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1.SUMMARY

The aim of the present work was to study how to maximize indoor environmental quality and energy performance in classrooms, when having different ventilation alternatives combined with a visual CO_2 feedback. In this effort, in heating and cooling seasons, field experiments were carried out in pairs of naturally and mechanically ventilated classrooms during normal school hours with and without CO_2 sensors that provided a green/yellow/red visual indication. At the end of each week children reported their perceptions and symptoms using a questionnaire. The classroom temperature, humidity and CO_2 levels were continuously measured together with the outdoor conditions. Magnetic sensors recorded opening of windows and classrooms energy usage was recorded by the meters installed on water-based radiators. An energy simulation model was created in IDA-ICE-4 to reproduce and compare energy demands/performance. With the CO_2 feedback more windows were open and the levels of CO_2 were reduced, as expected. As a consequence of more windows opened in this condition the energy use for heating in winter was increased and for cooling in summer reduced. Results show that split-cooling in summer can have negative effects on air quality when no CO_2 feedback is installed, as less windows are opened then suggesting temperature as the main factor causing window opening. Children reported that they liked to use the CO_2 feedback, with their perceptions and symptoms somewhat improved when feedback was installed but the results did not reach statistical significance. To improve indoor air quality in schools, CO_2 feedback was shown to be an effective tool in naturally ventilated classrooms.

2.INTRODUCTION

In the last years, the attention for indoor air quality (IAQ) in schools has grown. The promotion of good IAQ in schools is of particular concern since children spend more than 30% of their time inside classrooms and because they are generally more susceptible to environmental pollutants than common workers (Landrigan, 1998; Avigo Jr et al. 2008). Low ventilation is also associated with the effects on comfort, sick building syndrome symptoms, respiratory problems and reduction of short-term sick leave; improving outdoor air ventilation rates can improve student performance. (e.q. Shendell et al, 2004; Wargocki et al., 2006). Indoor air quality problems in schools may be very different from these observed in industrial, office or residential buildings, because occupancy in schools is usually denser than in these spaces.
Several studies have reported CO_2 concentrations in classrooms above the actual recommendations of 1000 ppm, indicating insufficient ventilation.

To improve the IAQ in schools, expensive adaptations regarding ventilation equipment may be needed. These solutions can be costly and in some cases can take long time to install which is not always feasible. As an alternative solution, ventilation can be improved by simple retrofit solutions, which are easy to implement and can additionally improve indoor environmental quality in classrooms with as low as possible energy cost. Many schools have operable windows. Their main function is to provide adequate control of the classroom air quality, and their secondary function is to avoid overheating in warm weather, in particular in classrooms with natural ventilation. Access to windows can potentially also improve psychological comfort of the occupants (Brager et al. 2004). Using operable windows in classrooms pupils and teachers will have some control over the indoor environment.

To secure proper and conscious use of operable windows which should secure proper classroom ventilation, the objective of this project is to examine the use CO_2 concentration as an indicator for window opening. Field trials were performed in a school to evaluate an inexpensive retrofit solution using the feedback levels of CO_2. It was examined whether opening of windows in naturally and mechanically ventilated classrooms as a result of CO_2 feedback would improve classroom air quality and what would be the consequences for perceptions and symptoms reported by pupils as well as energy use. Field trials were supplemented with numerical simulations of energy use in classrooms with and without the retrofit solution.

3. DESIGN METHODOLOGY

Experiments were performed in a school which is about 30 km north of Copenhagen in a rural area. The school has an average class size of 23 children. The main construction of school building is of bricks and concrete, and all the school buildings have sloping roofs. Each classroom consists of an entrance hall with a floor area of 15 m^2 and a ceiling height of 2.2 m, which is open to a classroom with a floor area of 50 m^2. Besides 3 large glazed areas, there are 5 narrow windows in the lower area, each with an area of 0.4 m^2, can be opened by students and the teacher. The classrooms are heated by water-radiators, which are located under the windows and are equipped with thermostatic valves which were set up to the same position during the experiments.

The measurements in the school were performed in identical and parallel classrooms over a period in the heating season (March-April 2011) and cooling season (June 2011). Pilot measurements were made prior to these studies.

In the heating season two pairs of classrooms were selected, one with natural ventilation and one with mechanical air handling units (with heat recovery). The study was carried in two weeks, with one classroom in each pair receiving the retrofit solution for a week in a crossover design. During the cooling season, two pairs of naturally ventilated classrooms were examined. One pair with split cooling and another pair without. The split units are normally switched off and operated occasionally during hot periods. The retrofit solution was installed in one classroom of each pair and a cross-over design was not used to make it possible to examine the behaviour over two school weeks.

The retrofit solution consisted of a feedback given by an apparatus (figure 1) performing CO_2 measurements and providing a green/yellow/red continuous visual indication with light-emitting diodes (LEDs) of CO_2 levels in the range from 400 to 2,000 ppm, in intervals of 200 ppm.

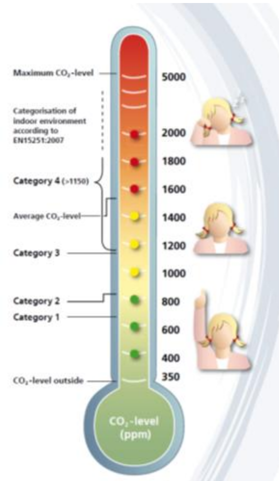


Figure 1 – CO2 feedback apparatus (Ref. Exhausto)

Prior to the experiment pupils and teachers were instructed how to open the windows using the apparatus with CO_2 feedback. The instructions given to children were as follows: the windows should be kept closed when the lights are green. If the CO_2 level is yellow one window should be opened. This approach should be systematic, so if the levels continue to increase even if windows are open, more windows should be open progressively. If the lights reach the red colour, pupils and teachers were told to open all windows and the main door, to achieve cross-ventilation and also to leave the classroom for a short period of time until CO_2 levels drop to yellow.

At the end of each week, children reported their perceptions and symptoms using a paper questionnaire that was distributed by the teachers. Different questions were answered (Table 1) on a scale where the typical linear scale was replaced by a set of “smiley’s” hoping to make it more appropriated for young pupils (Figure 2). The responses collected in the heating season were analysed using the Wilcoxon Matched-Pairs Signed Ranks test. In the cooling season the responses of different children in different classes were compared using the Mann-Whitney U test.

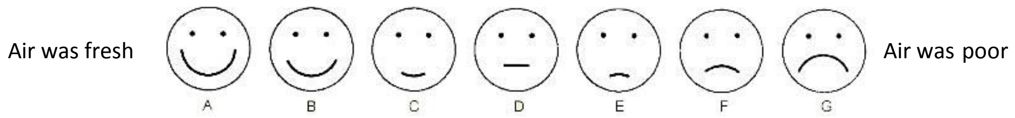


Figure 2. Example of scale used in surveys. The coding of the scale was: A=7, B=6, C=5, D=4, E=3, F=2 and G=1.

During experiments opening and duration of windows opened was recorded by magnetic sensors (ON/OFF). Classroom conditions (temperature, humidity, CO_2) were recorded at a frequency of five minutes. Outside conditions were registered by a weather station. Similar measurements were made in pilot tests prior to the experiments. Classroom heating usage was also recorded. Based on the physical measurements a computational model was created to perform monthly energy simulations under different scenarios and degree days were also used to estimate energy consumption. Annual energy use was estimated from the simulation program IDA-ICE 4, in which window opening behaviour in the condition with CO_2 feedback was assumed to take place according to the instructions given to students and teachers. In the condition without feedback window opening was simulated to match actual CO_2 levels measured in the classrooms and to maintain the set points for classroom temperature. An adjustment was made so that the relative difference in energy use for heating between the simulated conditions matched the ratio between energy use as measured by the heat meters installed in the classrooms in each condition.

4. RESULTS

Ambient conditions during the experiments are shown in figure 3 and in figure 4 it is illustrated how CO_2 feedback affected the opening of windows and classroom conditions for different ventilation strategies.
When there was an active feedback, children opened windows more frequently. As a result, the time weighted average of CO_2 in classrooms with the retrofit solution was generally below 1000 ppm, this is repeatedly seen in heating and cooling season. More windows open do not influence much the classroom temperature (figure 4). In naturally ventilated classrooms without feedback, in heating season CO_2 levels rose above 1800 ppm. In the mechanically ventilated classrooms independently of the feedback, both CO_2 levels and temperature were kept similar. Generally in this condition one window was always open, even if the CO_2 levels were below 1000 ppm.
In the cooling season, without split cooling, independently of CO_2 feedback the same number of windows was open. Only in the morning small differences were seen, when in the classrooms with CO_2 feedback, the CO_2 levels were lower, while the classroom temperature was not elevated. In the classrooms with split cooling and CO_2 feedback windows were opened more frequently by pupils compared to classrooms without feedback. The temperatures were maintained fairly constant independently of whether the feedback was present or not because of the split cooling.

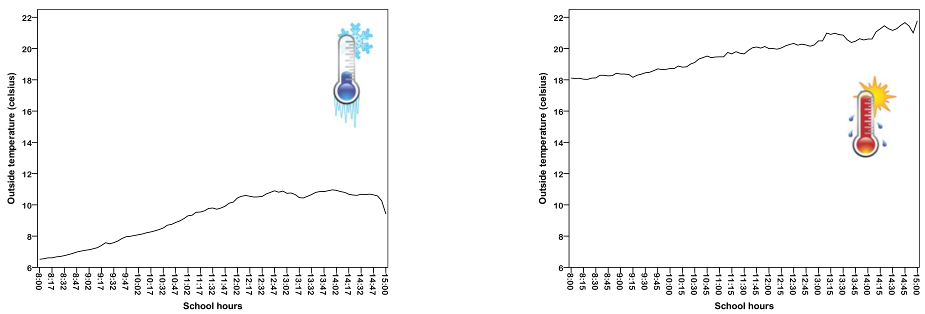


Figure 3 - Time weighted average of the outdoor temperatures registered during experiments

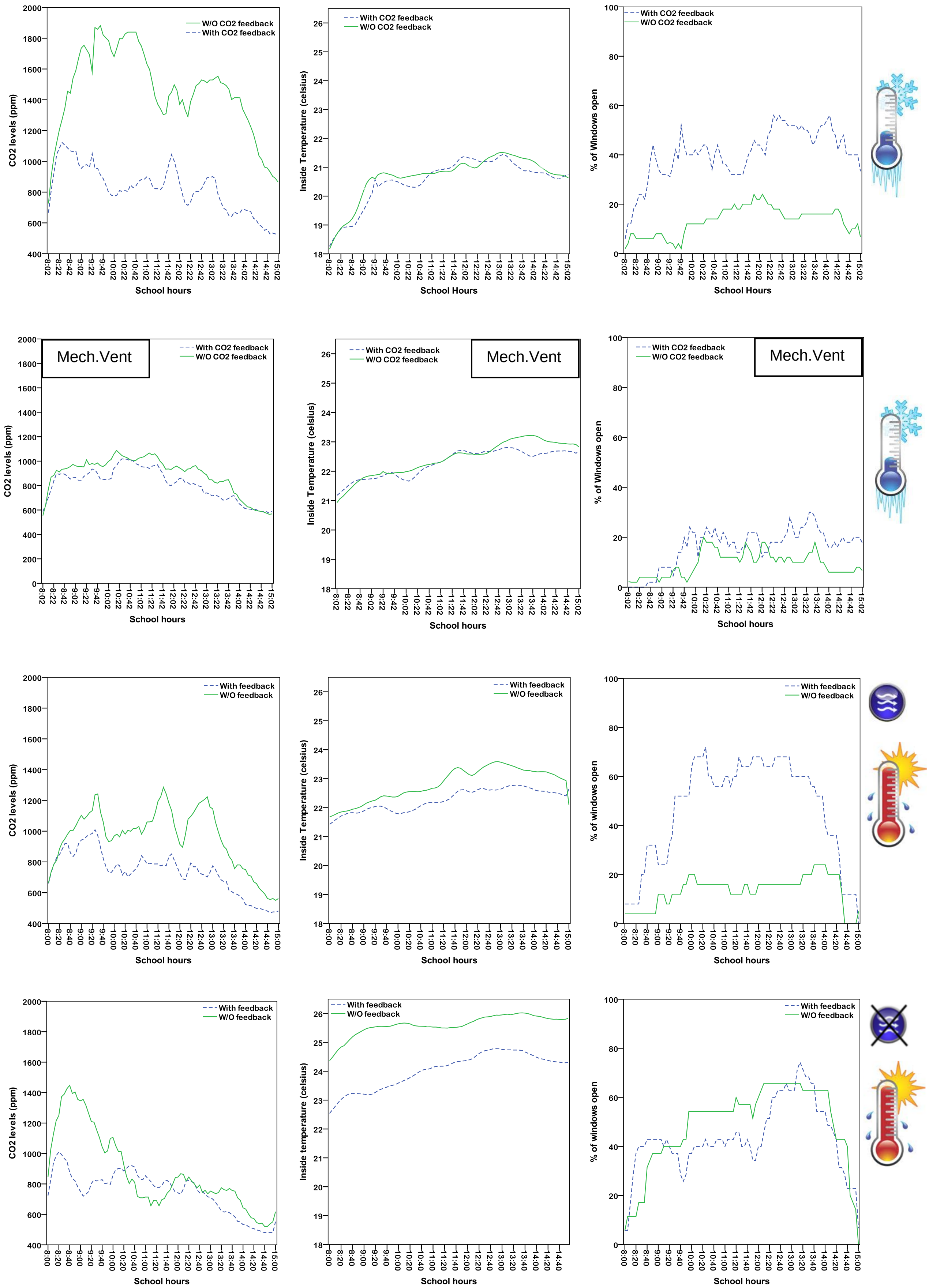
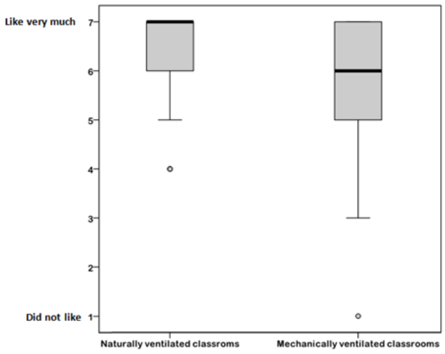


Figure 4. Time-weighted average of CO_2 concentration, classroom temperature and % windows opening, during school hours in classrooms with and without CO_2 feedback; first and second rows with figures show the results from winter (heating season) with natural and mechanical ventilation respectively. Third and fourth rows with figures show results from summer (cooling season) with and w/o split cooling. (20% correspond to 1 window/100% to 5 windows)



Pupils did not bother to have CO_2 feedback in naturally and mechanically ventilated classrooms (figure 5). This result was also supported by comments from teachers and pupils received weekly by experimenters. Table 1 shows that perceptions and satisfaction with environment increased when feedback was given, however, only some differences in perceptions and symptoms indicated by pupils between conditions reached statistical significance. In heating season the group of pupils in naturally ventilated classrooms reported better satisfaction compared to the pupils in mechanically ventilated classrooms, but in this case two different groups of children were compared.

Figure 5 – CO_2 feedback satisfaction

	Heating Season (Natural ventilation)			Heating Season(Mechanical ventilation)			Cooling Season (with split cooling)			Cooling Season (w/o split cooling)		
	With CO_2 feedback (n=43)	w/o CO_2 feedback (n=43)	P (Wilcoxon)	With CO_2 feedback (n=34)	w/o CO_2 feedback (n=34)	P (Wilcoxon)	With CO_2 feedback (n=23)	w/o CO_2 feedback (n=21)	P (Mann-Whitney)	With CO_2 feedback (n=47)	w/o CO_2 feedback (n=46)	P (Mann-Whithey)
How was the classroom environment during the week?												
Very Good (7)-Very Bad (1)	6 [5-6,5]	6 [5-6,5]	0,75	5[5-6]	5[4-5]	0,005*	6 [5-6]	6 [6-7]	0,18	5,5 [5-6]	5 [3-5]	0,001*
How was the classroom this week?												
Too cold (7)-Too warm (1)	4 [4-5]	4 [3-5]	0,35	4[3-5]	4[2-5]	0,22	4 [3-5]	5 [4-5]	0,15	4 [3-4]	2 [2-3]	<0.001*
Air was fresh (7)-was poor (1)	5 [4,5-6]	5 [4-6]	0,15	4[4-6]	4[2-5]	0,018*	5 [5-6]	6 [5-6]	0,2	5 [3-5]	3 [2-4]	0,001*
Air was still (7)–was drafty (1)	5 [4-6]	6 [4,5-6,5]	0,19	5[3-6]	4,5[3-7]	0,87	6 [5-7]	6 [5-7]	0,41	6 [5-7]	4 [3-5]	<0.001*
Too much noise (7)-Too silent (1)	5 [4-5]	5 [4-5]	0,27	4,5[4-5]	5[4-5]	0,41	5 [5-6]	4 [4-4]	0,001	4 [4-5]	4 [3-4]	0,03*
Too Humid (7)-Too dry (1)	4 [4-4]	4 [4-4]	0,84	4[3-4]	4[3-4]	0,81	4 [4-5]	4 [4-4]	0,72	4 [4-4]	4 [3-4]	0,02*
Too much (7)-Too little (1) light	4 [4-4,5]	4 [3-5]	0,22	4[4-5]	4[4-5]	0,24	4 [4-4]	4 [4-5]	0,22	4 [4-5]	4 [3-4]	0,2
How did you felt this week, while you were in school?												
Could breathe freely (7)-Nose blocked (1)	6 [5-7]	6 [4-6,5]	0,32	5[4-6]	4[3-5]	0,015*	6 [5-7]	6 [6-7]	0,21	6 [4-6]	4 [3-5]	0,001*
Not tired (7)-felt very tired (1)	5 [4-6]	5 [3-6]	0,18	3,5[3-5]	3[2-4]	0,03*	5 [4-6]	5 [3-6]	0,8	4 [3-6]	3 [2-5]	0,2
No headache (7)-severe headache (1)	6 [5-7]	6 [3,5-7]	0,23	5[3-6]	4[3-5]	0,026*	6 [5-7]	6 [5-7]	0,6	5,5 [4-7]	4 [2-7]	0,06
Felt like working (7)-felt not like working (1)	6 [5-6]	5 [4-6]	0,02*	5[4-6]	4[3-5]	0,17	6 [5-6]	6 [4-6]	0,88	6 [5-6]	4,5 [4-5]	0,005*
Not dry lips (7)-dry lips (1)	6 [4-7]	5 [4-7]	0,12	5[4-6]	4[3-5]	0,014*	6 [5-7]	6 [2-6]	0,23	6 [4-7]	5 [3-7]	0,15
Not dry skin (7)-dry skin (1)	6 [4-7]	5 [4-7]	0,79	5[3-6]	4[3-6]	0,44	7 [6-7]	6 [4-7]	0,21	6 [5-7]	3 [6-7]	0,1
Not dry throat (7)-dry Throat (1)	6 [5-7]	6 [4-7]	0,05*	5[4-6]	4[3-6]	0,06*	6 [5-7]	6 [4-7]	0,71	6 [5-7]	5 [3-7]	0,11
Felt good (7)-not felt good (1)	7 [6-7]	6 [5-7]	0,02*	5[5-6]	5[4-6]	0,12	6 [6-7]	7 [5-7]	0,9	6 [5-7]	6 [3-7]	0,29

Table 1 - Median [25th percentile -75th percentile] environment perceptions and symptoms indicated by pupils; (*) show whether the differences between classrooms with and without CO_2 feedback were statistically significant

Energy simulations revealed that use of CO_2 feedback in naturally ventilated classrooms, caused an increase between 10 and 20% in monthly heating demand compared to classrooms without feedback. In the cooling season (school calendar) the use of split cooling without CO_2 feedback caused an increase of energy use (10 to 30 %), because windows are open less and thus no effective use is made of moderate outside temperatures in Denmark in the cooling season. Mechanically ventilated classrooms used less heating energy compared to naturally ventilated classrooms with CO_2 feedback because of the heat recovery equipment in the air handling units. Installing a CO_2 feedback in classrooms with mechanical ventilation did not have effect in energy use as pupils open the windows, independently of whether the feedback indicates green or not.

5. DISCUSSION

Without any feedback on CO_2 windows were opened more often when the classroom temperatures were elevated, but not when CO_2 levels increased. Pupils did not feel the need to open windows even when air quality was poor. Providing pupils with a visual feedback indicating when the windows should be opened reduced the levels of classroom CO_2 and improved indoor air quality. This means that teachers and pupils need some kind of information of when windows should be opened and closed. This is especially important in naturally ventilated classrooms.

With CO_2 feedback the perceptions and symptoms of pupils were not much different from classrooms without feedback. This may have happen because children this age may have difficulty in interpreting some questions and happened even though children were presented scales with smileys. Other reasons for lack of differences can be the short duration of the experiment and too low number of responses.

In mechanically ventilated classrooms, windows were opened in spite the feedback indicated no need. This result can be used in energy simulations as a minimum window opening activity indicator, as pupils will open windows despite the environment conditions.

In energy simulations it was assumed that windows were always closed below 1000 ppm while this was not the case in classrooms, thus energy consumption might be higher in some cases.

When there are poor budgets for new or upgraded ventilation systems in schools or the outside ambient conditions are moderate (e.g. pollution, noise, temperature), the CO_2 feedback seem to be an effective and feasible solution to improve air quality in classrooms with natural ventilation. If classrooms have mechanical ventilation systems already installed or there are plans for school renovations, one solution to minimize the cost of energy can be the conversion to a mixed-mode system, where CO_2 feedback can be used as an indicator when windows should be open, reducing the use of mechanical ventilation.

Present results should not be extrapolated if the outdoor temperatures are considerably lower or higher than those in the present study, unless new experimental data for other conditions are available.

6. CONCLUSIONS

The indoor air quality in naturally ventilated classrooms was improved when CO_2 feedback was used. In mechanically ventilated classrooms, the influence of CO_2 feedback on the IAQ was lower; the improvements were not significant, because the mechanical ventilation system was sufficient to achieve good IAQ.

Classroom temperature seems to be the main factor affecting window opening. Cooling of naturally ventilated classrooms will thus have a negative effect on this behavioural response and may result in poor classroom air quality.

Pupils liked to open windows following the CO_2 indicator but let them stay open after the CO_2 levels were at acceptable levels.

ACKNOWLEDGEMENTS

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