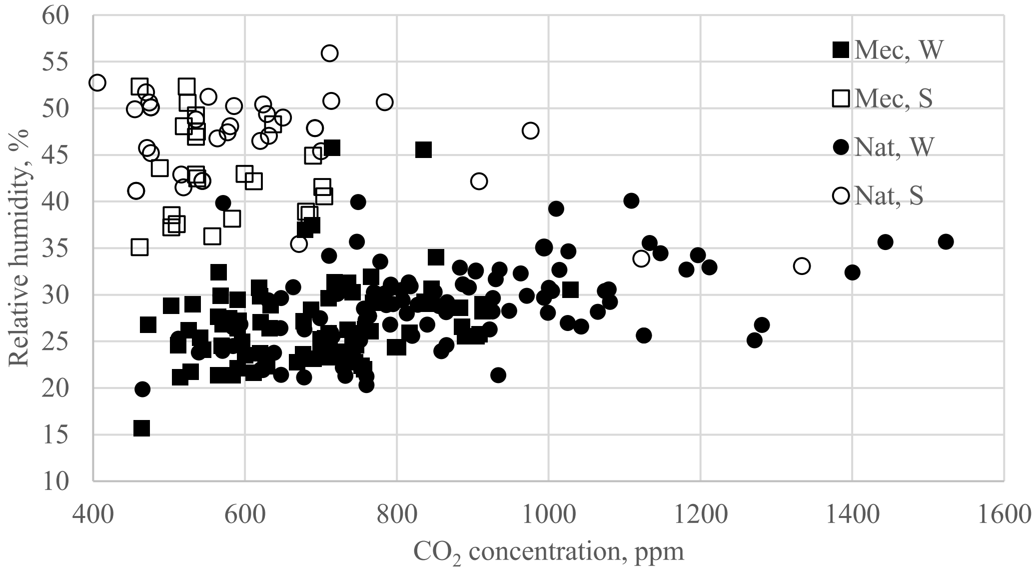

Figure 1. Average relative humidity and CO_2 concentration in each classroom, sorted by season (Winter or Summer) and ventilation system (Mechanical or Natural).

In Figure 1, each dot represents the average CO_2 concentration and relative humidity for one classroom during occupancy, for the two seasons.

It can be seen that a few classrooms can keep the average CO_2 concentration in winter below 1000 ppm together with an average relative humidity above 40%, showing implicitly that both natural and mechanical ventilation systems are able to simultaneously ensure a correct CO_2 concentration and air humidity.

3.3 VOCs
Regarding total VOCs, a large difference appeared between mechanically and naturally ventilated classrooms with respectively a 75-percentile located at 150 µg/m³ and 350 µg/m³ equivalent in toluene. These findings were similar for PM and radon, which depicts a lower IAQ in naturally ventilated classrooms. As expected, all monitored pollutants were recorded with lower concentrations at the outdoor measurement points.

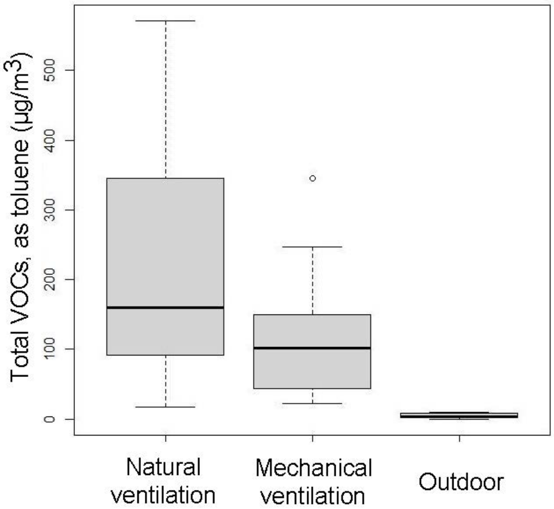

Figure 2: Distribution of total VOCs during Fall 2021 measurement campaign in naturally ventilated classrooms, mechanically ventilated classrooms, and at outdoor measurement points.

3.4 Seasonal effects
These preliminary results revealed an IAQ difference between naturally and mechanically ventilated classrooms, emphasizing disparities within the canton. Besides, Fall 2021 campaign was carried out while SARS-CoV-2 protection measures were in force, which indirectly implies a better IAQ than before the pandemic. Results also support a strong need to increase knowledge on ventilation systems' actual operation modes in schools. The eleven schools equipped with mechanical ventilation systems were further analysed to clearly identify their deficiencies and to optimize their operation. On the long-term, these results will be useful to address a list of recommendations for both ventilation system installers, maintenance staff and building owners.

3.5 Management of the mechanical ventilation systems
As mentioned in the methodology sections, several in-depths analyses of the ventilation systems were carried out in mechanical ventilated schools. The purpose was to assess different parameters relevant to evaluate these ventilation systems and to better understand our results. Many different data were therefore retrieved:

- Brand of the air-treatment main unit;
- Year on construction of the monobloc;
- In- and out- nominal -flow rates according to plans. Nominal flow rates were estimated for 23 children and one teacher in every classroom;
- Air flow regimes;
- Ventilation schedule;
- Presence of a variable flow rate depending on a CO_2 sensing probe;
- Heat recovery system installed;
- Presence of a moisture-recovery system;
- In- and out- typical -flow rate measured in a classroom when it was possible to measure them. If it was impossible, tracer gases were used;

Unsurprisingly, mechanically ventilated schools are the most recent ones in our sample. They were all built since the 2000s, with a median in 2015. On the opposite, the median construction year for naturally ventilated schools is 1943. Besides, the oldest investigated school was built in 1835.

We noticed a relative consistency between the different air-treatment main unit installed in the investigated schools. Among the installed units, six were from the brand Depair [4], two from Seven Air [5], one from Swegon Gold [6] and one from Weger [7]. Both Depair and Sevenair are Swiss brands. The nominal flow rate announced in each school would suggest that a major part of the installations have been designed to put classrooms under a slight overpressure, which ideally includes toilets at the end of the floors. This consists in the most conventional method. Nevertheless, huge differences between designed and measured airflow rates were identified across the different schools, although the aim of the mechanical ventilation systems are the same, *i.e.,* ventilating primary classrooms. These differences spread from one to three-times the value of the nominal airflow rates. This finding is surprising because these buildings are labelled Minergie [8], or comply with a similar label, and are supposed to be optimized to host children in the best environmental conditions.

It was also observed that all the ventilation systems installed have probably modulating fans, except for one still equipped with a double-wiring motor. This presents the advantage of enhancing energy-efficiency for multi-speed installations. However, we noted that only two out of the 11 installations took the advantage of using the fan modulation capability. All the others were still using the traditional 2-speeds solution. Similarly, none of the installations were taking advantage of the possibility of reducing the airflow in cold weather to keep the ambient humidity, as recommended by standard SIA 382/1: 2007 & 2014.

Moreover, the analysis of ventilation systems' operating times also showed that major part of installations was running far too long and too strong during the day. Ventilation systems' operating times should be more finely set and consider the schedules of school occupancy. This would result in a substantially high electrical and thermal savings, as well as in a reduction in maintenance costs. Furthermore, and above all, this measure would result in a reduction of the air-dryness in classrooms during winter periods. Finally, we noticed the absence of a prior assessment method to control the expected the airflows. This results in the inability to assess the reliability and the performances of the mechanical ventilation systems, and consequently to adjust afterwards the systems' balance. However, we located valves access to ventilation ducts behind the false ceiling of the bathrooms in some of the investigated schools. But these valves remain usually very difficult to access.

To ensure the highest performance of the ventilation system, it would be better to have standard IRIS dampers which allows both adjustments and airflow rate measurements. Among the investigated buildings, only one was partially equipped with IRIS dampers installed only on main ducts leaving the monobloc. Even in this building, the final adjustments were made through difficult to access valves.

4 Discussion and conclusion

The first results of the Scol'Air-FR project presented in this paper might be explained by several factors observed during the analysis of mechanically ventilated schools.

We first noted some important and statistically significant differences between naturally and mechanically ventilated schools in terms of carbon dioxide level, indoor air relative humidity and total VOCs, and this among the different campaign. We also denoted the influence of SARS-CoV-2 protection measures and energy saving restrictions on indoor air quality in primary schools of the canton of Fribourg. Complementary analyses were carried out on mechanical ventilation system to identify their strengths and weaknesses. This resulted in the following observations.

At first, the installation of moisture recovery systems is clearly not yet a common practice, even though it is a recognized system for keeping at comfortable level the ambient relative humidity, especially during the winter period. However, this system is not sufficient on its own to solve all air-dryness related issues. Ideally, to keep indoor relative humidity on a sufficient level, moisture recovery systems must be combined with optimal airflow rates that are strictly calculated and adapted to requirements and operating. It was also observed that the highest nominal airflow rates were observed in two of the three schools equipped with rotary heat exchanger (*i.e.* heat recovery system) units that also allow humidity recovery. This highlights the following interrogation: Did high airflow rates motivated designers to include moisture recovery, or the installation of a moisture recovery system by the designers that lead consequently to increase the airflow rates? Unfortunately, results underlined a global over-ventilation which consequently canceled the advantages of moisture recovery system.

In the case of an under-pressurized classroom which should be normally slightly over-pressurized, the classroom will be partly supplied by pre-polluted air from another classroom. Therefore, CO_2 are more kind to raise quicker during teaching hours and decrease slower during breaks or at the end of the lesson. Air renewal is therefore insufficient and inadequate to provide optimal teaching and studying conditions for the children. Overall, protection measures taken during the SARS-CoV-2 pandemic, which had a strong impact on IAQ at the time they were enforced, did not influence our behavior on the long term and in general, indoor air comfort and quality is lower two years after being lifted.

Finally, since the electric energy consumption is proportional to the cube of the air flowrate, a small decrease in the ventilation speed will result both in a lighter air flow rate, and consequently in substantial energy savings. In the present context of environmental changes and more precisely energy savings in Europe, it is very important to implement every method which aims to result in a decrease of energy consumption

Globally, the same issues are still being encountered:

- Airflow balancing is not done systematically and extensively;
- In most of the installations analyzed, the terminal airflows in the classroom's air vents were not measured during commissioning by professionals. In the best cases, the airflow measurement protocols only mention the airflows of the main branches, whereas the terminal airflow within classrooms is significant, decisive and useful for the indoor air quality and well-being;
- Finally, the airflow balancing of the whole ventilation system is a long and tedious job. Therefore, it should be expressly mentioned and described in the tender specifications. Otherwise, there is a strong risk that the latter will not be carried out at the end of the process, as it is confirmed by the present observations. Lastly and to avoid the shortcomings observed, we recommend that an independent inspection of the ventilation system's proper functioning upon receipt be required.

To conclude, we observed that most of the IAQ related issues in mechanically ventilating buildings are due to an unbalanced ventilation system, the lack of knowledge of some professionals, and the absence of inspection upon receipt. In naturally ventilated classrooms, the occupant is the main regulator of indoor air renewal. We observed that the present context largely influences its behavior in terms of ventilation, especially during winter times.

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