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Effective Energy-efficient Classroom Ventilation for Temperate Zones

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Effective Energy-efficient Classroom Ventilation for Temperate Zones

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Sissel Graversgaard Hartelius	Comparison of different methods of school ventilation and the effect on pupil performance
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Sebastian Søgaard Møller	Indoor climate and energy consumption with different ventilation solutions at Ravnsholtskolen
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Anna Heebøll	Evaluation of indoor environment and energy optimizing retrofit solutions for public schools
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Bjørn-Erik Kölsch	Skoleventilation (Ventilation of schools)
Joachim Andersen and Peter Wulff Harslund	Indeklima med energieffektiv skoleventilation (Indoor environment with energy-efficient school ventilation)
Ida Gundlach	Validation of the simulation models used to assess the performance of the retrofit solutions in different climates

Contents

1 Executive summary

To study the performance of different solutions for retrofit of classroom ventilation, an intervention study was carried out in an elementary school located in a temperate climate north of Copenhagen, Denmark. Three classrooms were retrofitted with four different ventilation solutions, which were:

- a decentralized, mechanical ventilation system
- a system allowing automatic window opening
- a system allowing automatic window opening assisted by an exhaust fan
- a system allowing automatic window opening supported by heat recovery units

In a separate classroom that was not retrofitted with a dedicated ventilation system, the intervention was to let teachers and pupils use a device providing visual feedback on the CO_2 concentration in the classroom, informing them when the windows should be opened. All solutions were compared with a reference classroom in which pupils and teachers manually had to open windows, as was the only means of ventilation in all the studied classrooms prior to any intervention.

During three six-week intervention periods including both heating and non-heating seasons, the performance of all five solutions for improving ventilation was evaluated based on measurement of the conditions in the classrooms, the window opening behavior of pupils and teachers, pupil's perceptions of the classroom environment, their acute health symptoms, their performance of school work, the energy use, and the costs incurred in acquiring, installing, and operating the systems. Also, simulations were carried out to evaluate the indoor environment and energy use with the ventilation solutions used at schools located in different climates. The sensitivity of the simulated indoor environment and energy use was also studied with different window and door opening behavior.

The decentralized mechanical ventilation system, the system with automatic window opening assisted by an exhaust fan performed best overall. These systems improved the air quality in the classroom to a higher degree than the other systems and the effect of running the systems on pupils' cognitive performance was more consistent. There was no clear effect on pupils' perceptions and wellbeing of using these two systems to ventilate the classrooms. The decentralized mechanical ventilation system and the system with automatic window opening assisted by an exhaust fan used more energy than the other retrofit solution for which energy use was recorded.

The solution with automatically operable windows and heat recovery units performed better than the one with automatically operable windows or a visual CO_2 feedback device. However, the latter two solutions used the least energy.

The experimental findings were used in a simple qualitative ranking of all the solutions tested in the elementary school, based on classroom environmental parameters, pupils' perceptions, symptoms and performance, and the energy use.

With equal weighting of the different performance metrics, the decentralized system scored best, the system with automatic window opening and an exhaust fan scored second best, and the system with automatic window opening and heat recovery units came third. These systems were able to sustain a lower CO_2 concentration during a major part of the occupied time and although differences in pupil performance between retrofit systems were modest, these systems improved most consistently the performance of tasks requiring logical thinking, concentration and attention. The higher performance of these systems was to some degree penalized by their higher energy use, which was not the case for the other retrofits. The system with automatic window opening and the system with a visual display unit providing feedback on the CO_2 concentration scored equal and worst.

In a second intervention study the performance of a sorbent type gas-phase air cleaner was investigated in a classroom at the Technical University of Denmark. During two afternoon lectures, the classroom was ventilated by the ventilation system and on two other afternoons the ventilation system was in operation together with a gaseous air cleaner. Under both conditions, students assessed the air quality and other conditions in the classroom, and completed a performance test examining their concentration and ability to think logically.

Operation of the sorbent type gas-phase air cleaner resulted in improved performance of the applied logical reasoning test. The students also reported that they put more effort into performing the task and that they felt slightly cooler when the air cleaner was running. No changes in the reported intensity of symptoms were seen between operation modes, except for the perceived dryness of the air. The air quality and odor intensity assessed by the students did not change with different modes of operating the air cleaner. The assessments of air quality were consistent with the chemical measurements performed in the classroom, which were also comparable between operation modes.

The need for retrofitting ventilation is urgent in many schools located in temperate climates and particularly during the heating season, when pupils and teachers do not open windows to sustain ventilation. All the retrofit solutions included in this study were able to improve the air quality in the classrooms, although to a different degree. In particular, the solutions with automatically controlled and fan supported ventilation performed the best in terms of the indoor environment and the effect on pupil performance. These solutions were also the most costly. Low-cost solutions as the visual display unit may be used as a temporary solution, which may yield some improvement until a more permanent solution becomes available in the budget. The results from the university classroom indicate that this sorbent type gas-phase air cleaner does not yet seem to be ready for practical application.

Due to the multitude of dimensions used to quantify the performance of the studied retrofit solutions, it has not been possible to identify one, distinct solution with the best overall performance and thereby to recommend one outstanding retrofit solution. Instead, the study results may be used to evaluate system performance in classrooms in which retrofitted ventilation solutions may be installed and operated as they would be in any given school subject to a similar retrofit. The measurements and observations therefore represent the variation in indoor environment, pupil perceptions and responses, behavior, and energy use that can be expected in schools with similar retrofits, when they are located in temperate climates.

2 Introduction

The main purpose of classroom ventilation is to create indoor environmental conditions that reduce the risk of health problems among pupils, that minimize their discomfort, and that eliminate any negative effects on learning. Many studies have found that the environmental conditions in elementary schools are so inadequate that they are failing to achieve these goals. The most common problem is inadequate ventilation. The reasons for this include insufficient outdoor air supplied to classrooms; elevated and varying temperatures; inadequate exhaust airflows; poor air distribution or balance; and poor maintenance of heating, ventilation and air-conditioning systems (Daisey et al., 2003).

There are many reasons why classroom environmental conditions are poor. The most common reasons are inadequate financial resources for the maintenance and upgrade of school buildings. Also, retrofitting the existing building stock may take many years to complete. It is thus important to examine different systems that can potentially be swiftly retrofitted to improve classroom ventilation and thus indoor environmental quality. The experimental data on this issue are scarce.

The aim of this study was thus to compare the performance of different retrofit solutions to improve classroom ventilation and the indoor environment in classrooms in schools located in temperate climates.

3 Background

Children are quite vulnerable and more susceptible to environmental impacts than healthy adults (Landrigan, 1998). They spend more than 30% of their waking hours in classrooms. They must attend schools even when the air quality and thermal conditions in the classrooms are unsuitable, because it is obligatory to take part in elementary education. As a result of unsuitable environmental conditions in classrooms, children can experience acute health symptoms, better known as Building Related symptoms or Sick Building Syndrome symptoms (Daisey et al., 2003; Norbäck & Nordström, 2008; Mi et al., 2006; Salleh et al., 2011). Inadequate classroom ventilation can reduce the speed at which language-based and mathematical tasks that are typical of schoolwork are performed by pupils (Bakó-Biró et al., 2012; Wargocki and Wyon, 2013), and can reduce progress in learning as measured by the number of pupils who pass standard mathematics and language tests (Haverinen-Shaughnessy et al., 2011). It can also increase absenteeism (Shendell et al., 2004; Mendell et al., 2013), which is likely to have negative consequences for learning. These effects can give rise to significant socio-economic costs (Chetty et al., 2010; Marxen et al., 2011; Slotsholm, 2012).

Outdoor air supply rates in schools are considerably lower than in offices, in many cases even lower than those observed in dwellings (Brelih, 2012; Dimitroulopoulou, 2012). As a result, carbon dioxide (CO_2) levels regularly exceed recommended levels, which are often required to remain below 1,000 ppm during school hours (Santamouris et al., 2008; Wyon et al., 2010), while classroom temperatures regularly drift above the recommended ranges in warm weather. The air quality in classrooms can also be improved by using gas-phase air cleaners. Theoretically, gas-phase air cleaners should provide the same effect that is obtained by ventilation, and they have thus been considered to be a potential alternative to ventilation, not only in school buildings, but also in other building types. They make it possible to reduce outdoor air supply rates and thus reduce the energy used to transport and condition ventilation air. However, there are very little data on the performance of different air cleaning technologies under field conditions in actual buildings. This was confirmed in a recent review of air cleaning methods (Zhang et al. 2011). This review concluded that sorbent-type air cleaners are a promising technology that can remove gaseous air pollutants with no negative side-effects such as by-products that may be more adverse than their precursors, although there is no information on their long-term performance. Air cleaners do not require a centralized system and can be retrofitted fairly quickly in classrooms so they could be a very attractive means of improving classroom air quality.

The few studies that examined one or more aspects of improving classroom ventilation and addressed some of the issues mentioned above are summarized in the following.

Wyon and Wargocki (2008) examined the window opening behavior of children under different classroom environmental conditions. They observed that if temperatures were allowed to rise by 2-3^{o}C (3.6-5.4^{o}F), windows and doors were opened much more often, while even large reductions in outdoor air supply rate did not result in any increase in window-opening. Their results indicate that pupils open the windows in response to elevated classroom temperature rather than because the air quality is poor; Fabi et al. (2013) also found that temperature is an important factor that determines whether windows are opened or closed.

Airing of classrooms by manual opening of windows depends to a high degree on outdoor conditions, including the location of the school (urban and/or rural) and climatic conditions (wind speed and direction, outdoor temperatures), as well as on the window opening behavior of pupils and teachers. Wargocki and Silva (2012) investigated to what extent a feedback system informing pupils when operable windows should be opened in classrooms can influence classroom temperature and air quality. They showed that providing a visual indication that classroom ventilation is inadequate (classroom CO_2 level was used for this purpose) caused pupils to open the windows more frequently. This resulted in reduced classroom CO_2 levels that were similar to what was obtained in a large number of Dutch schools when visual CO_2 indicators were installed (Geelen et al., 2008). Wargocki and da Silva (2012) also showed that providing mechanical cooling in the classrooms would restrict window opening, resulting in poor air quality, confirming that classroom temperature rather than poor air quality is likely to be the main reason why windows are opened by pupils in schools.

Mumovic et al. (2007; 2009) carried out measurements in three new secondary schools during the heating season in the UK; the ventilation systems studied included automatically operable windows, exhaust (extract) ventilation and balanced mechanical ventilation. They found that regardless of the type of ventilation system, most classrooms met the requirements of the Building Bulletin 101 (ODPM, 2005) regarding daily average CO_2 concentration, which in the UK should not exceed 1,500 ppm.

Gao et al. (2013a,b) studied different methods of classroom ventilation during heating and non-heating seasons. They observed that the classroom aired by manually operable windows had the highest air temperatures and CO_2 concentrations during both non-heating and heating season. The classroom with mechanical ventilation kept CO_2 concentrations low independently of the season, as did automatic operation of the windows in the heating season. Windows were frequently opened in the non-heating season, regardless of the ventilation system, but very seldom in the heating season.

Kinshella et al. (2001) examined indoor climate conditions in elementary schools with window unit ventilators, a constant air volume system and a variable air volume system. The results showed that schools ventilated with constant air volume had the highest outdoor air supply rates and those with unit ventilators had the lowest. The prevalence of symptoms experienced by the faculty and staff was lowest in schools with variable air volume and the highest in the classrooms with unit ventilators; complaints of nasal congestion, sore throat, headache, and dustiness were among the more frequently reported symptoms.

Wålinder et al. (1998) investigated the influence of ventilation rates and ventilation system type on the nasal symptoms of school personnel in randomly selected primary schools in Sweden. They found that nasal symptoms were worse in the mechanically ventilated classrooms (with balanced supply and exhaust) than in the naturally ventilated classrooms, even though the former had higher air exchange rates. The only exceptions were the mechanically ventilated classrooms with displacement ventilation, in which nasal symptoms were less frequent. Poor maintenance of the mechanical ventilation systems was presumed to be the reason for the observed results. This presumption is supported by Seppänen et al. (1999), who showed that the risk of Sick Building Syndrome symptoms in commercial buildings with mechanical ventilation systems is greater than in naturally ventilated buildings (presumably aired by manually operable windows) or in buildings with extract ventilation only (Seppänen and Fisk, 2002).

Toftum et al. (2015) has recently performed pilot experiments in Denmark comparing the results of a national scheme for testing progress in learning in schools between different ventilation systems. They retrospectively identified the national test scores obtained in 400 schools in which spot and 2 week measurements of CO_2 were available from other experiments attempting to benchmark classroom air quality in Danish schools by measuring CO_2 and temperature (Menå and Larsen, 2010, reported by Wyon et al., 2010). Analyses showed that pupils in schools with a mechanical ventilation system scored on average significantly higher on the national tests examining proficiency in language, math and natural sciences than pupils in schools aired only by windows opened manually by pupils and the teachers.

Perna et al. (2011) studied several alternative ventilation strategies in a school in Italy to collect data on the optimization of indoor environmental quality and energy consumption. The following three ventilation strategies were compared with a basic ventilation strategy: (1) natural ventilation, in which the windows were opened and closed by the users according to the indicated indoor CO_2 concentration; (2) mechanical ventilation with constant airflow; (3) a wind driven extractor installed in the classroom ceiling. The classrooms with natural ventilation and a CO_2 feedback display and with the wind driven extractor had acceptable environmental quality according to Standard EN 15251 (2007), but the energy consumption of both of these systems was higher than that of mechanical ventilation.

In model studies, Steiger et al. (2012) found quite a large reduction in energy use in classrooms with hybrid ventilation compared with the mechanical ventilation system. They simulated energy use in schools with natural ventilation systems, mechanical ventilation systems and hybrid ventilation systems and showed that the energy used in the first two types of school was similar, while it was up to 52% lower in a school with hybrid ventilation.

Fang (2011) and Fang et al. (2008) studied the feasibility of using a desiccant wheel as a gas-phase absorption air cleaner. In laboratory experiments, they measured whether the operation of a desiccant wheel improved the air quality as described by chemical analysis and as perceived by human subjects. The air quality in the climate chamber and the simulated office room was modified by adding pollutants such as formaldehyde, ethanol, toluene and 1,2 dichlorobenzene, and by adding sources of pollution typically found in buildings: two types of flooring material and human subjects as a source of bioeffluents. The results showed that the efficiency of the desiccant wheel in removing chemicals was ≥94%. The percentage dissatisfied with the air quality was reduced from 70% to 20% when the wheel was in operation; the odor intensity was also reduced significantly, from moderate to slight. The perceived air quality improved both when the model room was polluted by flooring materials and by human bioeffluents. The observed result for human bioeffluents is particularly relevant to classroom air quality since humans are the dominant source of pollution in classrooms, but no additional studies have been performed in schools to validate this conclusion. It should be noted that although a broad spectrum of gas-phase pollutants is removed by a desiccant wheel, it does not remove the CO_2 that is conventionally used as an indicator of air quality, so it must be evaluated in terms of perceived air quality, acute health symptoms and the performance of schoolwork.

There are many reasons why classroom environmental conditions are poor. The most common reasons are inadequate financial resources for the maintenance and upgrade of school buildings, and an overemphasis on energy conservation that gives rise to conditions that are worse than what is stipulated by the relevant standards and building codes. As a result, classroom ventilation is still achieved in many schools only if teachers and pupils open the windows. These schools have to be retrofitted with systems that ensure adequate air quality and temperature if they are to ensure improved indoor environmental quality in classrooms at all times. The systems which are retrofitted may use either natural or mechanical forces. Examples include automatically operable windows, extract ventilation using exhaust fans or mechanical ventilation systems with balanced supply and exhaust from a central or local air handling unit. In either case, the retrofit may be quite expensive. The expense is due not only to the potentially high first costs but also to the increased energy and maintenance costs that are incurred when systems that ensure high classroom air quality are in operation.

Retrofitting the existing building stock may take many years to complete. It can also disturb teaching, unless it is carried out during school vacations. It is thus important to examine different systems that can potentially be swiftly retrofitted to improve classroom ventilation and thus indoor environmental quality. The experimental data on this issue are scarce and there is a lack of studies that have systematically compared the benefits of different systems for classroom ventilation by comparing simultaneously their performance in the heating and non-heating season in temperate climates in terms of how well they provide adequate environmental conditions, eliminate discomfort and health risks, safeguard learning abilities and minimize energy use. Also there is very little systematic data on the window opening behavior of pupils and its effect on classroom ventilation.

ASHRAE research project RP1624 Effective Energy-efficient Classroom Ventilation for Temperate Zones was undertaken to systematically study the performance of different systems for retrofit of school ventilation during both heating and non-heating seasons in a temperate climate.

4 Specific objectives

The main objective of this study was to provide information on how different methods of classroom ventilation influence the conditions in classrooms, the window opening behavior of children and teachers, pupil's perceptions of the environment in classrooms, their acute health symptoms, their performance of school work and energy use. The solutions that were tested and compared with a reference classroom in which pupils and teachers manually had to open windows included:

1. CO_2 based control of automatic window opening
2. CO_2 based control of automatic window opening and fan assisted exhaust
3. A decentralized mechanical ventilation system
4. Manual window opening in response to visual feedback on CO_2
5. CO_2 based control of automatic window opening and heat recovery units
6. Sorbent type gas-phase air cleaner and window opening

5 Methods

The research activities in this project were divided into four stages comprising

1) Intervention studies on the performance of retrofit solutions 1 to 5 in a Danish elementary public school

2) Analysis of window and door opening behavior and measurements of the classroom conditions during a non-intervention period in the same school with retrofit solutions 2 to 5 in operation

3) An intervention study on the performance of solution 6 in a classroom at the Technical University of Denmark

4) Examination of the performance of all retrofit solutions in different climates, based on simulations of the energy use and indoor environment

Stages 1, 3, and 4 are included in the main report while stage 2 is described in a paper submitted to ASHRAEs archival journal Science and Technology for the Built Environment. A draft version of the paper is included as Appendix A.

5.1 Intervention studies on the performance of retrofit solutions 1 to 5 in a Danish elementary public school

Three intervention studies were performed in a Danish elementary public school covering both the heating and non-heating seasons. Each study lasted six weeks, during which the effects of the different retrofit solutions were investigated in classrooms used by the pupils of an elementary school, grades 3 to 5. In three randomly selected weeks during the six-week intervention period, the retrofits were activated and in three weeks they were idled. One classroom was used as a reference, where no intervention was made. Each week the pupils assessed conditions in the classrooms, reported whether they experienced symptoms or whether the conditions caused any nuisance, and they performed different cognitive tests examining their abilities to learn. Thermal, air quality, and acoustical conditions were monitored continuously together with the frequency and duration of periods with open windows and doors.

5.1.1 Location - Ravnsholtskolen

The school where the intervention studies were performed was located in a rural area north of Copenhagen, Denmark. It was built from 1979 to 1986 (Ravnsholtskolen 2015). There were 543 pupils in 25 classes with 2-3 classes at each grade level:

- Pre-school, 0 to 2nd grade, age 6-8

- Primary school, 3rd to 6th grade, age 9-13
- Lower secondary school (junior high), 7th to 9th grade, age 14-16

No ventilation system was installed in the school classrooms prior to the intervention studies. The pupils and teachers had to open windows and doors manually to air the classrooms. The municipality together with the school management decided to retrofit the school with a ventilation system to improve the classroom environment. However, before selecting the ventilation solution to be applied in the school, i.e. the one that was the best fit for the school considering its typology, layout of the classrooms, etc., they decided first to examine different solutions in a section of the school to compare their performance. Consequently, three classrooms were retrofitted with four different ventilation solutions: a decentralized, mechanical ventilation system, a system allowing automatic window opening assisted by an exhaust fan, a system allowing automatic window opening, and the same system with automatic window opening supported by heat recovery units; the latter two systems were installed in the same classroom and could be operated independently of each other.

Figure 5.1.1 shows an aerial image of the school; the building where the retrofits were installed is encircled, while the arrows show the locations where the images of the school building in Figure 5.1.2 were taken.

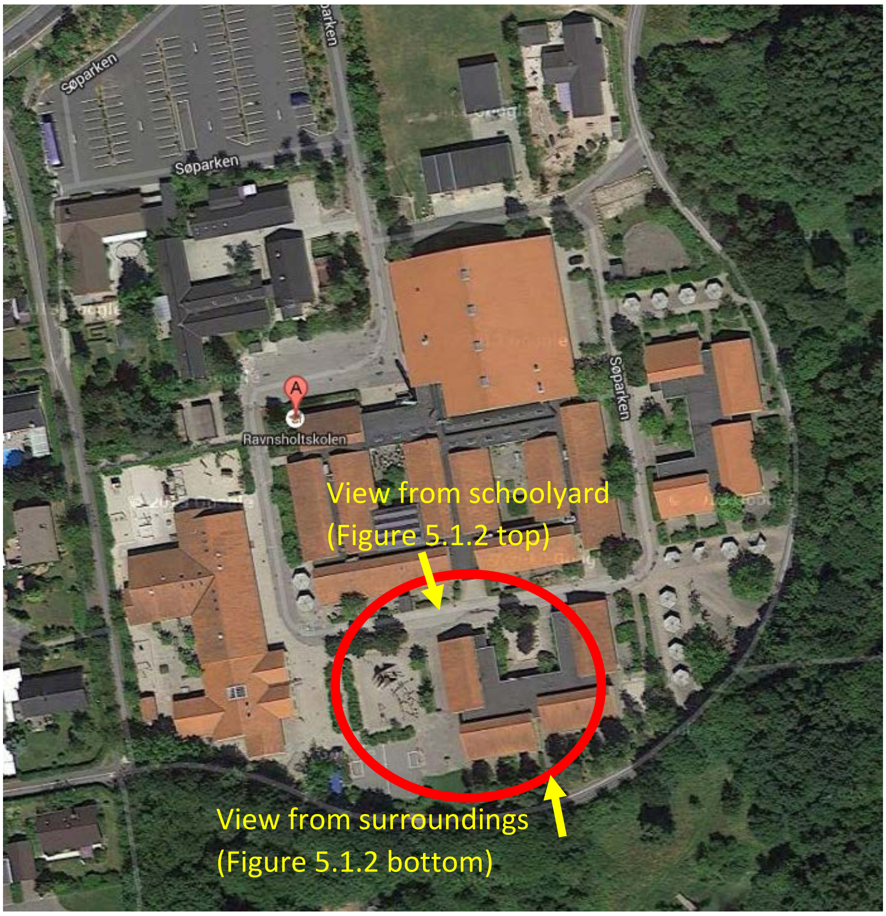


Figure 5.1.1. Aerial image of the school and the case building (South Wing).

The classrooms in which the retrofits were installed were located in a one-story building that had been commissioned in 1980. Besides the three classrooms where the retrofits were installed, two other classrooms were used. One served as the reference where no retrofit was installed and in one classroom, the teachers and pupils used a device that provided visual feedback on the CO_2 concentration in the classroom, informing them when the windows should be opened. The classrooms were occupied by pupils in the 4th and 5th grades, approximately aged 11 to 12 years.

Figure 5.1.2. Exterior of the school building seen from the schoolyard (top) and from the surrounding green area (bottom).

Figure 5.1.3 shows a plan drawing of the southern wing of the school where the intervention studies were carried out; classroom identifiers are in red. During the first two intervention studies classrooms S3 and S4 were used by the 5th graders and classrooms S5, S7, and S8 by the 4th graders. During the third intervention study performed in classrooms S5 and S8, these two classrooms were used by the 5th graders. Classrooms S1, S2, and S6 did not participate in the experiments.

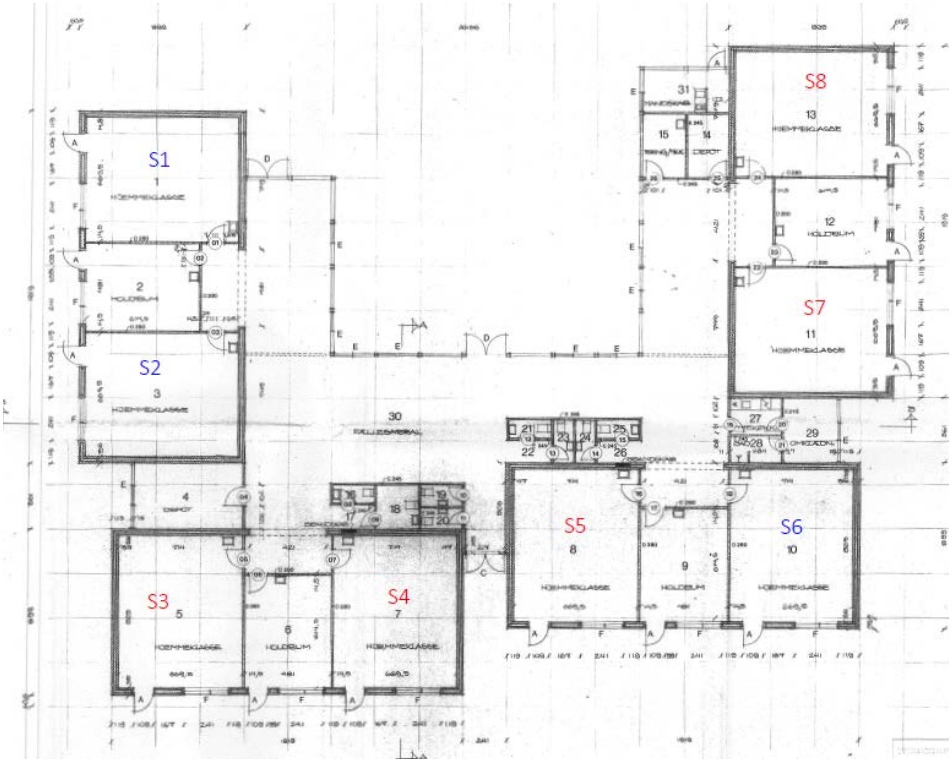


Figure 5.1.3. Plan drawing of the south wing where the intervention studies took place. Numbers in red indicate the classrooms that were included in the study. A decentralized mechanical ventilation system was installed in classroom S3. A system with automatic window opening assisted by an exhaust fan was installed in classroom S4. A system with automatic window opening and heat recovery units was installed in classroom S5. No special systems were retrofitted in classrooms S7 and S8. Pupils in classrooms S8 used a device that provided visual feedback on the CO_2 concentration indicating when the windows should be opened.

5.1.2 Classrooms

The classrooms where the interventions took place were rectangular with a ceiling that in one end raised diagonally to the overhead windows as illustrated in Figure 5.1.5. Each classroom had an area of 56 m^2 and a volume of 160 m^3. The classrooms had brick walls, acoustic ceilings and linoleum floors; the interior was nearly identical between classrooms (Figure 5.1.4). All classrooms were heated by water-filled radiators mounted below the façade windows and water-filled convectors installed below the overhead windows. Both radiators and convectors had manually adjustable thermostats.

Figure 5.1.4. Interior of a typical classroom in which the interventions were tested.

The classrooms had overhead windows, windows in the façade with a view to the outside, and two doors, one to a common hallway and one to the outdoor yard. Both the façade and overhead windows could be opened manually prior to installation of the retrofits. The location of the windows on two opposite facades enabled to achieve cross-ventilation. The windows in the façade of the classrooms S3-S5, where the retrofits were installed were replaced with new ones prior to the installation of the retrofits. In classrooms S7 and S8, the original, manually operable windows were retained. Some windows in classrooms S3-S5 could still be opened manually, independently of the installed ventilation solution. Figure 5.1.5 shows a sectional drawing of one classroom.

The total window area and the openable window area differed between the classrooms as a consequence of the retrofits (Table 5.1.1). In classroom S4, the total window area was smaller than in the other rooms because the exhaust fan was mounted in the overhead window.

Table 5.1.1. Overview of total window area and openable window area in each classroom.

Room	Openable windows	Area of openable windows (m^2)	Total window area (m^2)
S3	Win1, Win2, Win3, WinH	2.9	6.3
S4	Win2, Win3, WinH	2.9	5.4
S5	Win2, Win3, WinH	2.9	6.3
S7, S8	Win2, WinH	2.3	6.3

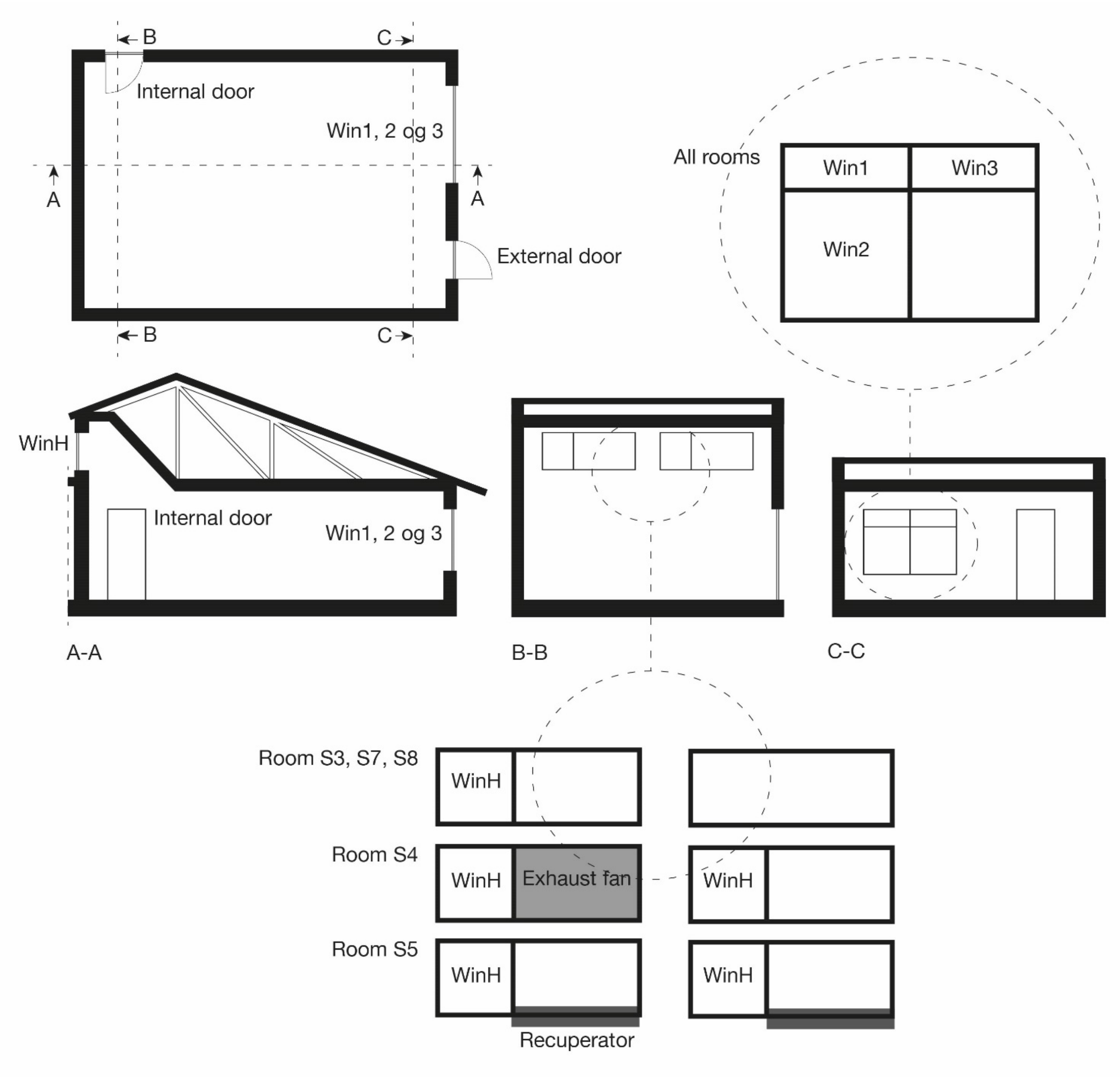


Figure 5.1.5. Cross section, floor plan, elevations of classroom and location of openable windows (windows which could not be opened are not named).

The classroom without the retrofit solutions had single-sided ventilation when either the façade or overhead windows were open, or two-sided (cross ventilation) when windows in both sides were open simultaneously (Figure 5.1.6). The overhead window could be opened by using a crank handle. Figure 5.1.5 shows the window configuration.

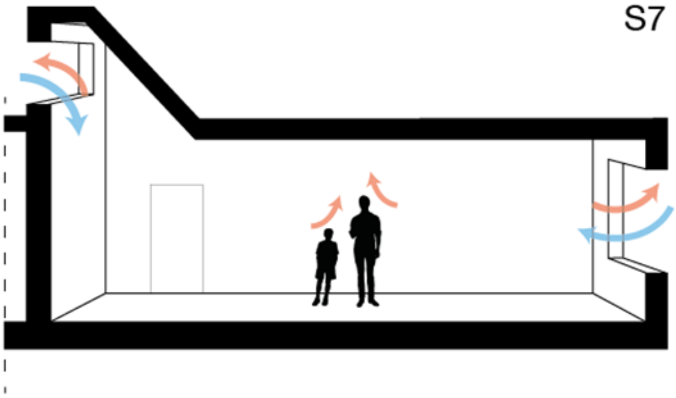


Figure 5.1.6. Ventilation principle in the reference classroom (S7).

The nominal number of pupils in each class was between 23 and 26. The actual number of pupils present in the classrooms during the study period was typically between 22 and 25 pupils. Assuming a nominal number of 25 occupants (24 pupils plus 1 teacher), the minimum outdoor air supply rate in each classroom as required by the Danish building code should have been about 520 m^3/h (145 L/s) (Danish Building Code 2015).

5.1.3 Retrofit solutions

The four ventilation solutions retrofitted in the classrooms were as follows:

- A mechanical decentralized ventilation unit with balanced supply and exhaust airflow controlled by the classroom CO_2 concentration. The unit was suspended from the ceiling in classroom S3 (Figure 5.1.7)

- A system providing ventilation by automatic opening of windows supported by an exhaust fan both controlled by the classroom CO_2 concentration. The system was installed in classroom S4 (Figure 5.1.8). Two facade windows Win 1, Win 3 and two overhead windows WinH could be opened automatically; in addition, the exhaust fan was installed in part of an overhead window (Figure 5.1.5)

- Two systems, one providing ventilation by automatic opening of windows and one with five alternating counter-flow heat recovery units, both being controlled by the CO_2 concentration; the systems could be operated independently of each other. These systems were installed in classroom S5 (Figure 5.1.9). Two facade windows Win 1, Win 3 and two overhead windows WinH could be opened automatically (Figure 5.1.5). The units were installed in slots in the facade walls and under the overhead windows WinH (Figure 5.1.9 and Figure 5.1.10).

- A visual CO_2 feedback display unit was provided to pupils and teachers in classroom S8 (Figure 5.1.11). The unit indicated when the CO_2 concentration was high and thereby when windows should be opened. No special installations were needed. The unit was hung on the classroom wall next to the whiteboard (Figure 5.1.11).

The retrofitted systems were in operation in August 2014 after being installed during the summer vacation 2014.

5.1.3.1 Decentralized mechanical ventilation unit, classroom S3

A decentralized mechanical ventilation unit installed in classroom S3 was equipped with a filter (class EU7), a heat recovery unit, an electrical pre-heater, and a water-to-air heating coil. It could deliver outside air at a maximum airflow rate of 725 m^3/h (201 L/s). The noise level at the maximum airflow rate was 35 dB(A) as specified by the manufacturer. The minimum airflow rate was 200 m^3/h (56 L/s).

The airflow rate was controlled by the classroom CO_2 concentration. The low airflow rate was supplied when the classroom CO_2 concentration was below 600 ppm. The airflow rate was at maximum at a concentration above 800 ppm. Between 600 ppm and 800 ppm, the airflow rate increased linearly from the minimum to the maximum level (Figure 5.3.3). The supply air temperature was adjusted by a thermostat to keep the room air temperature at 23°C.

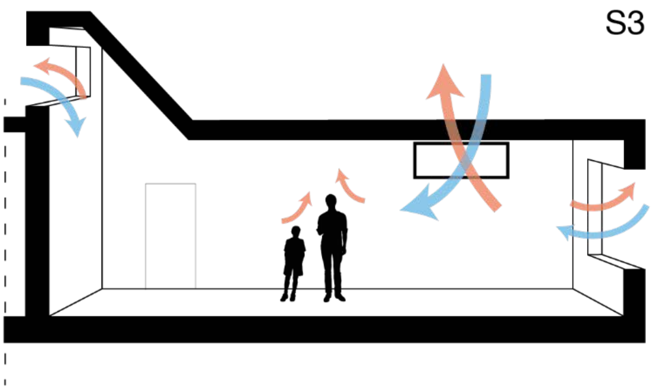


Figure 5.1.7. Decentralized mechanical ventilation system – the ventilation retrofit installed in classroom S3. In this classroom, façade windows Win1, Win2 and Win3, and the overhead window WinH could still be opened manually as before the retrofit.

5.1.3.2 Automatic window opening, classrooms S4 and S5

Actuators were installed on the façade windows Win1, Win3, and the overhead windows WinH (Figure 5.1.5). The actuators were installed in classrooms S4 and S5. The CO_2 concentration, air temperature, outdoor weather conditions and time of day were used as input to the window opening control system. A timer control was used to open the windows at the start of each clock hour of the school day if the CO_2 concentration was above 800 ppm.

The windows were controlled in so-called “pulse” and “trickle” modes. In the pulse mode when the CO_2 concentration increased rapidly to a level above 800 ppm, the windows were opened to the maximum opening degree for 3 minutes; the opening was 50% of the maximum achievable opening of the windows during the heating season (mid-October to mid-April) and 80% during the non-heating season (mid-April to mid-September). The “pulse” control mode was usually used during the heating season. In the “trickle” control mode, the windows were gradually opened to the season-dependent maximum opening degree, when the CO_2 concentration increased from 750 ppm to 1000 ppm. The control algorithm was overruled and windows were not opened when the indoor air temperature was below 19°C. During precipitation, strong winds and other unfavorable weather conditions the window opening degree was reduced as well. The occupants had the possibility to manually override the system by pushing a wall-mounted button, which opened the windows fully. When this happened, the system reverted to the original control setting 15 minutes after the button had been pushed.

5.1.3.3 Exhaust fan, classroom S4

The system for automatic opening of windows in classroom S4 was supplemented by an exhaust fan. The fan was mounted in the overhead window opening to achieve cross-ventilation in the classroom (Figure 5.1.8). The fan’s nominal airflow rate was 749 m^3/h (208 L/s) at a noise level of 40 dB(A) 10 meters from the fan as specified by the manufacturer. The fan was started when the classroom CO_2 concentration reached 700 ppm and the maximum speed was reached when the concentration reached 1000 ppm. No heat was recovered from the exhaust flow. The fan could still be in operation even though the automatic windows were closed. This could happen during periods with low outdoor temperatures or unfavorable weather conditions. In such a case the make-up air was drawn from the hallway, through the window and door in the façade (if opened) or through any opening or crack in the wall or ceiling.

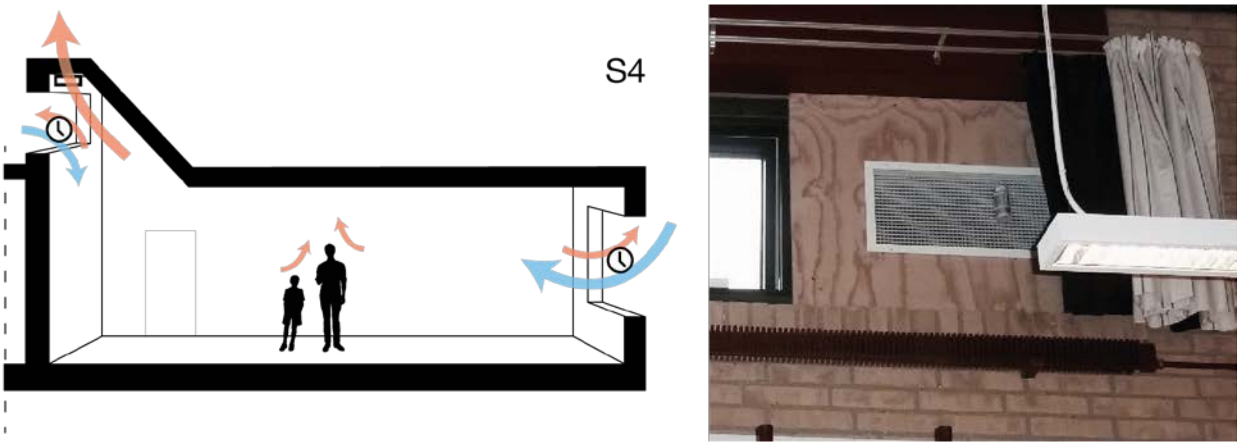


Figure 5.1.8. The system with automatic window opening and an exhaust fan – the ventilation retrofit installed in classroom S4. Window Win2 could still be opened manually by pupils and teachers.

5.1.3.4 Heat recovery units, classroom S5

A system consisting of six heat recovery units was installed in classroom S5 to supplement the system for automatic opening of windows. Each unit consisted of a heat absorbing material and a row of 5 to 7 small fans (Figure 5.1.9). Altogether six heat recovery units were installed in slots in the outside wall and under the overhead windows. The units worked in pairs with opposite flow directions that reversed every minute. When the units exhausted the air, heat was absorbed in the absorbing material and when the air was supplied to the classroom the heat absorbed in the material was used to pre-heat the supply air. The thermal efficiency of the heat recovery was about 85%. The units contained no filter and therefore any pollution trapped in the unit could be reintroduced to the classroom again.

The five units installed in the classroom could nominally deliver outdoor air at a maximum rate of 468 m^3/h (130 L/s); the SFP was 300 J/m^3 because of the low pressure loss. At this airflow rate, the nominal noise level of one unit was approximately 35 dB(A) as specified by the manufacturer.
The units were operated at minimum speed (39 L/s) when the CO_2 concentration in the classroom was below 650 ppm and their speed was progressively increased so that the maximum airflow rate could be reached when classroom CO_2 concentration was 750 ppm.

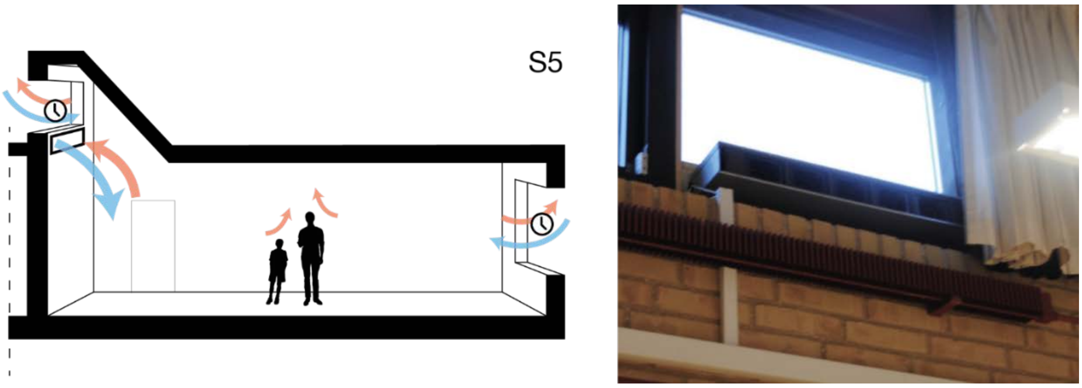


Figure 5.1.9. The system with automatic window opening and heat recovery units – the ventilation retrofit installed in classroom S5. Window Win2 and the overhead window WinH could still be opened manually by pupils and teachers. Right: The unit installed in one of the overhead windows.

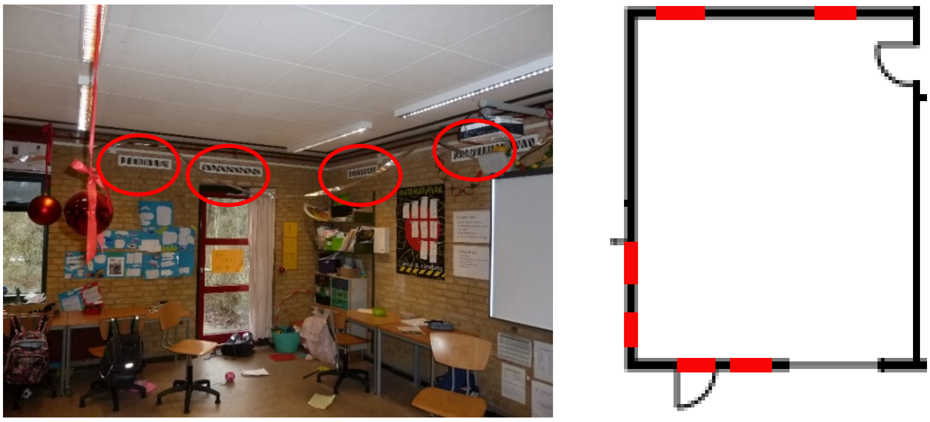


Figure 5.1.10. The system with automatic window opening and heat recovery units. Left: The units installed in the façade; Right: Red color indicates the position of all six units.

5.1.3.5 A visual CO_2 feedback display unit, classroom S8

In classroom S8, a display unit providing visual feedback on the CO_2 concentration was mounted on the wall (Figure 5.1.11). It had a scale from 250 ppm to 5000 ppm with LEDs from 400 ppm to 2000 ppm in steps of 200 ppm. The pupils and teachers were instructed to open the windows when the lights were yellow, i.e. when the CO_2 concentration was between 1000 ppm and 1600 ppm, as indicated on the scale of the feedback display. When the lights turned red, i.e. when the CO_2 concentration exceeded 1600 ppm, they were instructed to open all windows and doors for five minutes to achieve cross-ventilation. During this time, they were asked to leave the classroom. The ventilation in this classroom could be achieved by opening windows in the façade and the overhead window as well as the doors, similarly as in classroom S7, where no retrofit solutions were installed.

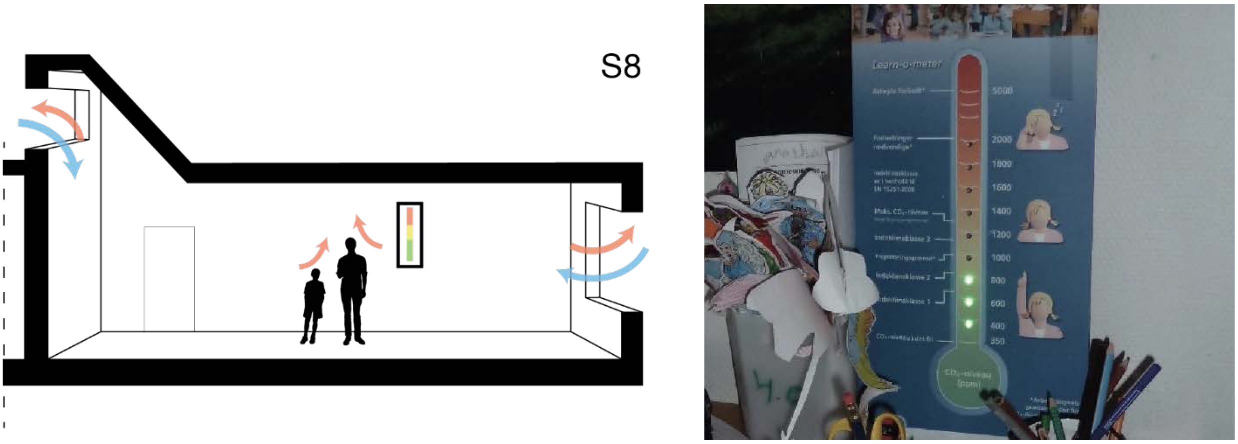


Figure 5.1.11. A visual CO_2 feedback display unit installed in classroom S8 to guide pupils and the teacher as to when the windows should be opened.

5.1.4 Experimental plan

During three six-week intervention periods, the classrooms were aired alternately by manual opening of windows, as prior to retrofitting the rooms, or with the use of the retrofitted systems. During the time with manual window opening, the retrofits were idled (disabled). Two intervention periods were in the heating season and one was in the non-heating season. The experiments were carried out during six weeks, thus creating three repetitions of a two-week block that compared the condition with retrofits idled and activated; in the reference classroom no interventions were made. The retrofit solutions in classroom S5 were tested during two periods: In one period only automatic window opening was activated and in the other period both the automatic window opening and the heat recovery units were activated. During the weeks when the retrofits were idled or activated, the manually operable windows and doors could be open at will. Table 5.1.2 provides an overview of the intervention periods and the system control modes during the heating and non-heating seasons.

During each week-long period, the children assessed their wellbeing and their acute health symptoms and performed language and arithmetical tasks typical of school work that measured their ability to read and understand the material, as well as tasks examining whether they could think logically and concentrate. During the intervention periods, the quality of the environment in the classrooms was monitored continuously by data loggers measuring the thermal, acoustical, and air quality conditions. The frequency and duration of window- and door opening was also logged, as well as the heating energy used in the classrooms, and the electrical energy needed to operate and activate the systems. A local weather station at the school monitored wind speed and direction, air temperature, precipitation, and relative humidity.

Prior to the beginning of each intervention period, meetings were set up with the teachers in the selected classes where they were explained the purpose of the experiments and their role in the distribution and management of tests and questionnaires. Also, comprehensive information material describing the tests and questionnaires was presented to the teachers. This material was in Danish and therefore not included in the present report. Parents to the pupils were informed about the activities, but were not given complete description of the study so as to keep the pupils blind to the planned interventions.

Table 5.1.2. Experimental plan showing the three intervention periods in the heating and non-heating seasons and the schedule of alternating system control. Classroom S7 is not included in the table as no intervention was made in this classroom.

Intervention period		S3 Decentralized mechanical ventilation	S4 Automatic window opening, exhaust fan	S5 Automatic window opening	S5 Automatic window opening, heat recovery units	S8 Visual display unit
Heating season 2014	Week 1, 27.10-31.10	Activated	Idled	Idled		Activated
	Week 2, 03.11-07.11	Idled	Activated	Activated		Idled*
	Week 3, 10.11-14.11	Idled	Activated	Activated		Idled
	Week 4, 17.11-21.11	Activated	Idled	Idled		Activated
	Week 5, 24.11-28.11	Activated	Idled	Idled		Idled
	Week 6, 01.12-05.12	Idled	Activated	Activated	Not examined	Activated
Non-heating season 2015	Week 1, 20.04-24.04	Activated	Activated	Activated		Activated
	Week 2, 27.04-30.04	Idled	Idled	Idled		Idled
	Week 3, 04.05-08.05	Activated	Activated	Activated		Activated
	Week 4, 01.06-04.06	Idled	Idled	Idled		Idled
	Week 5, 08.06-12.06	Activated	Activated	Activated		Activated
	Week 6, 15.06-19.06	Idled	Idled	Idled		Idled
Heating season 2016	Week 1, 29.02-04.03				Idled	
	Week 2, 07.03-11.03				Activated	
	Week 3, 04.04-08.04		Not examined		Activated	
	Week 4, 11.04-15.04				Idled	
	Week 5, 18.04-21.04				Idled	
	Week 6, 25.04-29.04				Activated	

*Idled means that the visual display unit was not present in the classroom.

The Danish heating season starts in September and ends by the end of April. Because of national holidays during the spring term and the summer vacation, the first two weeks of the non-heating season intervention period overlapped with the transition from the heating to the non-heating season. To circumvent national holidays, the intervention periods included non-consecutive weeks in 2015 and 2016 and some weeks ended on Thursdays and therefore included only four school days. However, this did not affect the study design as most tests involving pupils were scheduled to take place no later than on Thursday.

The overall timeline of the project activities in the elementary school is shown below:

Jan 2014: Pre-measurements
June-Aug 2014: Installation of retrofits
27 October to 5 December 2014: Intervention study solutions 1, 2, 3, 4 in a heating season scenario
20 April to 19 June 2015: Intervention study solutions 1, 2, 3, 4 in a non-heating season scenario
29 February to 29 April: Intervention study solution 5 in a heating season scenario
29 September to 24 November 2016: Intervention study solution 6 in a heating season scenario

5.1.5 Measurements

5.1.5.1 The quality of the classroom environment

Measurements of indoor climate parameters were made in different classrooms in the school prior to installation of the ventilation retrofits and after they were installed. Measurements prior to installation of retrofits were made between the 14th January 2014 and the 30th January 2014. Measurement stations were installed in all classrooms in the South Wing, two rooms in the East Wing, and two rooms in the West Wing (Figure 5.1.1).

One measurement station consisting of a Vaisala CO_2 transmitter model GMW22 (CO_2 range: 0-5000 ppm ± 100 ppm + 2% of reading) connected to an Onset HOBO data logger model U12-012 (signal range: ± 2mV ± 2.5% of reading) that also monitored temperature (range: -20-70°C, ±0.35°C in the range 0-50°C) and relative humidity (±2.5% from 10%-90% RH) was installed in each classroom. Measurements were recorded in five-minute intervals. The measurement station was located away from the windows at a height of approximately 1.5 m above the floor next to the whiteboard. Figure 5.1.12 shows a measurement station in room S3 with the decentralized ventilation system.

Window and door opening events were recorded with Onset HOBO State U9 Data Loggers. The loggers and the magnets were mounted on the frames of all operable doors and windows. The state loggers recorded binary events (window/door open/closed) and a timestamp of the event. Figure 5.1.13 shows a state logger mounted on a window frame.

Figure 5.1.12. Measurement station with a CO_2 transmitter and a datalogger that also recorded temperature and air humidity.

Figure 5.1.13. State logger mounted on a window frame.

5.1.5.2 Subjective evaluations

Every week, the pupils were asked to rate the indoor climate and their well-being on scales constructed of smileys. The scales were printed on paper and the pupils marked the smiley that expressed at best their answer to the question posed. The questions asked about mucosal irritation in the eyes, nose and throat, skin irritation and common symptoms such as concentration difficulties, tiredness, and well-being. The questions pertained also to the conditions in the classroom, i.e. whether it was warm or cold, noisy, dark, stuffy or whether the air was perceived as fresh. An example of the scale used by the pupils is shown in Figure 1.1.13. The questions referred to the perceptions and well-being during the week when the scale was presented to the pupils.

Different versions of the questionnaire were used during the first intervention period in the heating season 2014 and the second and third intervention periods in the non-heating season 2015 and the heating season 2016. Fewer questions were used in the latter periods and five instead of seven smileys were included in a scale. Additionally, the selected questions were simplified to make it easier for the pupils to complete the questionnaire. The change was made following the experience gained during the first intervention period in 2014. An example of a scale included in the first intervention period and the subsequent intervention periods is shown in Figure 5.1.14. The full questionnaires with all questions are included in Appendix B and Appendix C. The questionnaires were in Danish, but were translated for inclusion in this report. The schedule of presentation of the questionnaires in the different intervention periods is shown in Appendix D.

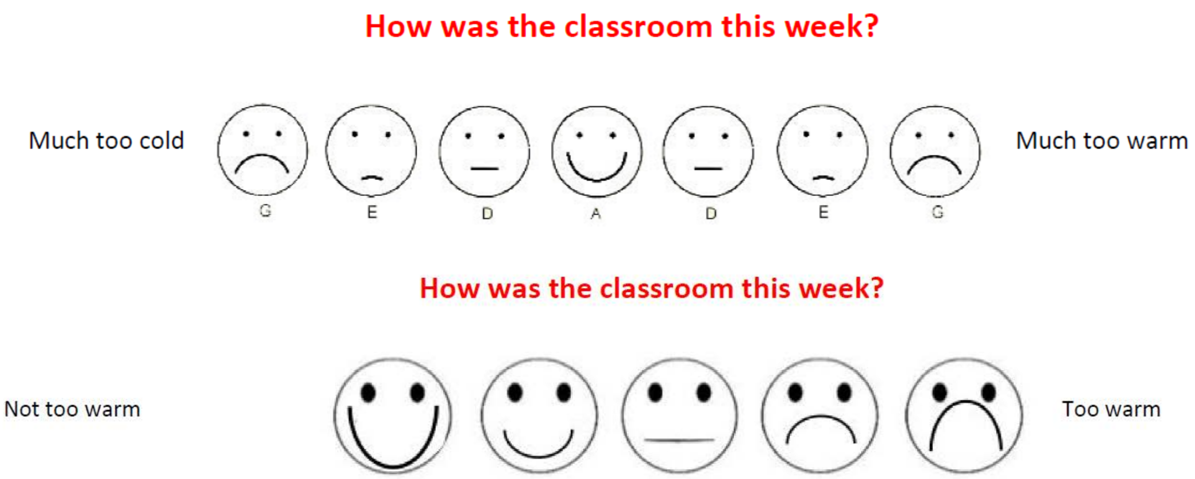


Figure 5.1.14. Example of a question from the questionnaire applied in the first intervention period in 2014 (top) and in the second and third intervention periods (bottom).

During the first intervention period in 2014, the teachers were also asked to rate their perceptions of the classroom conditions and the pupils' behavior, but the response rate was too low to obtain meaningful results. Consequently, the teacher questionnaire was not used in the intervention periods in 2015 and 2016. The questionnaire presented to the teachers is included as Appendix E.

To minimize the risk of errors, the questionnaire responses were read from the scales and digitized independently by two students recruited for the purpose among the students enrolled at the Technical University of Denmark.

5.1.5.3 Cognitive performance

A battery of tests was used to measure the cognitive performance of the pupils. Typical school tasks were used as well as psychological tests. The former included tasks examining the pupils' ability to perform mathematical calculations (subtraction and multiplication) and language based tasks examining their ability to read and understand a text (reading and comprehension). The latter included a logical test (grammatical reasoning) and a test of attention (d2 test). Each week during the intervention periods, the pupils were presented to a selection of math or language-based tasks, or logical tests, and each week consistently to the d2 test (Appendix D). After the first intervention period it was decided not to continue the use of the Reading and comprehension test due to difficulties with its application and scoring. All tests were completed with pen and paper.

The difficulty and presentation of the tests were adjusted to match the abilities and customs of a class as well as to fit to the extent possible into the regular teaching routines. Each test comprised 5 to 10 pages and the pupils had no more than 10 minutes to complete it. If anyone completed the test before the indicated time, all other pupils were stopped as well, marked where they finished the test and the teacher noted the time that was used to complete the test. Appendix D indicates the actual time used by the pupils when they performed the different tests. It was planned that the tasks should be presented later in the week and later during the day so that the pupils were exposed to the classroom conditions for as long time as possible. However, it was also important that the tests matched the lesson taught, i.e. that the arithmetical tasks were presented during math and reading and comprehension during language (Danish) class. Consequently, the presentation of the tasks followed the class schedule, which was not changed for the purpose of the experiments and the tests could therefore not always be presented late in the afternoon or late during the week (Appendix D). The tests were presented by the teachers.

To minimize the risk of errors, the results of the tests were checked and digitized independently by two students recruited for the purpose among the students enrolled at the Technical University of Denmark.

Subtraction test

The subtraction test was prepared in consultation with the teachers teaching mathematics in the classes where the experiments took place. In the subtraction test, columns of three and four digit numbers without zeros were subtracted. The test result was the number of subtractions attempted by each pupil during the available time, i.e. the speed at which the task was performed, and the proportion of incorrect answers, i.e. the percentage of errors (relative to the number of subtraction units completed). Figure 5.1.15 shows an example of the subtraction test.

$$\begin{array}{r} 3746 \\ -\ 2345 \\ \hline \end{array}$$

Figure 5.1.15. Example of the subtraction test.

Multiplication test

The multiplication test was also prepared in consultation with the teachers teaching mathematics. In the multiplication tests, pupils multiplied two one-, two-, or three-digit numbers. The pupils from the 4th grade classes multiplied numbers between 1 and 12 and the pupils from the 5th grade between 1 and 99. The test result was the number of multiplications attempted by each pupil, i.e. the speed at which the test was completed, and the proportion of incorrect answers, i.e the percentage of errors relative to the number of units multiplied. An example of the multiplication test is shown in Figure 5.1.16.

$3 \cdot 59$ $\quad$ $4 \cdot 17$ $\quad$ $6 \cdot 63$ $\quad$ $9 \cdot 23$

Figure 5.1.16. Example of the multiplication test.

Modified math test

Experience gained during the first intervention period in the heating-season 2014 was used to modify the math test so that the subtraction and multiplication tests were combined into one math test. The adjustment was made to avoid each test becoming too monotonous. The calculations were the same as in the original two tests, but the modified version consisted of alternating subtraction and multiplication tasks, as shown in Figure 5.1.17. A time limit of eight minutes was set for this test.

$$\begin{array}{r} 725 \\ -\ 106 \\ \hline \end{array} \qquad 7 \cdot 2 \qquad \begin{array}{r} 561 \\ -\ 100 \\ \hline \end{array}$$

Figure 5.1.17. Example of the math test.

Grammatical reasoning

This test was developed based on the 3 min Baddeley test (Baddeley 1963), which has been shown to be sensitive to environmental stressors. In this test, the pupils categorized statements as being either true or false. The statements expressed the order of two letters A and B; examples are given in Figure 5.1.18, where the right answers are T (true) in case of both statements. The number of statements attempted by each pupil in the available time and the proportion of incorrect answers were used as the measure of performance. The former presented the speed at which the task was performed and the latter the percentage of errors relative to the number of statements attempted.

B does not precede A	AB	T	F
B does not follow A	BA	T	F

Figure 5.1.18. Example of the grammatical reasoning test (Baddeley test).

Modified grammatical reasoning test (graphical-logical test)
Experience gained during the first intervention period in the heating-season 2014 was used to modify the grammatical reasoning test. The original test was replaced by a graphical-logical test. In the earlier version of the test, the pupils marked if a statement was true or false. In the revised version, the sentence did not address the order of two letters but the composition of geometrical figures (circle/square/triangle). Figure 5.1.19 shows an example of the graphical-logical test where the sentence is: The square is larger than the circle. In case of this test a time limit of 5 min for completion was set.

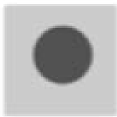
Firkanten er større end cirklen  S F

Figure 5.1.19. Example of the graphical-logical test, S stands for sand (true) and F for falsk (false)

Reading speed and comprehension
This test consisted of texts of an adequate level of difficulty. Inside the text, choice points containing three words were inserted, which could all be used in connection with the preceding sentence, but only one was correct in the context. Choice points were inserted at regular intervals in the text. The pupils had to read the text in the available time and mark the correct words. The measures of performance were the number of lines read in the available time expressing the speed of completing the task and the proportion of choice points in which the answer was incorrect, indicating the percentage of errors relative to the number of choice points attempted (i.e. present in the lines completed). Figure 5.1.20 shows an excerpt from the text, in Danish, where the choice point is indicated; the right answer in the present text is Iben.

- Det går da ret godt på den her måde, siger Iben.
Siden hun kom hjem fra sygehuset, har hendes klasselærer sendt mail
til mor og far om, hvad klassen har læst eller foretaget sig,
og [Iben, far, mor] har lavet det samme derhjemme.

Figure 5.1.20. Example of the reading and comprehension test.

d2-test

The d2-test is a validated test to measure concentration ability. The test consists of 14 rows of the characters d and p with one or two dashes above and/or below each character. The task is to mark as many of the target characters as possible; the target character being a character d with 2 dashes either above or below or one above and one below (therefore the tests is called d2-test). A row must be completed in maximum 20 seconds. Once the time is elapsed, the next row must be started. The performance of the test is measured by the number of attempted characters, indicating the speed at which the test was performed, the total number of errors indicating the number of d2 characters omitted plus the number of distracting characters marked mistakenly, percentage of errors, number of characters completed minus number of errors. The so called concentration performance is the number of correctly marked d2 characters minus the number of distracting characters marked mistakenly; the numbers are totaled across all 14 rows. Furthermore, to check the consistency of responses, the fluctuation rate is calculated (FR) which is the difference between the row with the highest and the lowest number of characters. Figure 5.1.21 shows an example of the d2-test.

Figure 5.1.21. Example of the d2-test.

5.1.5.4 Acoustical conditions

The A-weighted sound pressure level in each classroom was measured continuously with Netatmo weather stations, which in addition to the sound pressure level also measured humidity, temperature, CO_2-concentration, and pressure. The instrument measures the A-weighted sound pressure level in the range from 35 dB_A to 120 dB_A (www.netatmo.com, 2015).

The reverberation time of selected classrooms was measured with a Brüel & Kjær 2250 Sound Level Meter. The same instrument was used to compare as a reference with the A-weighted sound pressure level measured with the Netatmo. The Brüel & Kjær 2250 has a range of 16.6 dB_A to 140 dB_A.

The measurements of reverberation time were made according to the interrupted noise method (DS/EN 3382-2 2008). The Brüel & Kjær 2250, an amplifier and an omni-directional speaker were used to measure reverberation time in classrooms S3 and S5.

The speaker was placed in two different locations in the classroom and the sound level meter was placed in three different locations for each position of the speaker, yielding a total of six measurements per classroom. The approximate positions of the omnidirectional speaker and the sound meter during the measurements are shown in Figure 5.1.22.

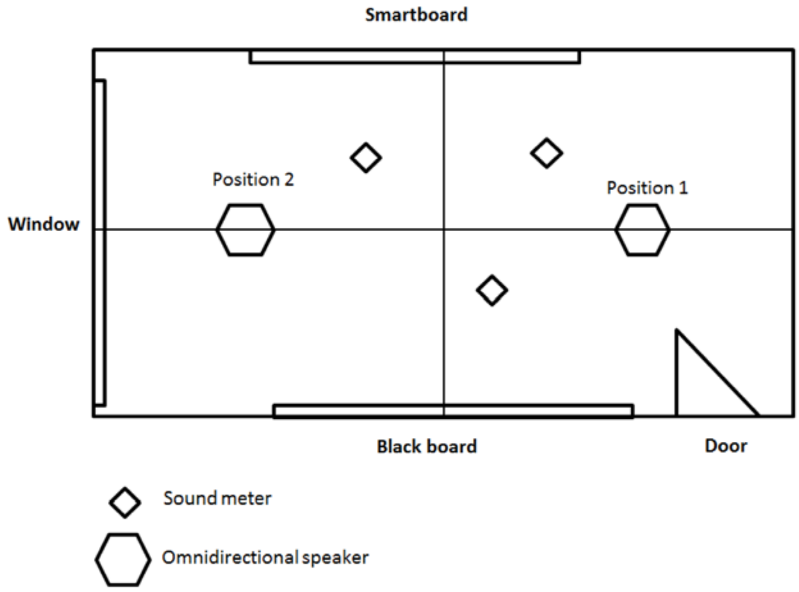


Figure 5.1.22. Approximate positions of the omnidirectional speaker and the sound level meter.

The reverberation time was assessed as T20. The omni-directional speaker was set to a sound output at least 30 dB louder than the background noise. The background noise was detected to be between 30 and 40 dB and the amplifier was therefore set to around 80 dB. The omnidirectional speaker generated a sound for four seconds at a time, three times in total, and the sound meter measured the time it took for the sound pressure level to decrease to 60 dB after the sound output. During the measurements, the rooms were vacant.

To verify the validity of the Netatmo measurements, spot measurements with the Brüel & Kjær 2250 were made. The Brüel & Kjær 2250 was attached to a tripod in approximately the same height as the Netatmos that were attached to the water pipes. The B&K 2250 was set to measure actual values with a frequency of one minute, to make it easier to compare with the Netatmo, which had a logging frequency of five minutes.

5.1.5.5 Ventilation measurements

Ventilation measurements were made in each classroom by measuring air change rate using the decay method. Different scenarios were modelled. In these scenarios, the retrofitted systems were either idled or ran at full speed. In classrooms where the windows were opened automatically the condition with windows open half-way was set up as well. The scenarios included also conditions with windows that were fully open or fully closed.

On two days, the measurements were carried out in the empty rooms after the classes were completed: on March 9 2015 when ambient temperature was around 10°C and on May 8 2015 when it was around 14°C; on both days the wind speed was low.

During the measurements, Freon 134a was released into the classroom and tabletop fans ensured that it was well mixed within the entire volume. A multi-gas monitor connected to a multipoint dosing and sampling unit was used to sample the air from the room for approximately 20 minutes after the gas had been released. Figure 5.1.23 shows the instrumentation used to measure air change rate.

Figure 5.1.23. Innova Multigas Analyzer 1312 (bottom) and multipoint sampling and dosing unit 1302 (top).

5.1.5.6 Energy use

In classrooms S3, S4 and S5 where the retrofits were installed, the electricity used by the systems was recorded. Energy meters were also installed on the radiators, convectors, and the water-to-air heating coil in the mechanical system in classroom S3. No energy meters were installed in classrooms S7 and S8 because the monitoring of the conditions in these classrooms was decided after the retrofits had been installed in the other classrooms

5.1.6 Data processing and analyses

Box plots were used to present the measurements performed in the classrooms. Figure 5.1.24 explains the construction of the box plots; the adjacent values were the most extreme values within a distance of 1.5 times the inter-quartile range of the nearer quartile.

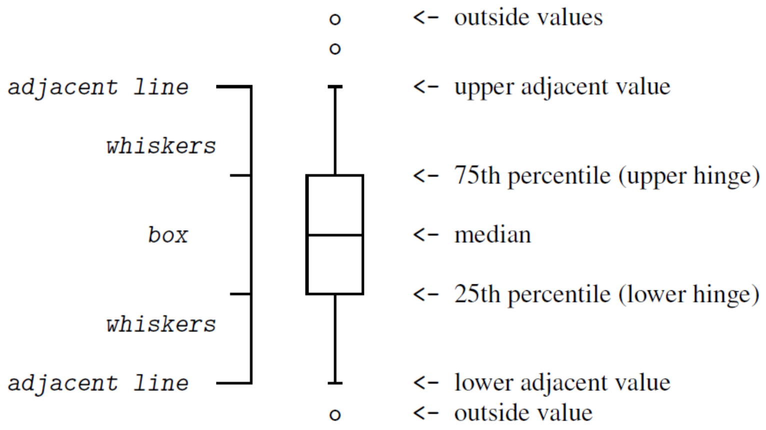


Figure 5.1.24. The different statistics shown in a Box-and-Whiskers plot (Stata.com).

Simple linear regression was used to associate the classroom heating energy use with outdoor temperature to evaluate the energy performance of the retrofitted ventilation systems.

CO_2 concentration and temperatures were compared between system operation modes (system control idling or activated) using analysis of variance. The response variable was either CO_2 concentration or temperature and the explanatory variables were system control mode, lesson, weekday, and the interaction between lesson and weekday. Only lessons when the classrooms were occupied were included in the analyses. It was assured that the distribution of the residuals followed a Gaussian distribution.

Sound pressure levels did not follow a Gaussian distribution and therefore the non-parametric Wilcoxon rank-sum test was used to compare sound pressure levels between system operation modes.

Pupil responses recorded by the questionnaires were rescaled so that the left end of the scale was coded as 0 and the right end as 100. For each pupil participating in the experiments, the medians of the responses calculated for the weeks with retrofits activated and the retrofits idled were calculated; the medians were calculated based on all available responses and even when some responses were missing. Responses from pupils for whom no single data were available on the weeks with either retrofits activated or idled were not included. The median responses from the weeks when the retrofits were idled were considered to form the baseline. They were subtracted from the median responses on the weeks when the retrofits were activated. The differences were used to calculate the percentages of responses above and below the baseline. These percentages indicated the effect of the retrofits on the different subjective responses and were subjected to the non-parametric sign test. A significance level of $P < 0.05$ indicated that the responses changed from the baseline.

Additionally, the non-parametric Wilcoxon sign-rank test was used to compare median responses at baseline when the retrofits were idled with median responses when they were activated. A significance level of $P < 0.05$ indicated that the median responses were significantly different from each other.

With responses from the reference classroom, where no retrofits were installed, a similar analytical approach was used. It was assumed that the responses from the weeks when retrofits were idled in the parallel classrooms where retrofits were installed formed the baseline, and from the other weeks were equivalent to responses from the weeks when retrofits in the parallel classrooms were activated. No change from the baseline was expected in this case and any significant change would indicate either spurious result or an effect of an uncontrollable external factor.

The results of the performance tests were analyzed similarly as the questionnaire responses. The performance scores (speed, % errors and the product of speed times the % errors or any other performance metric that was used) were neither normalized nor rescaled and the analyses were made using the raw data. For each pupil participating in the experiments the median score was calculated using the scores on the weeks with retrofits activated and idled. All available scores were included, even if the scores from some weeks were missing. Excluded were scores from the pupils in case when no data were available on either the weeks with retrofits activated or idled. The median score recorded during the weeks with retrofits idled was considered as baseline. It was subtracted from the median score from weeks when the retrofit systems were activated. The differences were used to calculate the effect of the retrofit on cognitive performance – the change from baseline, which was either positive or negative.

Cohen's d was calculated to illustrate the size of the effect; a d effect of 0.2 indicated small effect, 0.5 medium effect and 0.8 large effect. Median score at baseline and median score with systems activated were subjected to Wilcoxon signed-rank test. The differences were considered significant at $P<0.05$.

In case of performance scores in the reference classroom, where no retrofits were installed, a similar analytical approach was used. It was assumed that the scores obtained in the weeks when the retrofits were idled in the parallel classrooms where the retrofits were installed formed the baseline and from the other weeks were equivalent to performance scores from the weeks when retrofits in parallel classrooms were activated. No change from the baseline was expected in this case and any significant change would indicate either spurious result or an effect of uncontrollable external factors.

The analyses of subjective responses on questionnaires and of the results from the performance tests and tasks were carried out using IBM SPSS Statistics software Version 19.

Generalized linear mixed effects models were used to test associations between classroom exposures and test performance. The mean of the CO_2-concentration and temperature of the lesson when a test was presented to the pupils, were used as exposure variables. Pupil ID nested within class was used to control for individual and group characteristics and week number (1 to 6) to control for learning effects. The model included both random intercepts at pupil level and random coefficients accounting for differences in the effect of the CO_2 concentration and temperature between pupils. The model accounted for autocorrelation between intervention weeks (learning effect) by estimating distinct variances for each within-group error. These analyses were carried out with Stata IC version 12.0 (Statacorp, TX, USA).

5.2 Intervention study of the performance of retrofit solution 6 in a university classroom

An intervention study was performed in a classroom at the Technical University of Denmark on four afternoons during the fall of 2016 with graduate students taking the Ventilation and Climatic System Course. During two afternoons, the classroom was ventilated by the ventilation system and on two other afternoons the ventilation system was in operation together with a gaseous air cleaner.

Under both conditions, the total volume of air delivered to the classroom was the same. On the days when the ventilation system was in operation without the air cleaner, only outdoor air was used to ventilate the classroom and part of the air exhausted from the classroom was recirculated.

When the air cleaner was in operation, the outdoor air supply rate was unchanged, but the volume flowrate that was exhausted from the classroom and recirculated by passing it through the air cleaner thus effectively increasing the total volume of unpolluted air delivered to the classroom.

Under both conditions, the students participating in the course assessed the air quality and other conditions in the classroom, and indicated whether they experienced any acute health symptoms. They took one performance test examining their concentration and ability to think logically.

Thermal and air quality conditions were monitored continuously during the study. On two occasions, chemical measurements were carried out as well. It was originally planned that the experiments with the air cleaner should have been carried out in the elementary school described earlier. However because of logistical problems connected with the installation and operation of the air cleaner and because only a prototype of the air cleaner was available and it already was installed in the ventilation system in one classroom in a building at the Technical University of Denmark (Figure 5.2.1).

5.2.1 Location and the classroom

The study building was erected in the late 1960s/early 1970s and renovated in the late 1990s/early 2000s: the floor covering was changed from felt carpet to hard floor covering made of polyolefine and the windows were replaced with double glazed windows with low U-value. The classroom where the study was performed was 11.9 m long, 6.3 m wide and 2.8 m high. It had six windows facing east (Figure 5.2.1). The classroom was retrofitted with the ventilation systems and floor heating in the early 2000. Later, the air cleaner was installed in the air handling unit.

Figure 5.2.1 The classroom and the building where the intervention study was carried out

1.2.2 Retrofit solution – a sorption gaseous air cleaner

The ventilation system in the classroom was retrofitted with a prototype of the gaseous air cleaner described in detail by Fang et al. (2008) and Fang (2011), Figure 5.2.3. The air cleaner used a gas-phase sorbent cleaning principle and it used a commercially available regenerative silica gel rotor (desiccant wheel). The principle of operation was that the pollutants in the air passing through the rotating silica gel rotor were adsorbed on the surface of the rotor and then purged by hot air so that the silica gel could be regenerated and reused for the purpose of cleaning.

Earlier laboratory experiments with the silica gel rotor showed that the gaseous pollutants emitted by building materials and humans could be effectively removed from the air stream using this principle. The single pass efficiency was estimated to be at least 90%. Based on these preliminary experiments, a prototype of the air cleaner was designed, constructed and installed in the ventilation system for further testing (Figure 5.2.1). This prototype combined the air cleaner with a heat pump that was used to heat the purging airstream. The design of the system allowed to use the total energy output of the heat pump (both condenser and evaporator) for cooling during summer operation and for heating during winter operation.

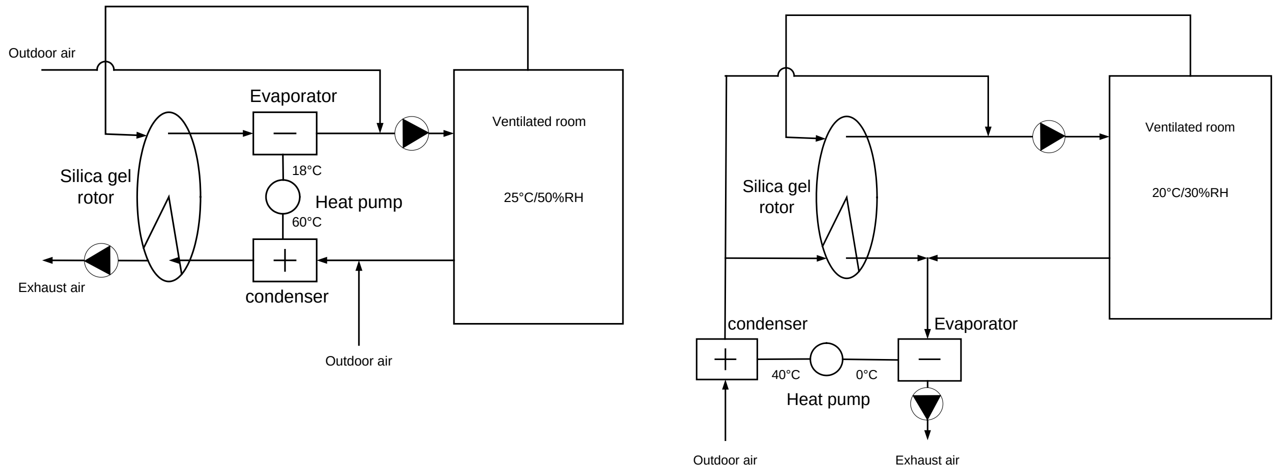


Figure 5.2.2. The operation principle of the gas-phase sorbent air cleaner during summer (left) and winter (right).

Figure 5.2.3. Prototype of the air cleaner installed in the ventilation system is shown with a section of the air handling unit.

5.2.2 Experimental plan

The air cleaning intervention study was performed in the fall semester of 2016 on four Thursdays (9/29, 10/13, 11/17 and 11/24) in the afternoon during the 4-hour teaching module of the course starting at 1 pm. The course was attended by 40 graduate students at the 7th and the 9th semester. During the study, the classroom was kept at 23°C and ventilated with a total airflow of 280 L/s. Of the total airflow 100 L/s was outdoor air and the remaining 180 L/s was recirculated. The recirculated air passed through the air cleaner. On two days (9/29 and 11/24), the air cleaner was activated, i.e. the rotor was revolving and the silica gel was regenerated, while on the other two days (10/13 and 11/17) it was idled, i.e. the rotor was not moving and the silica gel was not regenerated by the hot air. Consequently, on the days with the air cleaner activated, the volume flowrate of unpolluted air theoretically should have been 2-3 times higher than on the days when the air cleaner was idled, assuming an efficiency of the air cleaner of 100%. The volume flowrate of air delivered to the classroom was measured prior to the start of the experiments.

At the beginning of the teaching module, the students assessed the air quality and the odour intensity in the classroom using the scales presented in Figure 5.2.4. Then the normal teaching began. After approximately 1 to 1,5 hours of uninterrupted teaching, the students performed the Baddeley test (grammatical reasoning test) described earlier; they had 3 minutes to complete the test. Then they assessed the conditions in the classroom and the intensity of any acute health symptom experienced using the visual analogue scales presented in Figure 5.2.4. After that, they left the classroom for about 1 to 2 minutes to refresh their senses and upon returning to the classroom they assessed the air quality and odor intensity. The teaching was re-commenced after the short break. The students practiced the scales and the test prior to the intervention study and were not informed about the changes in the classroom conditions.

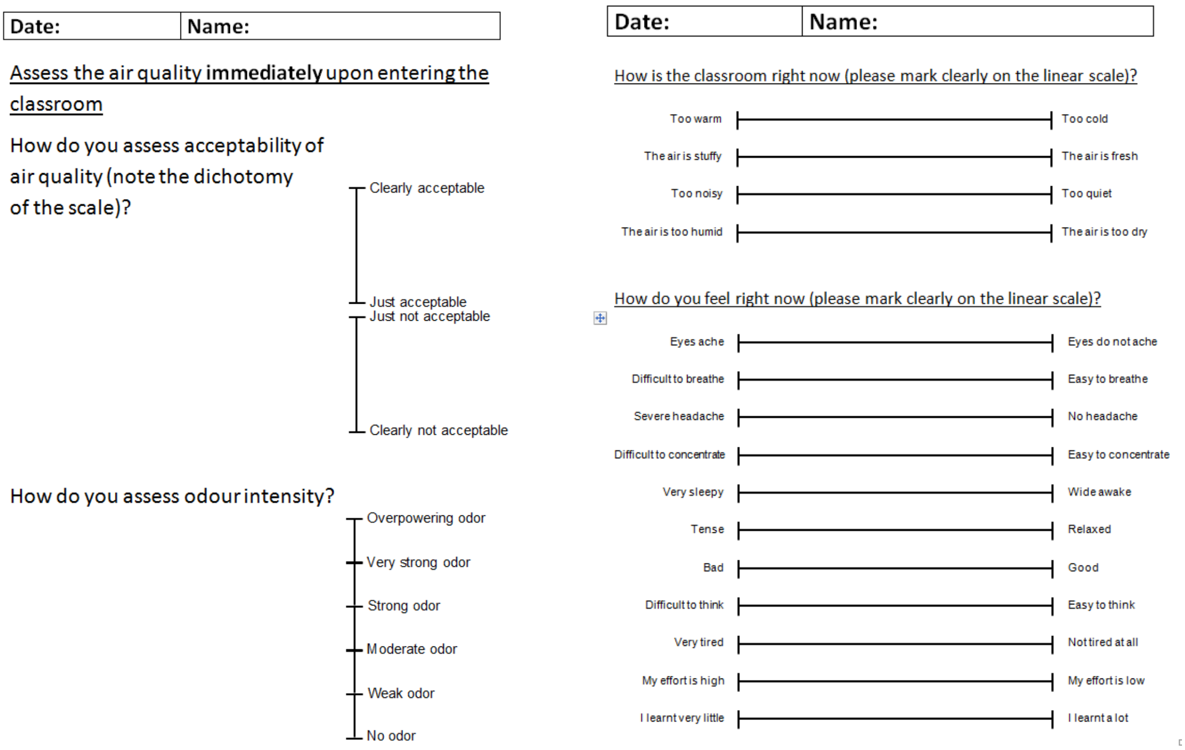


Figure 5.2.4. Scales for assessing air quality, odor intensity and the conditions in the classroom, as well as the intensity of any experienced acute health symptoms.

On two Thursdays (11/17 and 11/24) the air in the classroom was sampled on Supelco Lp-DNPH cartridges and on Tenax tubes for subsequent chemical analysis on HPLC and GC/MS. It was planned to sample 60 L of air on DNPH at a flow of 1000 ml/min and 6 L on Tenax tubes at the flow of 100 ml/min. The actual volume of the sampled air was noted; it was not different from the planned volume. Calibrated pumps were used to take the samples. Blanks were used, but no replicates were taken. Separate samples were taken prior to the commencement of the class and during the teaching period that ended with the students taking the cognitive test. The samples were analyzed by a commercial laboratory. The DNPH cartridges were analyzed by one laboratory according to IS016000 Part 3: Determination of formaldehyde and other carbonyl compounds. The Tenax tubes were analyzed by another laboratory.

The tubes were desorbed in an automated thermal desorption/purge and trap injector. After transferring to a non-polar capillary column, the trapped compounds were separated in a gas chromatograph and detected in a mass spectrometer. Identification of the compounds was done using mass spectra libraries (NIST, Wiley). Identified compounds were quantified against pure reference compounds. The method covered volatile compounds from C5 to C22. Compounds in the range from C6 to C16 were reported as VOCs, those more volatile as VVOCs and those eluting after C16 as SVOCs. The measurements were performed according to DIN EN ISO 1600 part 6. Chromatograms and the concentrations of detected compounds were returned from the laboratories.

Subjective responses and the results from the cognitive test were analyzed with the Wilcoxon signed-rank test. The differences between conditions were considered significant at $P<0.05$. Medians were used as the measure of central tendency. The analyses were carried out using IBM SPSS Statistics software Version 19.

5.3 Investigation of the performance of the retrofit solutions in different climates

Simulations were carried out to study the indoor environment and energy use with and without the same retrofitted system installed in <u>all</u> classrooms in the south wing of Ravnsholtskolen; the condition without the retrofit was considered as the reference. For comparison, simulations were also made with a central ventilation system.

Simulations were carried out with weather data for Copenhagen (Cfb Köppen-Geiger, warm temperate, fully humid, warm summer) and for other climates representing New York (Cfa, warm temperate, fully humid, hot summer), Chicago (Dfa, cold temperate, snow, fully humid, hot summer), and Los Angeles (Csa, warm temperate, steppe, hot summer).

Two sets of simulations were made: one set where it was assumed that manual window opening (venting) supplemented the automatically controlled systems in the classrooms, and one set without supplementary manual window opening. All simulations were made with IDA ICE (IDA Indoor Climate and Energy).

5.3.1 Model geometry

The building was modeled based on blueprints provided by Allerød municipality. Figure 5.3.1 shows the layout of the simulated rooms in the south wing and Figure 5.3.2 shows a 3D view of the simulated geometry. The reference school had the old windows, while all other models had new windows installed. Detailed specification of the geometry and material properties of the model(s) are shown in Appendix F.

5.3.2 Description of the simulated systems

Common for all systems was:

- No mechanical cooling
- The systems were activated on weekdays from 7-16. The systems were not activated during weekends or school holidays. Since the model included the whole building, the number of occupied hours differed between rooms. The occupancy of the classrooms followed the class schedules.
- Only the classrooms had mechanical ventilation (except the toilets, which had a separate exhaust system).
- The supply temperature of the heating system was constant at 60ºC. The boiler was in operation all year.
- The building was rotated 8 degrees compared to the north/south axis.
- Domestic hot water (DHW) was not included in the simulations.
- The COP of the heating system was set to 1.

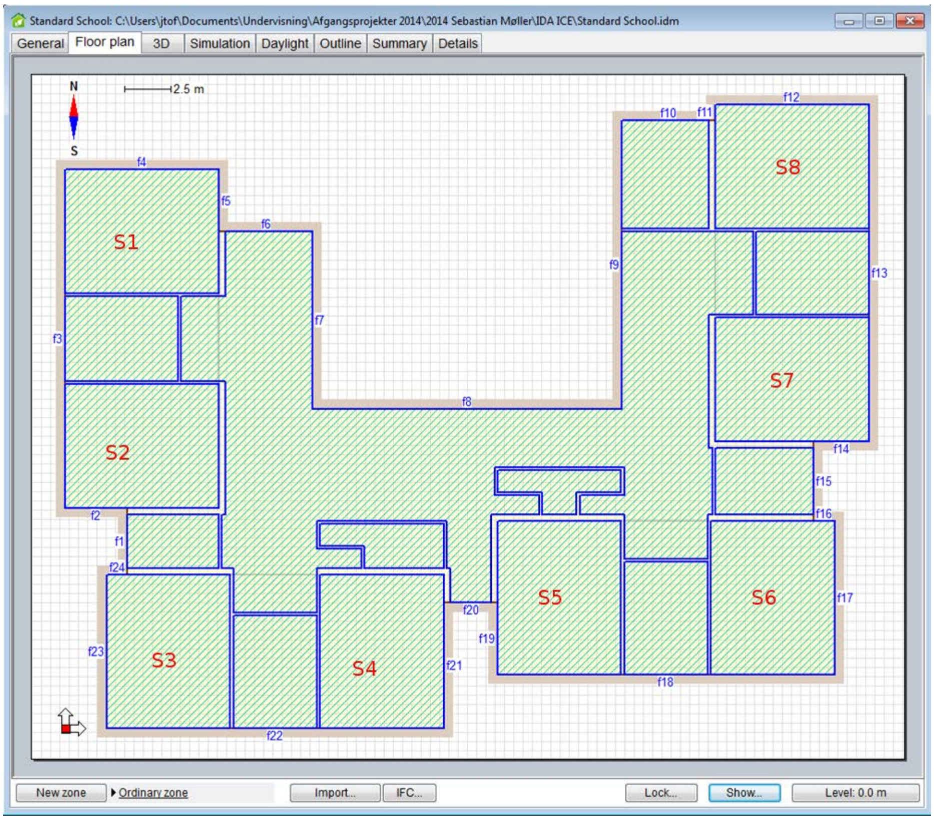


Figure 5.3.1. Layout of the model of the south wing of Ravnsholtskolen used to simulate indoor environment and energy use.

In simulations with manual venting, the control was specified so that opening of the windows started at a temperature of 21°C and the window was fully opened at 24°C. The window had a maximum opening of 30% of the total area.

5.3.2.1 Decentralized ventilation system

An air-handling unit was simulated in each classroom. The unit was controlled so the supply air temperature depended on the air temperature in each room. The heat recovery efficiency was set to 82 % and the SFP to 820 J/m^3. The supply air temperature was adjusted to keep the room air temperature at 23^{o}C, with a maximum supply air temperature of 25^{o}C and a minimum supply air temperature of 18^{o}C. The system had a heating coil after the heat recovery unit. The system had no electrical preheater, and therefore the minimum allowed discharge temperature of the heat recovery unit was set at 1^{o}C.

The flowrate was controlled by the CO_2 concentration. The minimum flowrate was 56 L/s (1.01 L/s m^2), and the maximum flowrate was 201 L/s (3.62 L/s m^2). The flowrate was kept at the minimum when the CO_2 concentration was below 600 ppm and it increased linearly to the maximum at 800 ppm as shown in Figure 5.3.3.

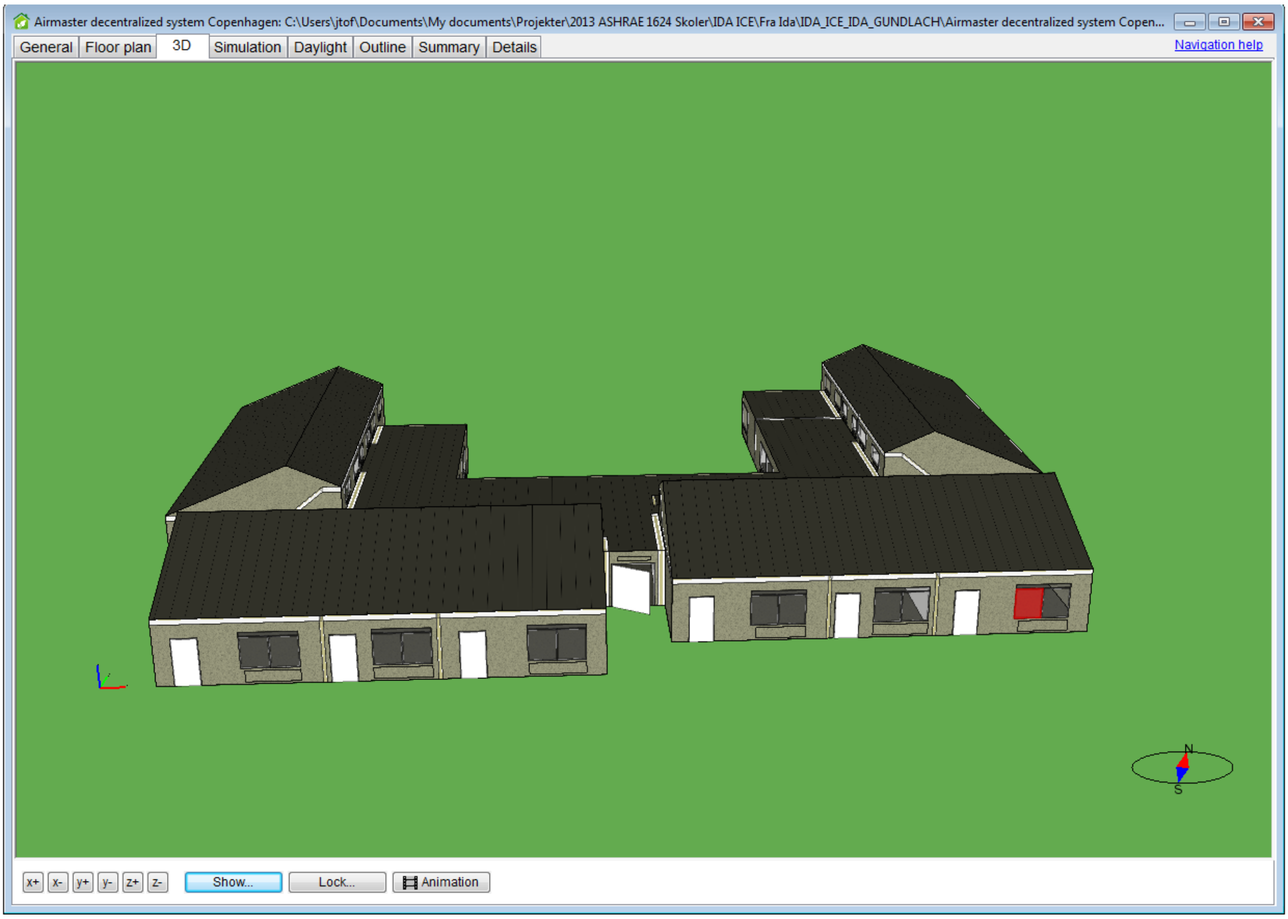


Figure 5.3.2. 3D image of the simulated geometry.

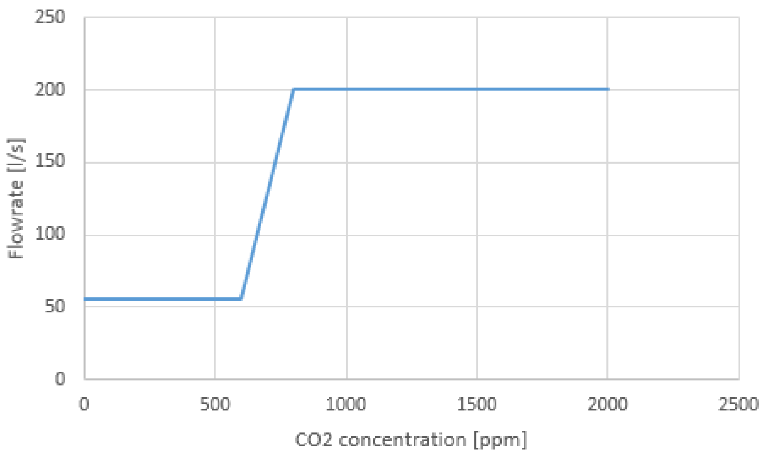


Figure 5.3.3. Curve for CO_2 control of the volume flow rate of the decentralized system.

5.3.2.2 Automatic window opening and exhaust fan

The control of the automatic window opening was identical in the classroom with the exhaust fan and the heat recovery units. With only an exhaust fan, this room was simulated without heat recovery, heating coil, or cooling coil. The SFP of the exhaust fan was 683 J/m^3 as specified by the manufacturer. The control of the fan was activated on schooldays from 7-16. The flowrate was controlled by the CO_2 concentration. There was no minimum flowrate and the maximum flowrate was 208 L/s (3.74 L/(s m^2)). The flowrate of the exhaust fan was kept at 0 L/s when the CO_2 concentration was below 700 ppm above which it increased linearly and reached the maximum at 1000 ppm as shown in Figure 5.3.4.

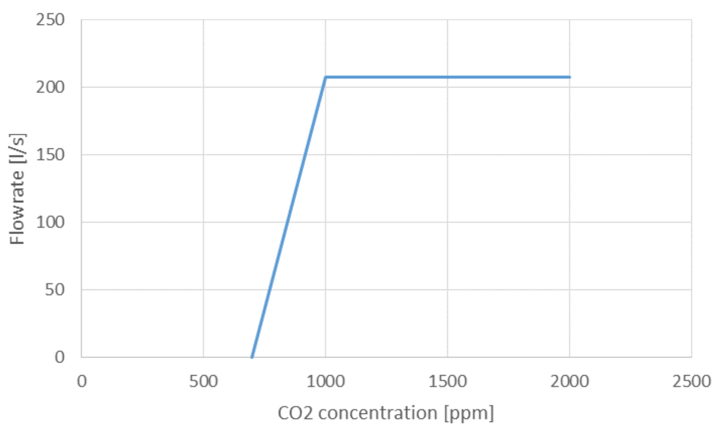


Figure 5.3.4. Curve for CO_2 control of the exhaust fan.

5.3.2.3 Automatic window opening and heat recovery units

The efficiency of the heat recovery units was set at 85 % and the SFP at 300 J/m^3. The supply air temperature was controlled by the efficiency of the heat exchanger because the system had no heating coil. The flowrate was controlled by the CO_2 concentration. The minimum flowrate was 39 L/s (0.70 L/s m^2) and the maximum flowrate was 130 L/s (2.34 L/s m^2). The flowrate was kept at the minimum when the CO_2 concentration was below 650 ppm and it increased linearly to the maximum of 750 ppm as shown in Figure 5.3.5.

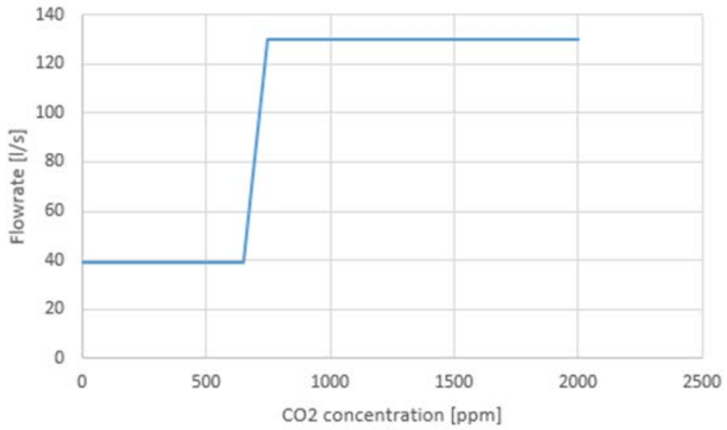


Figure 5.3.5. Curve for CO_2 control of the heat recovery units.

In this model, it was not possible to simulate the demand opening of Window 1, 3, and H and they were therefore controlled according to a predetermined schedule. At the beginning of each hour, starting at 9 am and ending at 4 pm, the windows were opened for 3 minutes and then closed. In the heating season (October to April), the maximum window opening degree was set at 50 % and in the non-heating season (April to October), the maximum window opening degree was 80 %. The windows were not opened during weekends and school holidays.

5.3.2.4 Central ventilation system

The central ventilation system that served all classrooms used in most cases the same settings as the decentralized system. The heat exchanger efficiency was set at 82 % and the SFP at 1500 J/m^3. The supply temperature was 19°C. Minimum and maximum volume flowrates and the demand control of the flowrate were the same as shown in Figure 5.3.3.

5.4 Influence of the user behavior on the classroom environment and energy use

The sensitivity of the simulated performance of the retrofit solutions was studied with different behavioral patterns by adjusting the simulations according to the recorded window and door opening behavior. The simulation models were calibrated against measured time-series of the indoor environment and energy used for heating and ventilation.

Opening of windows and doors by pupils/teachers was defined based on the window and door opening events recorded in the field measurements and the class schedules. Each individual schedule was defined in an iterative process, where both the observed time of day with open windows and doors as well as the total percentage of open windows were considered.

A calibration model was made to simulate the conditions observed in January 2015. The calibration model used the actual weather data recorded during that month and the simulated indoor environment and energy use were compared with the field measurements. The presence of occupants was defined based on the class schedules. Thus, the occupied time was defined similarly to the definition used in the analysis of the field measurements.

The performance of the retrofit solutions and the reference scenario was then studied on an annual basis. Three scenarios investigated the influence of different user behavior patterns as modelled by different window settings:

The first scenario used the same settings as the calibrated model to study the annual performance, i.e. whether the window and door opening behavior observed in January could be assumed to represent the entire year. The second and third scenarios studied more extreme situations and assessed the impact of variations in the behavior patterns.

In the second scenario, referred to as the simulation of "best-case" user behavior, the windows were controlled by the occupants and set to open when the CO_2 concentration exceeded 800 ppm. Thus, the behavior would facilitate a good classroom air quality.

In the third scenario, referred to as the simulation of "worst-case" user behavior, the manually controlled windows were set to open only when the outdoor temperatures exceeded 19°C. Thus, a major part of the year this scenario would cause a poor classroom air quality.

Table 5.4.1 gives an overview of the simulations that were used to assess the influence of user behavior on energy use and indoor environment in the classrooms.

Table 5.4.1. Overview of the simulations focusing on user behavior.

Scenario	Time period	Manually controlled windows	Automatically controlled windows
Calibration model	07-01-2015 to 02-02-2015	Schedules	Schedules
Calibration settings	2015	Schedules	Schedules
"Best-case" user behavior	2015	CO_2-controlled Opens 0-70% at 800-1500 ppm	CO_2-controlled Opens 0-70% at 750-1000 ppm
"Worst-case" user behavior	2015	Outdoor temperature controlled Opens 0-70% at 19-30°C	CO_2-controlled Opens 0-70% at 750-1000 ppm

5.5 Product, installation and maintenance costs

The evaluation of the retrofit solutions included the estimated product, installation and maintenance costs excluding taxes. The cost estimations were based on consultancy with the manufacturers and the details are included in Appendix G.

6 Results

6.1 Air quality and temperature prior to retrofitting classroom ventilation

Figure 6.1.1 shows the distribution of the CO_2 concentration and temperature in the five classrooms included in the intervention study of retrofit solutions 1 to 5. The figures are based on measurements made during scheduled lessons from the 14th to 30th January 2014, prior to retrofitting the classrooms. In particular, classrooms S3 and S4 suffered from very high CO_2 concentrations with median concentrations that reached up to 1540 ppm and 1640 ppm and maximum concentrations well above 4000 ppm (in S3). In classrooms S5, S7, and S8, the median CO_2 concentration was below 1000 ppm, which may indicate different window and door opening behavior of the classes that occupied these rooms as compared with S3 and S4. Nevertheless, unacceptably high concentrations were measured also in S5, S7, and S8 emphasizing the need for better ventilation in these classrooms. The temperatures in classrooms S5, S7, and S8 also seemed higher than in S3 and S4. Since the only means of airing the classrooms was by opening windows and doors, and lower CO_2 concentration thus indicated longer duration with open windows or doors, the thermostat settings most likely differed between S3 and S4 and the other classrooms. The lowest temperatures in S4, S5, and S7 were recorded during the earliest morning lesson when the CO_2 concentration indicated that only few persons were present in these rooms.

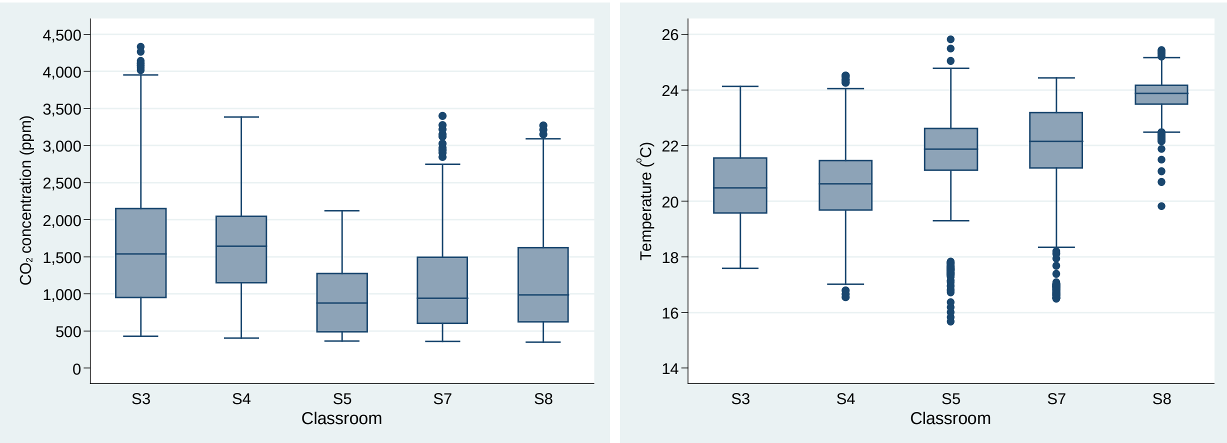


Figure 6.1.1. Boxplots of the distribution of the CO_2 concentration (left) and temperature (right) measured in the classrooms included in the intervention study during the period 14 January 2014 to 30 January 2014 prior to retrofitting classroom ventilation.

6.2 Outdoor weather conditions during the intervention periods

Figure 6.2.1 shows the diurnal variation of the outdoor temperature for each of the three intervention periods in 2014 (heating season), 2015 (non-heating season), and 2016 (heating season). The intervention periods in 2015 and 2016 spanned a wider date range than in 2014 due to interference with national holidays during which the school was closed.

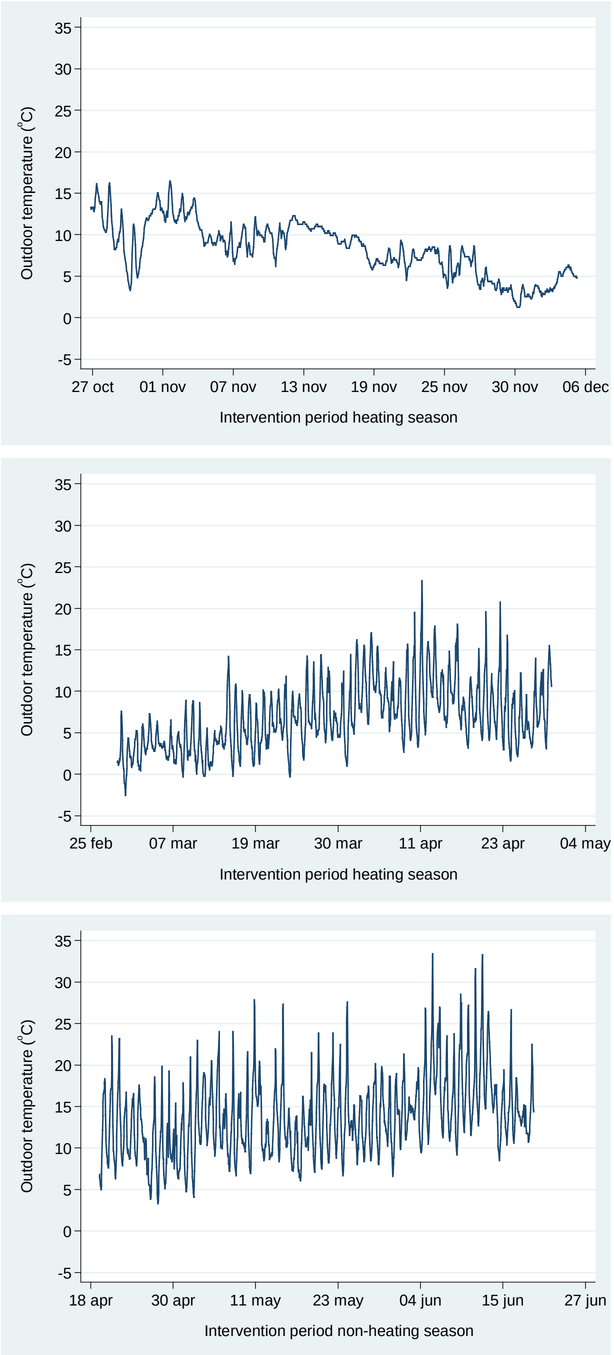


Figure 6.2.1. Outdoor temperature measured during the three intervention periods in the heating season in 2014 (top), heating season in 2016 (middle), and non-heating season in 2015 (bottom).

Table 6.2.1 summarizes the outdoor weather conditions, aggregated for the occupied time of each intervention week. The system with automatically controlled windows and heat recovery units was the only one tested during the heating season in 2016; all other solutions were tested in the heating season in 2014. Because of the number of national holidays and the summer vacation, the first two weeks of the non-heating season intervention period overlapped with the transition from the heating to the non-heating season. Even so, the average outdoor temperature was clearly higher during the non-heating season.

Table 6.2.1. Mean, standard deviation (s.d.), minimum, and maximum of the outdoor temperature determined for the occupied time from 8:00 to 15:00 for each week in the six-week intervention periods in 2014 (heating season), 2015 (non-heating season), and 2016 (heating season).

Season	Intervention week	Date range	Mean (°C)	s.d. (°C)	Minimum (°C)	Maximum (°C)
Heating	1	27-31 Oct 2014	12.3	3.0	4.2	16.3
	2	3-7 Nov 2014	11.6	2.4	8.7	14.9
	3	10-14 Nov 2014	11.0	0.9	8.4	12.3
	4	17-21 Nov 2014	8.2	1.1	6.3	9.9
	5	24-28 Nov 2014	7.4	1.3	3.6	8.7
	6	1-4 Dec 2014	3.3	0.5	2.0	4.0
	Overall		9.2	3.3	2.0	16.3
Heating	1	29 Feb-4 Mar 2016	4.0	1.7	0.7	7.6
	2	7-11 Mar 2016	5.4	1.9	1.9	8.9
	3	4-8 Apr 2016	11.3	2.9	6.7	16.9
	4	11-14 Apr 2016	12.5	3.4	5.4	17.8
	5	18-21 Apr 2016	9.6	2.1	5.4	13.1
	6	25-29 Apr 2016	8.2	2.4	3.8	12.2
	Overall		8.5	3.9	0.7	17.8
Non-heating	1	20-24 Apr 2015	13.6	2.9	8.5	17.9
	2	27-30 Apr 2015	10.3	2.1	6.4	13.3
	3	4-8 may 2015	15.7	2.4	11.8	20.7
	4	11-15 May 2015	15.6	2.1	10.7	19.7
	5	18-21 May 2015	17.2	2.9	12.9	22.4
	6	25-29 May 2015	15.1	1.8	11.7	18.4
	Overall		14.8	3.1	6.4	22.4

Overall, the outdoor temperature was comparable between the two intervention periods during the heating seasons, although in 2016 some events with lower minimum temperature were recorded. In particular, the outdoor temperature may influence how frequent the pupils and teachers will open the windows and the door to the exterior. Presumably, the modest overall difference in outdoor temperature between heating season intervention periods did not affect the occupant window and door opening behavior.

6.3 Indoor air quality

6.3.1 Variation of the CO_2 concentration during the school day - Heating season

Figure 6.3.1 shows weekly profiles of the CO_2 concentration measured in all classrooms during the heating season intervention period. Classroom S5 was equipped with two systems (automatic window opening and heat recovery units) that were tested both individually and in combination. Automatic window opening alone was tested in parallel with the solutions in classrooms S3, S4, and S8 from 27 October to 5 December 2014. The combination of automatic window opening and heat recovery units was tested from 29 February 2016 to 29 April 2016. Furthermore, the solution with automatic window opening and heat recovery units was tested only during the heating season. Data in Figure 6.3.1 includes Monday morning to Friday afternoon and excludes weekends.

Figure 6.3.1 shows the effect during each school day of running the retrofitted ventilation system. In all classrooms, the peak CO_2 concentration generally was reduced with activated system control. In the reference classroom (S7), the daily CO_2 concentration profiles were rather similar across the six-week intervention period. Most notable was the effect on the CO_2 concentration in classroom S3 with the decentralized mechanical ventilation system and in S4 with automatic window opening and an exhaust fan. In these rooms, the CO_2 concentration only exceeded 1000 ppm at a few events. Generally, any of the systems applied reduced the peak CO_2 concentrations to below 2000 ppm and even below 1500 ppm, despite the fact that when the systems were idled, the peak concentrations regularly reached above 3000 ppm.

Figure 6.3.1. Weekly profiles of the CO_2 concentration measured in each classroom during the six-week intervention period in the heating season. Red: System idled, Green: System activated.

6.3.2 Variation of the CO_2 concentration during the school day – Non-heating season

Figure 6.3.2 shows weekly profiles of the CO_2 concentration measured in all classrooms during the intervention period in the non-heating season spanning the date range from 20 April 2015 to 19 June 2015. Not surprisingly, the contrast between periods with idled or activated retrofit solution was smaller than during the heating season intervention, although events with high CO_2 concentrations occurred in all classrooms.

Figure 6.3.2. Weekly profiles of the CO_2 concentration measured in each classroom during the six-week intervention period in the non-heating season. Red: System control idled, Green: System control activated.

As during the winter season, the difference in CO_2 concentration between weeks with system control idling or activated was largest in classrooms S3 and S4. It is also worth noting that in the classrooms with automatic window opening, the differences in peak CO_2 concentrations between the periods with the retrofit solution activated and idled was smaller than during the heating season, probably because of the lower temperature difference between the classroom and outdoors (Table 6.2.1). In addition, the winds are usually stronger during fall and winter. In classroom S8, where the pupils and teachers had to manually open windows or doors to ventilate, there was only limited difference in the CO_2 concentration between weeks with system control activated or idled and the concentration was generally lower than during the heating season.

6.3.3 Distribution of the CO_2 concentration with the retrofit solution activated or idled – Heating season

For each of the classrooms, Figure 6.3.3 shows the CO_2 concentration aggregated for the two three-week periods during the heating season intervention when the retrofit systems were idled or activated. The CO_2 concentration measured in the retrofitted classrooms is compared with the concentration in the reference classroom with manual window opening, aggregated for the entire six-week intervention period. The figures include only the lessons when the measured concentration *per se* or the rate of increase of the concentration indicated that the classrooms were occupied.

In the figure showing classroom S5, the CO_2 concentration in the reference classroom (S8) was different due to the two intervention periods in 2014 (automatic window opening) and in 2016 (combination of automatic window opening and heat recovery units).

Both the median CO_2 concentration and the inter-quartile ranges were clearly lower with the retrofit solutions activated than when they were idled, in particular in classrooms S3 and S4 with the decentralized ventilation system and the automatically operable windows supported by the exhaust fan. In these two rooms, the 75th percentile was around 1000 ppm indicating that the CO_2 concentration was in the acceptable range around 75% of the occupied time. The fan supported ventilation solutions thus seemed to have a better ability to sustain a lower CO_2 concentration, more efficient ventilation, and better air quality during a major part of the occupied time.

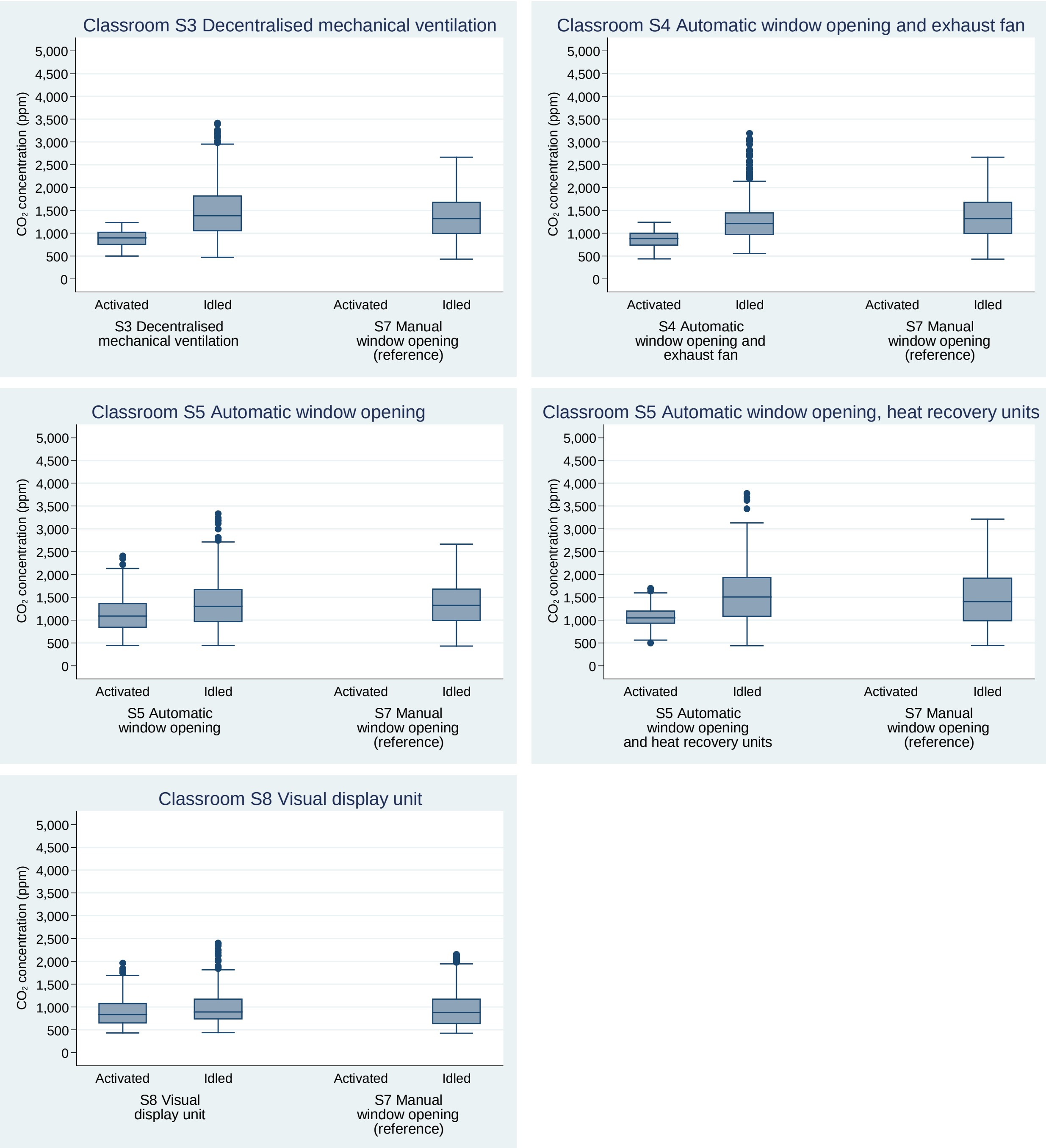


Figure 6.3.3. Box plots comparing the CO_2 concentration in the classrooms with the control of the retrofitted systems activated or idled and with the reference classroom with manual window opening. Only lessons when the classrooms were occupied were included. Heating season.

In classroom S5 with the automatic window opening and heat recovery units, the median CO_2 concentration was higher than in classrooms S3 and S4, but the interquartile range comparable to these rooms. Since the classrooms had the same size this result suggests that the period with elevated CO_2 concentration in classroom S5 was longer than in S3 and S4. The maximum airflow rate of the six heat recovery units was lower than the decentralized ventilation system and the exhaust fan (130 L/s vs. 201 L/s and 208 L/s) and thus insufficient to reach a median CO_2

concentration below 1000 ppm at full occupancy. In classrooms S5 and S8 with automatic and manual natural ventilation, respectively, the median CO_2 concentration was higher and the interquartile range larger than in the classrooms with fan supported ventilation when the control system was activated. In general, the CO_2 concentration during the periods when the retrofit solutions were idled was comparable with the concentration measured in the reference classroom, where windows were opened only manually. Appendix H shows CO_2 concentrations for all rooms aggregated for each intervention week.

6.3.4 Distribution of the CO_2 concentration with the retrofit solution activated or idled – Non-heating season

Figure 6.3.4 confirms that during the non-heating season the contrast between weeks with the retrofit solution activated or idled was smaller than during the heating season, mainly due to a lower CO_2 concentration when the retrofit solution was idled. In all classrooms, the median CO_2 concentration was below 1000 ppm when the retrofit solution was activated.

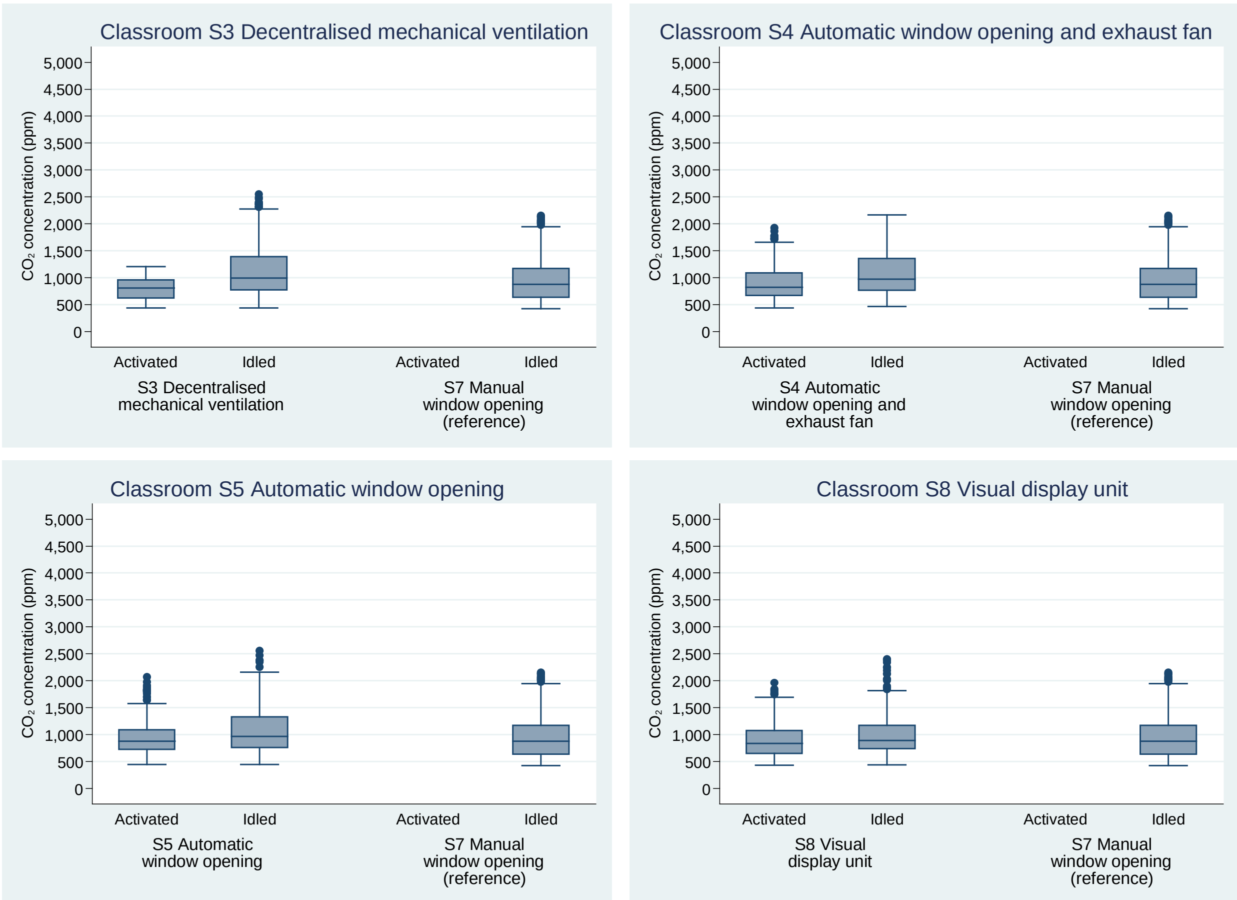


Figure 6.3.4. Box plots comparing the CO_2 concentration in the classrooms with the retrofit solutions activated or idled and in the reference classroom where airing was obtained only by opening the windows manually. Only lessons when the classrooms were occupied were included. The graphs show conditions during the non-heating season.

6.3.5 Comparison of the classroom CO_2 concentration with the retrofitted systems

Table 6.3.1 compares the CO_2 concentration between periods with the retrofit solutions idled and activated and quantifies the average difference between the control modes. Only the lessons when pupils occupied the classrooms were included in the analyses.

Table 6.3.1. Mean, standard deviation (s.d.), and maximum value (max) of the CO_2 concentration measured during the lessons when the classrooms were occupied with the retrofit solutions activated and idled. P indicates whether the differences in the CO_2 concentration between operation modes were statistically significant (ANOVA).

Classroom	Season	Mean idled (s.d., max.) (ppm)	Mean activated (s.d., max.) (ppm)	Diff. means (ppm)	Diff. max. (ppm)	P*
S3 Decentralised mechanical ventilation	Heating	1494 (599, 3411)	886 (190, 1236)	608	2175	<0.0001
	Non-heating	1126 (475, 2553)	802 (187, 1204)	324	1349	<0.0001
S4 Automatic window opening and exhaust fan	Heating	1269 (439, 3189)	856 (179, 1241)	413	1948	<0.0001
	Non-heating	1086 (409, 2167)	895 (300, 1927)	191	240	<0.0001
S5 Automatic window opening	Heating	1354 (536, 3332)	1113 (362, 2409)	241	923	<0.0001
	Non-heating	1048 (412, 2559)	926 (289, 2068)	122	491	
S5 Automatic window opening and heat recovery units	Heating	1559 (634, 3780)	1046 (218, 1692)	513	2088	<0.0001
S7 Reference classroom	Heating	1343 (463, 2665)				
	Non-heating	942 (385, 2156)				
S8 Visual display unit	Heating	1288 (506, 3347)	1043 (275, 2342)	245	1005	<0.0001
	Non-heating	984 (378, 2402)	895 (296, 1964)	89	438	<0.001

* The ANOVA model had the CO_2 concentration as response and system control mode, weekday, lesson and interaction between weekday and lesson as explanatory variables.

All retrofit solutions systematically and significantly reduced the concentration of CO_2 as expected, because they all increased the ventilation rate. The effect can particularly be seen during the heating season. Table 6.3.1 indicates that the retrofitted systems can be grouped according to their performance and that the decentralized mechanical ventilation system and the automatic window opening with exhaust fan and with heat recovery units provided the largest reductions of the CO_2 concentrations and particularly of the peak CO_2 concentration during the heating season. This may suggest that some means of mechanically supported system is required to intensify the classroom ventilation in moderate climates. Table 6.3.1 also shows that the decentralized ventilation system had the largest effect on the CO_2 concentration when the maximum concentration was taken into account, especially during the non-heating season with moderate outdoor temperatures. This may suggest that the decentralized system outperformed the other retrofit solutions with respect to ventilation effectiveness, both in the heating and the non-heating system.

Activated operation of the retrofitted systems reduced the CO_2 concentration between 41% (S3) and 18% (S5 automatic window opening alone and S8) in the heating season and between 29% (S3) and 9% (S8) in the non-heating season. Similarly, the maximum concentration was decreased between 61% (S3) and 28% (S5 automatic window opening alone) in the heating season and between 53% (S3) and 11% (S4) in the non-heating season. Appendix H shows CO_2 concentrations for all rooms aggregated for each intervention week.

6.3.6 Measurement of the air change rates in the classrooms

Table 6.3.2 shows the results of the measurements of the air change rates in the classrooms using tracer gas; the measurements took place in the empty classrooms after the classes were over.

Table 6.3.2. Air change rates and volume flowrates measured with tracer gas and under different room setups.

Classroom	Condition	Air change rate (h^{-1})	Volume flowrate (L/s)	Volume flowrate (L/s per person)
Decentralised mechanical ventilation	Minimum speed	1.3	58	2.3
	Full speed	3.3	146	5.8
Aut. window opening + exhaust fan	Windows closed, fan off	0.3	15	0.6
	All windows open, fan at 100%	3.3	146	5.8
Aut. window opening	Windows closed	0.5	22	0.9
	All windows 50% open	0.9	38	1.5
	All windows 100% open	1.9	82	3.3
Automatic window opening and heat recovery units	Windows closed, heat recovery units at full speed	3.3	146	5.8
	All windows open, heat recovery units at full speed	4.8	213	8.5
Reference / visual feedback	Windows closed	0.6	27	1.1
	All windows 100% open	4.8	213	8.5

1 h^{-1} corresponds to 160 m^3/h (5650 ft^3/h) or 1.8 l/(s person) (3.8 cfm/person) with 25 sedentary occupants

The results show that the classrooms were quite airtight as the air change rates were between 0.3 h^{-1} and 0.6 h^{-1} when the windows were closed and when the retrofit solutions were idled. With 25 pupils in a classroom, 0.3 h^{-1} would correspond to an airflow rate of 0.54 L/s per person (children in sedentary activity), which is around ten times lower than what is prescribed in the Danish building code (Danish Building Code 2015). This measurement clearly justifies the expenses incurred in upgrading the classrooms with better ventilation solutions.

Table 6.3.2 Also shows that a very high ventilation rate up to 4.8 h^{-1} could be obtained with cross ventilation through both the façade and overhead windows. With 25 pupils, the ventilation rate would be higher than 8 L/s per person. However, most likely this ventilation rate cannot be utilized in practice because it can cause cold discomfort or cold draught, especially during the heating season.

6.4 Temperature

Figure 6.4.1 shows profiles of the classroom temperatures measured during the heating season intervention period. Each classroom had a dedicated, thermostat-controlled heating system that counteracted the effect of changing the control mode of the ventilation system. Thus, the temperature variation seemed less affected by the intervention than the CO_2 concentration and in general, the temperature was in the comfortable range between 20°C and 26°C. In addition, the temperature did not vary considerably with decreasing or increasing outdoor temperature.

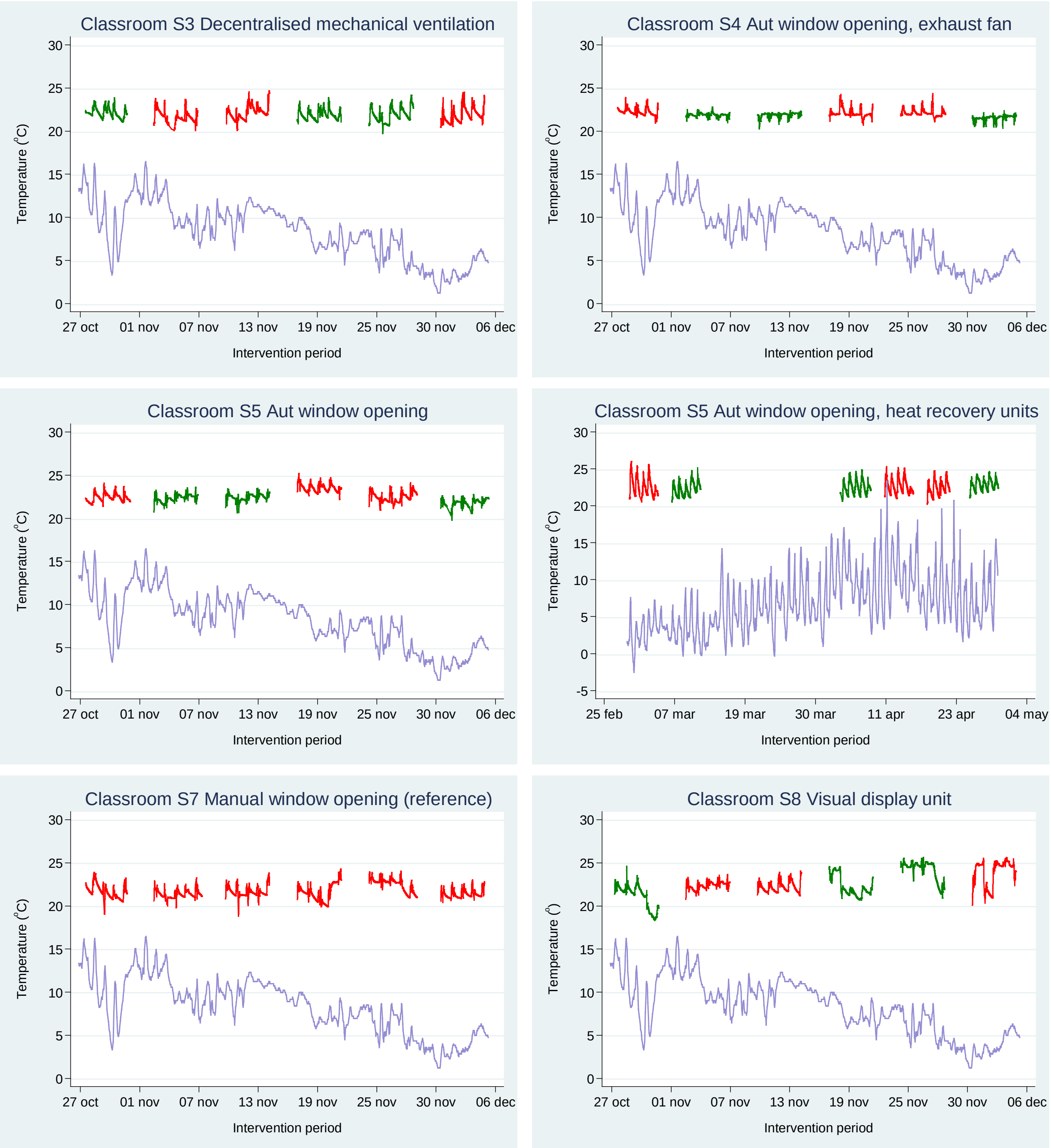


Figure 6.4.1. Weekly profiles of the temperature measured in each classroom during the six-week intervention period in the heating season. Red: Retrofit solution idled, Green: Retrofit solution activated. Outdoor temperature in blue.

Similarly, Figure 6.4.2 shows the daily variation of the classroom temperature during the non-heating season. In classroom S8, events with high temperatures were recorded on some occasions in the late afternoons, most likely due to the location of the measurement station, where it could be affected by solar radiation after school hours.

Figure 6.4.2. Weekly profiles of the temperature measured in each classroom during the six-week intervention period in the non-heating season. Red: Retrofit solution idled, Green: Retrofit solution activated. Outdoor temperature in blue.

No apparent systematic differences in temperatures when the retrofit solutions were activated or idled could be seen. Appendix H shows temperatures for all rooms aggregated for each intervention week.

Even though Figure 6.4.1 and Figure 6.4.2 do not suggest considerable differences in temperatures between the weeks when the retrofit systems were activated and idled, Table 6.4.1 shows that the marginal differences were non-random, systematic and statistically significant. Only in one case (classroom S5 during the non-heating season) were the temperatures randomly distributed between activated and idled automatic window opening (P=0.14). Even though the differences in temperature were statistically significant between the periods with the retrofit systems activated and idled, these differences were small and usually below 0.4°C and often as low as 0.1°C; only in two cases during the heating season the, difference reached 1°C. The statistically significant differences in temperature can be assumed to be of no practical importance and occurred probably because of the large number of recordings. In classrooms S4 and S5 where the temperature during the heating season was lower when the retrofit solutions were activated, the solutions did not include heat recovery and it was the radiator/convector thermostat settings that determined the classroom temperature and compensated for the increased heat loss due to ventilation. The results in Table 6.4.1 suggest that on average, the temperature should not create any serious disturbance when comparing the effectiveness of the retrofit solutions on pupils' responses and performance.

Table 6.4.1. Mean value, minimum, and maximum of the temperature measured during heating and non-heating seasons in the occupied classrooms with the retrofit solutions activated and idled.

Classroom	Season	Mean idled (min-max) (°C)	Mean activated (min-max) (°C)	Diff. mean (°C)	P*
S3 Decentralised mechanical ventilation	Heating	22.6 (20.2-24.7)	22.7 (20.9-22.7)	0.1	0.02
	Non-heating	23.8 (22.0-25.4)	23.9 (22.1-25.5)	0.1	0.0004
S4 Automatic window opening and exhaust fan	Heating	22.7 (21.2-24.2)	21.7 (20.5-22.5)	1.0	<0.0001
	Non-heating	23.0 (21.3-24.6)	22.9 (20.8-24.2)	0.1	0.0007
S5 Automatic window opening	Heating	23.3 (21.1-25.3)	22.4 (20.6-23.5)	0.1	<0.0001
	Non-heating	23.5 (21.1-25.3)	23.5 (21.8-24.5)	0	0.14
S5 Automatic window opening and heat recovery units	Heating	23.7 (21.2-26.1)	23.3 (21.1-25.3)	0.4	<0.0001
S7 Reference	Heating	22.2 (18.8-24.3)		n.a.	
	Non-heating	23.3 (20.8-25.5)		n.a.	
S8 Visual display unit	Heating	23.0 (20.1-25,5)	23.0 (19.5-26.6)	0	<0.0001
	Non-heating	23.1 (21.7-24.3)	23.5 (21.7-26.2)	0.4	<0.0001

* The ANOVA model had the classroom temperature as response and the mode of the operation of the retrofit solution (activated vs. idled), weekday, lesson and interaction between weekday and lesson as explanatory variables.

6.5 Air humidity

Figure 6.5.1 and Figure 6.5.2 show examples of profiles of the relative air humidity measured during the heating and non-heating season intervention periods in classrooms S3 with the decentralized mechanical ventilation system and in S4 with automatic window opening and an exhaust fan. The relative air humidity increased when the outdoor temperature decreased and vice versa, but in general it seemed to be rather independent of the operation mode of the ventilation systems. For all classrooms, Table 6.5.1 compares the relative air humidity during the intervention weeks with systems idled or activated across seasons. Although the table shows only minor differences between the operation modes and seasons, the mean air humidity seemed to be slightly higher during the heating season, which could be due to moisture generated by the pupils and lower outdoor air supply than during the non-heating season. However, the air humidity seemed not to be affected by the system operation mode, which affected the outdoor air supply. Overall, the classroom air humidity was in the recommended range and it did not depend on the system that was installed in a classroom or its operation mode. Air humidity will therefore not be dealt with further.

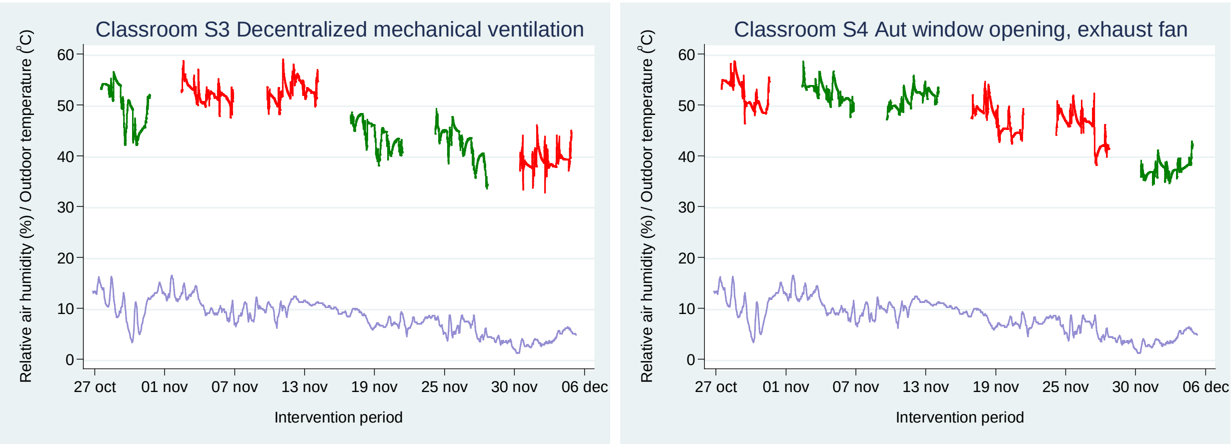


Figure 6.5.1. Outdoor temperature and relative air humidity measured in classrooms S3 (left) and S4 (right) during the heating season intervention period.

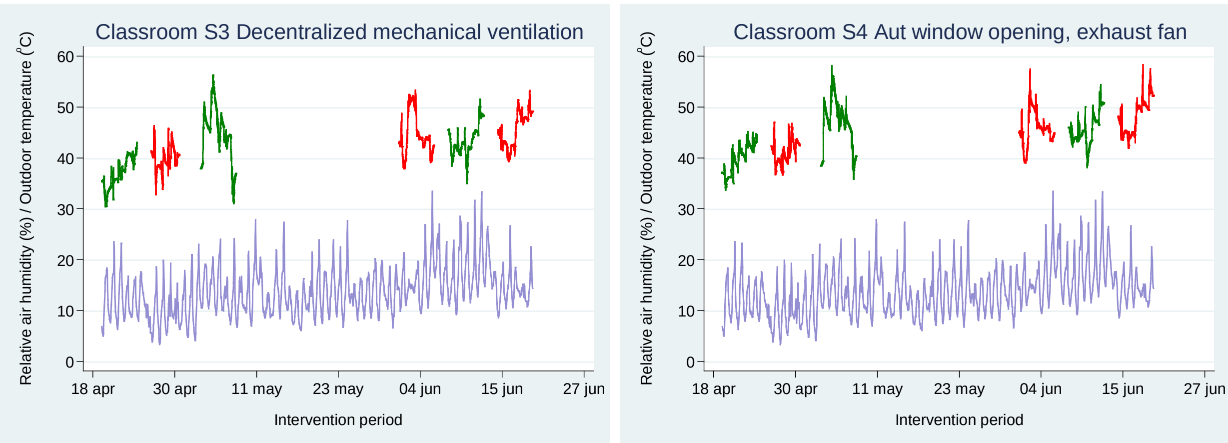


Figure 6.5.2. Outdoor temperature and relative air humidity measured in classrooms S3 (left) and S4 (right) during the non-heating season intervention period.

Table 6.5.1. Mean value and range (min-max) of the relative air humidity and the outdoor air temperature measured during the lessons when the classrooms were occupied and with the retrofit solutions activated and idled.

Classroom	Season	Mean idled (min-max) (%)	Mean activated (min-max) (%)	Mean outdoor temperature (°C)	
				Idled	Activated
S3 Decentralised mechanical ventilation	Heating	45 (34-54)	49 (33-58)	8.4	7.9
	Non-heating	44 (35-53)	42 (31-54)	13.2	14.7
S4 Automatic window opening and exhaust fan	Heating	49 (41-58)	47 (35-58)	7.9	8.4
	Non-heating	46 (37-57)	45 (34-58)	13.2	14.7
S5 Automatic window opening	Heating	46 (37-57)	45 (31-59)	7.9	8.4
	Non-heating	42 (30-51)	41 (30-50)	13.2	14.7
S5 Automatic window opening and heat recovery units	Heating	40 (31-46)	39 (33-46)	7.5	7.1
S7 Reference classroom	Heating	50 (37-61)		8.2	
	Non-heating	44 (33-55)		14.0	
S8 Visual display unit	Heating	45 (28-59)	44 (34-57)	8.4	7.9
	Non-heating	43 (32-57)	42 (30-56)	13.2	14.7

6.6 Sound pressure level

The measurements of sound pressure level in S5 with automatic window opening and heat recovery units could not be used due to instrument failure. For the other classrooms and systems, Figure 6.6.1 shows profiles of the sound pressure level measured during the first week of the intervention period in the heating season in 2014. In classrooms S3 with the decentralized ventilation system and in S8 with visual feedback, the retrofits were activated; they were idled in all other classrooms and there was no retrofit in the reference classroom. In general, the noise levels increased from around 8:00 and varied during the day until around 15:00, which reflects well the expected use pattern of the classrooms. The periodic pattern was similar for all the test weeks regardless of the control mode.

Figure 6.6.2 compares the distribution of sound pressure levels between weeks with system control idled or activated and with the sound pressure level measured in the reference classroom. With the current measurements, it was not possible to distinguish undesirable noise from sound caused by group work, the teacher's voice, etc. In general, it seemed that the noise level was affected more by the class occupying the room than the control mode *per se*. Classrooms S3 and S4 were occupied by fifth graders and S5, S7, and S8 by one year younger fourth graders, which might also contribute to the observed differences in the sound pressure levels measured in these classrooms. High peak values were observed in all rooms with both idling and activated control and the median sound pressure level also suggests a limited influence of the control mode on the noise level in the classes.

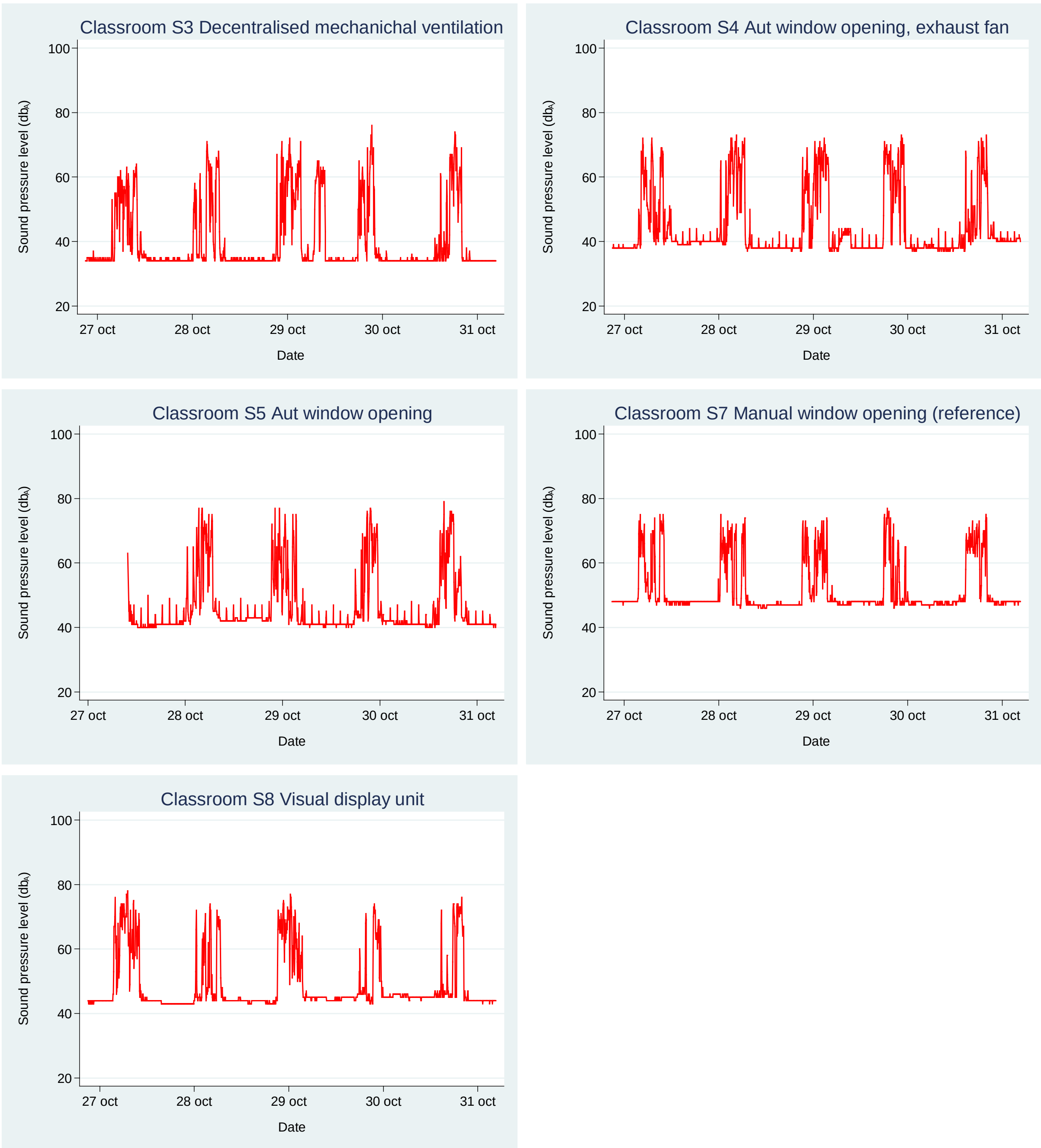


Figure 6.6.1. Sound pressure level measured during the first week of the intervention period in each classroom during the heating season. In classrooms S3 and S8 the retrofits were activated and they were idled in the other classrooms.

During the non-heating season, the median and the 25th percentile of the sound pressure level were low suggesting that the rooms were unoccupied during the lessons that were included in the calculations. However, inspection of the CO_2 concentrations measured during the lessons included in the non-heating season plots indicated that the rooms were occupied. The difference may also suggest a behavioral change due to the season caused e.g. by more often use of outdoor facilities during breaks.

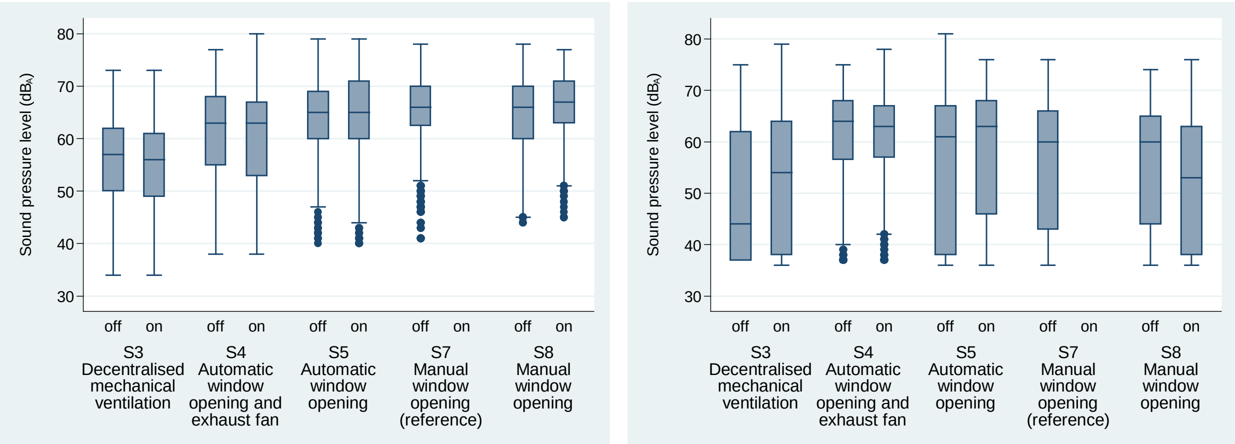


Figure 6.6.2. Box plots comparing the sound pressure levels in classrooms with retrofit solutions activated and idled. Left: heating season. Right: Non-heating season. Only lessons when classrooms were occupied are included.

Table 6.6.1 compares the sound pressure levels measured in classrooms with the retrofit solution activated or idled. Even though the sound pressure levels in some cases differed between operation modes, the differences did not exhibit systematic association with the operation mode. This suggests that noise should not, at least as regards the average levels, interfere with the testing of the interventions and their effects on the subjective responses of the pupils and their cognitive performance.

Table 6.6.1. Median, 25th and 75th percentiles of the sound pressure level measured during the lessons when the classrooms were occupied and when retrofit solutions were activated or idled. P<0.05 indicates that the difference was statistically significant; testing was made using the Wilcoxon rank-sum test.

Classroom	Season	Median idled (25th-75th percentile) (dB_A)	Median Activated (25th-75th percentile) (dB_A)	P
S3 Decentralised mechanical ventilation	Heating	57 (50 – 62)	56 (49 – 61)	0.052
	Non-heating	44 (37 - 62)	54 (38 - 64)	<0.0001
S4 Automatic window opening and exhaust fan	Heating	63 (55 – 68)	63 (53 – 67)	0.74
	Non-heating	64 (57 – 68)	63 (57 – 67)	0.28
S5 Automatic window opening	Heating	65 (60 – 69)	65 (60 – 71)	0.15
	Non-heating	61 (38 – 67)	63 (46 – 68)	0.0003
S7 Reference	Heating	66 (63 – 70)		
	Non-heating	60 (43 – 66)		
S8 Visual display unit	Heating	66 (60 – 70)	67 (63 – 71)	0.002
	Non-heating	60 (44 – 65)	53 (39 – 64)	<0.0001

During the heating season intervention in 2016, noise recordings in classroom S5 with automatic window opening and heat recovery units and in the reference classroom S7 were made with unreliable measurement instrumentation. They do therefore not qualify for inclusion in Table 6.6.1. However, based on the measurements supplementary analyses were made to provide estimates of the sound pressure levels with the heat recovery units activated or idled and to compare these with the measurements in the reference classroom. In S5 the median sound pressure level during the occupied time and with the units running was 62.6 dBA (95% CI 62.4-62.7 dBA) and it was 63.7 dBA (95% CI 63.7-64.4 dBA) when idled. In the reference classroom S7 the median sound pressure level was 64.5 dBA (95% CI 64.5-64.6 dBA). Although made with poor measurement instrumentation these values may indicate that there was no difference in the median classroom sound pressure level between periods when the heat recovery units were activated or idled. Also, the median sound pressure level was slightly higher in the reference classroom indicating that the noise level seemed to depend more on the class than on the mode of the ventilation system.

6.7 Classroom reverberation time

Reverberation time was measured in only two classrooms (S3 and S8), as the geometrical layout and the interior of all the classrooms in the school wing were very similar. In both classrooms S3 and S8, the reverberation time was 0.6 s, which complies with the requirements in the Danish building code (RT ≤ 0.6 s in the frequency range 125-4000 Hz (Lydbestemmelser 2013, Danish Building Code 2015).

6.8 Classroom with sorbent type gas-phase air cleaner

The conditions in the classroom where the sorbent air cleaner was retrofitted are shown in Table 6.8.1. No measurement of noise or reverberation time was performed in this classroom. The results show that the temperature was slightly lower when the air cleaner was activated and that during the two weeks when the air cleaner was idled, the CO_2 concentration was different, suggesting that there was a difference between weeks in ventilation effectiveness and that ventilation rate per person also differed. The results from week 1 when the sorbent air cleaner was activated could not be presented due to an experimental error.

Table 6.8.1. Mean conditions in the classroom when the sorbent air cleaner was activated and idled; measurements were performed in the heating season.

Parameter	Week 1 (9/29) Air cleaner activated	Week 2 (10/13) Air cleaner idled	Week 3 (11/10) Air cleaner idled	Week 4 (10/24) Air cleaner activated
Air temperature (°C)	n/a	23.5	22.0	21.0
CO_2 conc. (ppm)	n/a	2150	1110	1100
Sum VVOCs (<C6) (μg/m3)	n/a	n/a	10	11
Sum VOCs (C6-C16) (μg/m^3)	n/a	n/a	37	66
Sum sVOCs (μg/m^3)	n/a	n/a	<1	<1
TVOC Tol equiv. (ISO 16000-6) (μg/m^3)	n/a	n/a	48	77
Acceptability of air quality*	n/a	0.00	0.33	0.31
Odor intensity**	n/a	2.6	1.5	1.6

* Assessed by students upon entering the classroom on a continuous scale: -1: clearly unacceptable, 0: Just unacceptable/Just acceptable, 1: Clearly acceptable

** Assessed by students on an odor intensity scale: 0: no odor, 1: slight odor, 2: moderate odor; 3: strong odor; 4: very strong odor and 5: overwhelming odor

Students assessed the acceptability of the air quality and the odor intensity in the classroom. There were no differences in their ratings independently of whether the sorbent air cleaner was activated or idled. However, on comparing the two weeks when the sorbent air cleaner was idled, the acceptability was assessed to be lower and the odor intensity to be higher when the CO_2 concentration was higher, as expected.

Chemical measurements were done only during the two weeks when the air cleaner was activated in week 4 and idled in week 3. Table 6.8.1 shows that there was no effect of activating the air cleaner on the concentration of air pollutants. This is also illustrated in Figure 6.8.1, which shows chromatograms from both conditions. The concentration of VOCs was even slightly higher when the sorbent air cleaner was activated. This was probably because of the concentration of decamethylcyclopentasiloxane, which was much higher under this condition. This compound is usually associated with the use of deodorants, although other sources may also be possible.

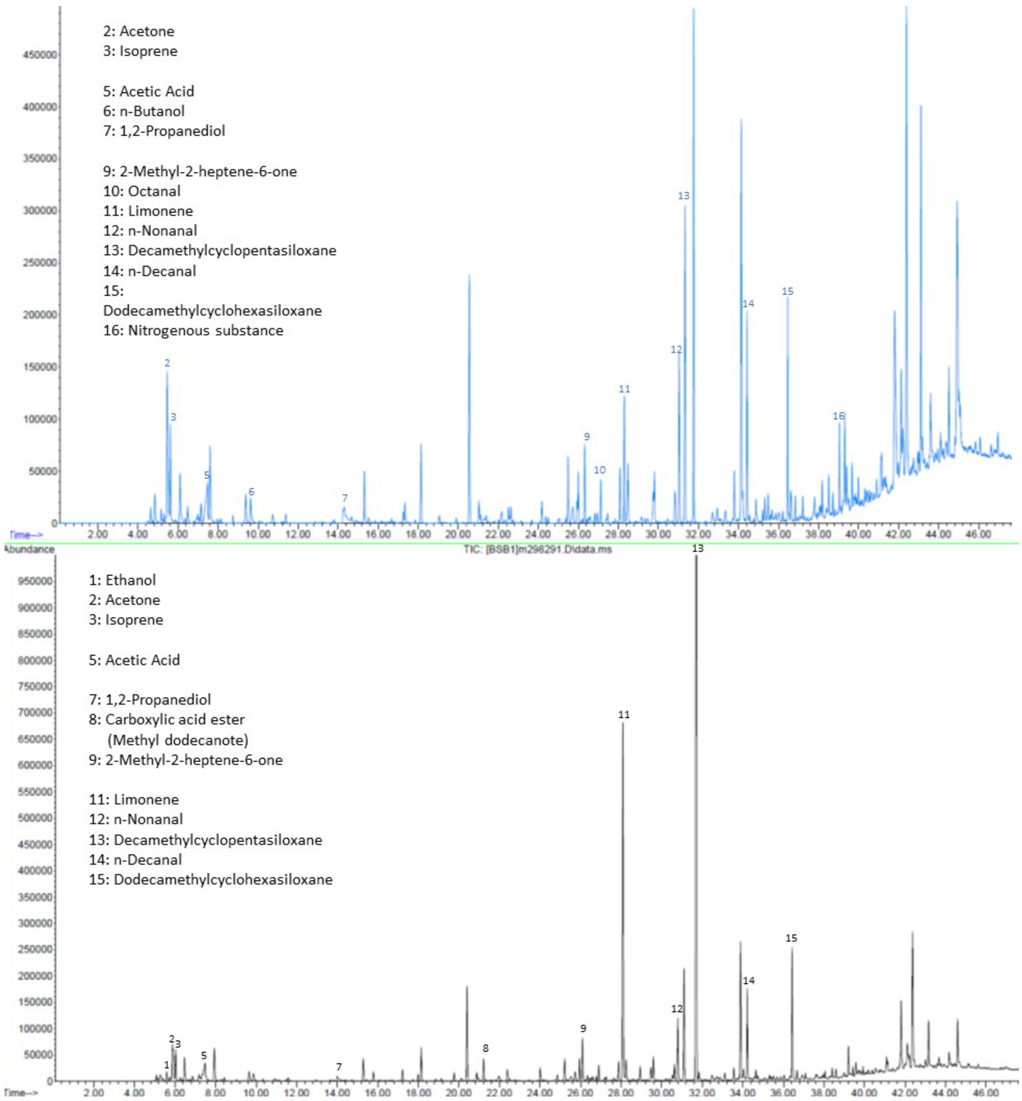


Figure 6.8.1. Results of chemical analyses of the air in the classroom when the sorbent air cleaner was idled (top) and activated (bottom).

6.9 Subjective responses

Table 6.9.1 to Table 6.9.9 show the subjective responses of the pupils under the different intervention conditions. The tables show the response of the pupils rating either the conditions in their classroom or their wellbeing and symptoms. The responses were marked on a scale with smileys, which was coded 0 on the left end and 100 on the right end. The tables show median responses on the weeks when the retrofit was idled and the change in responses to when it was activated, together with the results of statistical analyses. They also show the responses of the pupils in the reference classroom and whether their responses changed on the weeks when the retrofit was activated in the parallel classrooms, where the interventions took place. Table 6.9.10 shows the results from the tests performed with the sorbent air cleaner in the university classroom. In this case the responses were given by the students. Table 6.9.11 summarizes all results by indicating the direction of change in responses in case they were non-random, i.e. reached statistical significance.

The overall observation is that no systematic effects of the interventions on the responses of the pupils and students could be observed. Slightly more changes in responses reached statistical significance as regards the outcomes that were expected to change, such as wellbeing, easiness to breathe, or the freshness of the air, but even in this case no systematic changes in the responses could be seen. A few responses changed also in the reference classroom, although such change was not expected and could not be attributed to the use of the retrofit solutions. In this classroom, more pupils indicated problems with the eyes, both in the heating and non-heating seasons and more felt better in the heating season. These changes could be spurious, random (because no correction for repeated testing was applied) or could be caused by other uncontrollable factors.

Comparison of the two conditions in the classroom when the sorbent air cleaner was idled or activated and the difference in exposure level was remarkable (CO_2 concentration was 2150 ppm vs. 1100 ppm). Nevertheless,

Table 6.9.12 shows that there were no systematic effects of running the air cleaner or not. In this study, the exposure was shorter than with the pupils in the elementary school classrooms; the exposure was only slightly longer than one hour. Still, many more responses changed significantly, as the CO_2 concentration was reduced. This may suggest that the scale was sensitive and could detect the effects of reduced ventilation. Also, that university students may be better able to express their perceptions and responses than pupils in elementary schools. Therefore, another possible reason why no changes in the responses of the pupils were observed in the elementary school classroom could be that the scales were not sufficiently sensitive to capture the changes perceived by the pupils. Alternatively, the pupils could be less sensitive or less able to report and note the subtle changes that were expected as a result of using the retrofit solutions. Lack of change in the ratings of the conditions describing the perceived air quality could also be caused by the fact that the ratings were provided towards the end of the teaching period (lesson) when the pupils were likely adapted to the air quality conditions, which makes it even more difficult to identify any perception changes.

Table 6.9.1. Results of subjective evaluations of classroom conditions and well-being. The evaluations were performed during the heating season by the pupils in the classroom with CO_2 based control of automatic window opening and in the control classroom with manual window opening, where no intervention was made

Question	Intervention (system idled vs. system activated)				Control (no system installed)			
	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)
Perceptions								
Too cold (0)-Too warm (100)	26	50 (33-50)	31% (35%)	1.0 (0.76)	24	50 (33-54)	21% (25%)	1.0 (0.79)
Air fresh (0)-Air poor (100)	26	17 (17-48)	15% (27%)	0.55 (0.45)	24	33 (17-67)	29% (33%)	1.0 (0.53)
No draft (0)-Drafty (100)	26	17 (2-33)	19% (46%)	0.15 (0.27)	24	17 (0-33)	29% (25%)	1.0 (0.86)
Too much noise (0)-Too little noise (100)	26	50 (50-67)	19% (38%)	0.30 (0.59)	24	83 (67-83)	25% (21%)	1.0 (0.86)
Too humid (0)-Too dry (100)	26	50 (50-50)	31% (23%)	0.79 (0.40)	24	50 (50-67)	21% (25%)	1.0 (0.72)
Too little light (0)-Too much light (100)	26	50 (50-58)	23% (12%)	0.50 (0.31)	24	50 (50-60)	29% (17%)	0.55 (0.50)
Symptoms, general well-being, readiness to learn								
Able to breathe easily (0)-Blocked nose (100)	26	17 (2-29)	38% (15%)	0.18 (**0.02***)	24	25 (0-52)	17% (33%)	0.39 (0.64)
Not at all tired (0)-Feeling very tired (100)	25	33 (17-50)	28% (28%)	0.79 (0.49)	24	46 (29-67)	29% (21%)	0.77 (0.94)
No headache (0)-Headache (100)	26	17 (0-33)	35% (38%)	1.0 (0.51)	24	25 (0-54)	38% (29%)	0.80 (0.44)
Feel like working (0)-Unwilling to work (100)	26	17 (17-17)	8% (35%)	*0.07†* (**0.02***)	24	19 (0-50)	17% (29%)	0.55 (0.23)
Not dry lips (0)-Dry lips (100)	26	33 (17-56)	42% (27%)	0.48 (0.46)	24	50 (17-83)	29% (29%)	0.79 (0.62)
Not dry skin (0)-Dry skin (100)	26	17 (0-33)	19% (31%)	0.58 (0.44)	24	33 (0-50)	17% (29%)	0.55 (0.18)
Not dry throat (0)-Dry throat (100)	26	17 (0-40)	50% (23%)	0.17 (0.44)	24	25 (0-50)	29% (33%)	1.0 (0.91)
Feeling well (0)-Feeling poor (100)	26	17 (0-33)	8% (35%)	0.07† (0.25)	24	17 (0-38)	42% (8%)	**0.04*** (**0.02***)
No pain in eyes (0)-Eyes aching (100)	26	0 (0-29)	31% (19%)	0.58 (0.48)	24	17 (0-40)	38% (4%)	**0.03*** (**0.01***)
Easy to concentrate (0)-Difficult to con. (100)	26	17 (8-33)	38% (27%)	0.63 (0.59)	24	50 (31-67)	33% (33%)	0.80 (0.61)
Awake (0)-Very sleepy (100)	26	17 (0-40)	19% (38%)	0.30 (0.82)	24	33 (17-67)	21% (29%)	0.77 (0.97)

* Sign test; * if p≤0.05, † if 0.05<p≤0.10; ** Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10

Table 6.9.2. Results of subjective evaluations of classroom conditions and well-being. The evaluations were performed during the heating season by the pupils in the classroom with manual window opening in response to visual feedback on CO_2 and in the control classroom with manual window opening, where no intervention was made

Question	Intervention (system idled vs. system activated)				Control (no system installed)			
	Obs.	Median-baseline (25^{th}-75^{th} percentile)	% resp. >baseline (% resp. <baseline)	Effect P^{*} (p^{**})	Obs.	Median-baseline (25^{th}-75^{th} percentile)	% resp. >baseline (% resp. <baseline)	Effect P^{*} (p^{**})
Perceptions								
Too cold (0)-Too warm (100)	24	0 (0-50)	50% (4%)	**0.01*** (**0.01***)	24	50 (33-67)	25% (21%)	1.0 (0.79)
Air fresh (0)-Air poor (100)	24	17 (13-33)	33% (21%)	0.58 (0.15)	24	50 (23-67)	33% (29%)	1.0 (0.53)
No draft (0)-Drafty (100)	24	17 (0-33)	54% (13%)	**0.02*** (**0.01***)	24	17 (17-33)	25% (29%)	1.0 (0.86)
Too much noise (0)-Too little noise (100)	24	63 (50-67)	17% (13%)	1.0 (0.45)	24	83 (65-83)	21% (25%)	1.0 (0.86)
Too humid (0)-Too dry (100)	24	50 (50-58)	13% (17%)	1.0 (0.93)	24	50 (50-67)	25% (21%)	1.0 (0.72)
Too little light (0)-Too much light (100)	24	50 (48-50)	21% (13%)	0.72 (0.16)	24	50(50-60)	17% (29%)	0.55 (0.50)
Symptoms, general well-being, readiness to learn								
Able to breathe easily (0)-Blocked nose (100)	24	17 (0-42)	13% (33%)	0.23 (*0.06†*)	24	25 (0-50)	33% (17%)	0.39 (0.64)
Not at all tired (0)-Feeling very tired (100)	24	33 (17-67)	42% (21%)	0.30 (0.80)	24	46 (17-71)	21% (29%)	0.77 (0.94)
No headache (0)-Headache (100)	24	17 (0-67)	29% (38%)	0.80 (0.84)	24	17 (15-67)	29% (38%)	0.80 (0.44)
Feel like working (0)-Unwilling to work (100)	24	17 (0-33)	21% (25%)	1.0 (0.69)	24	17 (0-35)	29% (17%)	0.55 (0.23)
Not dry lips (0)-Dry lips (100)	24	33 (0-67)	33% (29%)	1.0 (0.80)	24	54 (23-83)	29% (29%)	0.79 (0.62)
Not dry skin (0)-Dry skin (100)	23	0 (0-33)	26% (22%)	1.0 (0.89)	24	21 (0-50)	29% (17%)	0.55 (0.18)
Not dry throat (0)-Dry throat (100)	24	17 (0-60)	17% (38%)	0.27 (0.36)	24	17 (8-67)	33% (29%)	1.0 (0.91)
Feeling well (0)-Feeling poor (100)	24	4 (0-33)	17% (29%)	**0.03*** (0.21)	24	21 (13-50)	8% (42%)	**0.04*** (**0.02***)
No pain in eyes (0)-Eyes aching (100)	24	17 (0-56)	17% (38%)	0.27 (0.28)	24	25 (17-54)	4% (38%)	**0.03*** (**0.01***)
Easy to concentrate (0)-Difficult to con. (100)	23	17 (0-38)	39% (9%)	*0.07†* (*0.06†*)	24	50 (33-54)	33% (33%)	0.80 (0.61)
Awake (0)-Very sleepy (100)	23	25 (0-50)	22% (26%)	1.0 (0.83)	24	33 (17-65)	29% (21%)	0.77 (0.97)

* Sign test; * if $p \le 0.05$, † if $0.05 < p \le 0.10$; ** Wilcoxon signed-rank test: * if $p \le 0.05$, † if $0.05 < p \le 0.10$

Table 6.9.3. Results of subjective evaluations of classroom conditions and well-being. Evaluations were performed during the heating season by the pupils in the classroom with a decentralized mechanical ventilation system and in the control classroom with manual window opening, where no intervention was made.

Question	Intervention (system idled vs. system activated)				Control (no system installed)			
	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)
Perceptions								
Too cold (0)-Too warm (100)	22	50 (50-67)	5% (41%)	**0.03*** (*0.07†*)	24	50 (33-67)	25% (21%)	1.0 (0.79)
Air fresh (0)-Air poor (100)	22	33 (17-56)	23% (36%)	0.58 (0.51)	24	50 (23-67)	33% (29%)	1.0 (0.53)
No draft (0)-Drafty (100)	22	17 (8-50)	23% (14%)	0.72 (0.94)	24	17 (17-33)	25% (29%)	1.0 (0.86)
Too much noise (0)-Too little noise (100)	22	58 (50-73)	23% (27%)	1.0 (0.56)	24	83 (65-83)	21% (25%)	1.0 (0.86)
Too humid (0)-Too dry (100)	22	50 (50-63)	23% (23%)	0.75 (0.88)	24	50 (50-67)	25% (21%)	1.0 (0.72)
Too little light (0)-Too much light (100)	22	50 (35-50)	18% (18%)	0.72 (0.58)	24	50(50-60)	17% (29%)	0.55 (0.50)
Symptoms, general well-being, readiness to learn								
Able to breathe easily (0)-Blocked nose (100)	22	33 (4-50)	50% (23%)	0.21 (*0.07†*)	24	25 (0-50)	33% (17%)	0.39 (0.64)
Not at all tired (0)-Feeling very tired (100)	22	50 (33-67)	18% (41%)	0.27 (0.26)	24	46 (17-71)	21% (29%)	0.77 (0.94)
No headache (0)-Headache (100)	22	17 (17-63)	14% (18%)	1.0 (0.80)	24	17 (15-67)	29% (38%)	0.80 (0.44)
Feel like working (0)-Unwilling to work (100)	22	25 (17-50)	9% (23%)	0.45 (0.27)	24	17 (0-35)	29% (17%)	0.55 (0.23)
Not dry lips (0)-Dry lips (100)	22	50 (21-67)	27% (23%)	1.0 (0.93)	24	54 (23-83)	29% (29%)	0.79 (0.62)
Not dry skin (0)-Dry skin (100)	22	17 (0-29)	27% (9%)	0.29 (0.58)	24	21 (0-50)	29% (17%)	0.55 (0.18)
Not dry throat (0)-Dry throat (100)	22	17 (17-50)	27% (23%)	1.0 (0.42)	24	17 (8-67)	33% (29%)	1.0 (0.91)
Feeling well (0)-Feeling poor (100)	22	17 (0-40)	27% (27%)	0.77 (0.72)	24	21 (13-50)	8% (42%)	**0.04*** (**0.02***)
No pain in eyes (0)-Eyes aching (100)	22	25 (17-50)	32% (23%)	0.77 (0.20)	24	25 (17-54)	4% (38%)	**0.03*** (**0.01***)
Easy to concentrate (0)-Difficult to con. (100)	22	33 (17-50)	32% (27%)	0.80 (0.60)	24	50 (33-54)	33% (33%)	0.80 (0.61)
Awake (0)-Very sleepy (100)	22	33 (17-67)	14% (23%)	0.72 (0.40)	24	33 (17-65)	29% (21%)	0.77 (0.97)

* Sign test; * if p≤0.05, † if 0.05<p≤0.10; ** Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10

Table 6.9.4. Results of subjective evaluations of classroom conditions and well-being. The evaluations were performed during the heating season by the pupils in the classroom with CO_2 based control of automatic window opening and fan assisted exhaust and in the control classroom with manual window opening, where no intervention was made.

Question	Intervention (system idled vs. system activated)				Control (no system installed)			
	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)
Perceptions								
Too cold (0)-Too warm (100)	23	67 (50-83)	13% (57%)	**0.02*** (**0.01***)	24	50 (33-54)	21% (25%)	1.0 (0.79)
Air fresh (0)-Air poor (100)	23	67 (54-75)	13% (78%)	**0.01*** (**0.01***)	24	33 (17-67)	29% (33%)	1.0 (0.53)
No draft (0)-Drafty (100)	23	33 (17-50)	48% (26%)	0.33 (0.39)	24	17 (0-33)	29% (25%)	1.0 (0.86)
Too much noise (0)-Too little noise (100)	20	50 (50-67)	30% (25%)	1.0 (1.0)	24	83 (67-83)	25% (21%)	1.0 (0.86)
Too humid (0)-Too dry (100)	23	50 (50-67)	26% (48%)	0.33 (0.19)	24	50 (50-67)	21% (25%)	1.0 (0.72)
Too little light (0)-Too much light (100)	23	50 (33-50)	17% (26%)	0.75 (0.88)	24	50 (50-60)	29% (17%)	0.55 (0.50)
Symptoms, general well-being, readiness to learn								
Able to breathe easily (0)-Blocked nose (100)	23	33 (17-67)	43% (39%)	1.0 (0.86)	24	25 (0-52)	17% (33%)	0.39 (0.64)
Not at all tired (0)-Feeling very tired (100)	23	50 (42-83)	30% (35%)	1.0 (0.26)	24	46 (29-67)	29% (21%)	0.77 (0.94)
No headache (0)-Headache (100)	23	50 (25-67)	39% (48%)	0.82 (0.67)	24	25 (0-54)	38% (29%)	0.80 (0.44)
Feel like working (0)-Unwilling to work (100)	23	33 (17-58)	39% (35%)	1.0 (0.59)	24	19 (0-50)	17% (29%)	0.55 (0.23)
Not dry lips (0)-Dry lips (100)	23	50 (17-83)	57% (26%)	0.29 (0.21)	24	50 (17-83)	29% (29%)	0.79 (0.62)
Not dry skin (0)-Dry skin (100)	23	50 (17-50)	43% (35%)	0.81 (0.34)	24	33 (0-50)	17% (29%)	0.55 (0.18)
Not dry throat (0)-Dry throat (100)	23	33 (17-50)	35% (43%)	0.81 (0.76)	24	25 (0-50)	29% (33%)	1.0 (0.91)
Feeling well (0)-Feeling poor (100)	23	33 (17-50)	35% (39%)	1.0 (0.70)	24	17 (0-38)	42% (8%)	**0.04*** (**0.02***)
No pain in eyes (0)-Eyes aching (100)	23	33 (17-58)	43% (43%)	0.82 (0.55)	24	17 (0-40)	38% (4%)	**0.03*** (**0.01***)
Easy to concentrate (0)-Difficult to conc. (100)	23	42 (33-54)	30% (43%)	0.63 (0.59)	24	50 (31-67)	33% (33%)	0.80 (0.61)
Awake (0)-Very sleepy (100)	23	50 (33-67)	26% (48%)	0.33 (0.22)	24	33 (17-67)	21% (29%)	0.77 (0.97)

* Sign test; * if p≤0.05, † if 0.05<p≤0.10; ** Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10

Table 6.9.5. Results of subjective evaluations of classroom conditions and well-being. The evaluations were performed during the non-heating season by the pupils in the classroom with CO_2 based control of automatic window opening and in the control classroom with manual window opening, where no intervention was made .

Question	Intervention (system idled vs. system activated)				Control (no system installed)			
	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P^* (p^{**})	Obs.	% resp. >median (% resp. <median)	% resp. >baseline (% resp. <baseline)	Effect P^* (p^{**})
Perceptions								
Not too warm (0)-Too warm (100)	26	25 (3-25)	27% (27%)	0.79 (0.88)	23	25 (13-38)	48% (30%)	0.48 (0.32)
Not too cold (0)-Cold (100)	26	25 (0-25)	35% (23%)	0.61 (0.13)	23	25 (6-25)	39% (30%)	0.80 (0.33)
No draft (0)-Drafty (100)	26	10 (0-25)	31% (19%)	0.58 (0.44)	23	13 (0-25)	26% (30%)	1.0 (0.70)
Air fresh (0)-Air poor (100)	26	25 (19-25)	27% (27%)	0.79 (0.57)	23	38 (25-50)	39% (22%)	0.42 (0.36)
Not too much noise (0)-Too much noise (100)	26	25 (25-25)	27% (15%)	0.55 (0.69)	23	50 (31-63)	30% (22%)	0.77 (0.88)
Not too much light (0) -Too much light (100)	26	25 (0-25)	12% (15%)	1.0 (0.93)	23	13 (0-25)	52% (26%)	0.24 (0.12)
Not too dark (0)-Too dark (100)	26	0 (0-25)	15% (15%)	0.72 (0.78)	23	13 (0-25)	35% (35%)	0.80 (0.98)
Symptoms, general well-being, readiness to learn								
Thermally pleasant (0)-Thermally not pl. (100)	26	25 (0-25)	31% (23%)	0.79 (0.49)	23	25 (13-35)	26% (26%)	0.77 (0.50)
Able to breathe easily (0)-Blocked nose (100)	26	25 (0-25)	31% (27%)	1.0 (0.53)	23	25 (13-44)	30% (30%)	0.79 (0.90)
Not dry skin (0)-Dry skin (100)	26	25 (25-36)	12% (31%)	0.23 (0.21)	23	13 (6-25)	39% (35%)	1.0 (0.91)
Not dry throat (0)-Dry throat (100)	26	25 (3-25)	35% (4%)	**0.03*** (**0.03***)	23	13 (0-25)	30% (17%)	0.55 (0.37)
Not tired eyes (0)-Tired eyes (100)	26	25 (25-47)	19% (35%)	0.42 (0.49)	23	25 (25-44)	52% (17%)	*0.08†* (**0.014***)
Not at all tired (0)-Feeling very tired (100)	25	25 (25-25)	44% (16%)	0.12 (**0.04***)	23	38 (25-50)	39% (17%)	0.27 (0.35)
No headache (0)-Headache (100)	26	0 (0-25)	27% (15%)	0.55 (0.101)	23	13 (0-25)	43% (22%)	0.30 (0.11)
Easy to concentrate (0)-Difficult to conc. (100)	26	25 (0-25)	23% (23%)	0.77 (0.87)	23	25 (25-44)	48% (22%)	0.21 (0.37)
Awake (0)-Very sleepy (100)	26	25 (0-25)	31% (15%)	0.39 (0.31)	23	25 (13-31)	48% (35%)	0.65 (0.26)
Feel like working (0)-Unwilling to work (100)	26	25 (0-25)	15% (23%)	0.75 (0.92)	23	25 (13-35)	43% (26%)	0.45 (0.30)
Feeling well (0)-Feeling poor (100)	26	0 (0-25)	15% (12%)	1.0 (0.40)	23	13 (0-25)	43% (22%)	0.30 (0.13)

* Sign test; * if p≤0.05, † if 0.05<p≤0.10; ** Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10

Table 6.9.6. Results of subjective evaluations of classroom conditions and well-being. The evaluations were performed during the non-heating season by the pupils in the classroom with manual window opening in response to visual feedback on CO_2 and in the control classroom with manual window opening, where no intervention was made.

Question	Intervention (system idled vs. system activated)				Control (no system installed)			
	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)
Perceptions								
Not too warm (0)-Too warm (100)	24	25 (0-38)	33% (25%)	0.79 (0.26)	23	25 (13-38)	48% (30%)	0.48 (0.32)
Not too cold (0)-Cold (100)	24	19 (0-28)	17% (33%)	0.39 (0.53)	23	25 (6-25)	39% (30%)	0.80 (0.33)
No draft (0)-Drafty (100)	24	0 (0-25)	21% (25%)	1.0 (0.86)	23	13 (0-25)	26% (30%)	1.0 (0.70)
Air fresh (0)-Air poor (100)	24	25 (13-50)	25% (38%)	0.61 (0.23)	23	38 (25-50)	39% (22%)	0.42 (0.36)
Not too much noise (0)-Too much noise (100)	24	38 (9-50)	21% (42%)	0.30 (0.19)	23	50 (31-63)	30% (22%)	0.77 (0.88)
Not too much light (0) -Too much light (100)	24	13 (0-25)	4% (42%)	**0.02*** (**0.004***)	23	13 (0-25)	52% (26%)	0.24 (0.12)
Not too dark (0)-Too dark (100)	24	6 (0-25)	17% (25%)	0.75 (0.39)	23	13 (0-25)	35% (35%)	0.80 (0.98)
Symptoms, general well-being, readiness to learn								
Thermally pleasant (0)-Thermally not pl. (100)	24	19 (13-25)	25% (42%)	0.45 (0.13)	23	25 (13-35)	26% (26%)	0.77 (0.50)
Able to breathe easily (0)-Blocked nose (100)	24	25 (0-38)	21% (33%)	0.58 (0.23)	23	25 (13-44)	30% (30%)	0.79 (0.90)
Not dry skin (0)-Dry skin (100)	24	6 (0-25)	33% (21%)	0.58 (0.97)	23	13 (6-25)	39% (35%)	1.0 (0.91)
Not dry throat (0)-Dry throat (100)	24	13 (0-25)	33% (8%)	0.11 (0.11)	23	13 (0-25)	30% (17%)	0.55 (0.37)
Not tired eyes (0)-Tired eyes (100)	24	25 (0-50)	33% (21%)	0.58 (0.89)	23	25 (25-44)	52% (17%)	*0.08†* (**0.014***)
Not at all tired (0)-Feeling very tired (100)	24	19 (9-50)	46% (25%)	0.33 (0.39)	23	38 (25-50)	39% (17%)	0.27 (0.35)
No headache (0)-Headache (100)	24	13 (0-41)	25% (29%)	1.0 (0.81)	23	13 (0-25)	43% (22%)	0.30 (0.11)
Easy to concentrate (0)-Difficult to conc. (100)	24	25 (0-25)	25% (29%)	1.0 (0.70)	23	25 (25-44)	48% (22%)	0.21 (0.37)
Awake (0)-Very sleepy (100)	24	6 (0-25)	25% (0%)	**0.04*** (**0.03***)	23	25 (13-31)	48% (35%)	0.65 (0.26)
Feel like working (0)-Unwilling to work (100)	24	23 (0-25)	25% (21%)	1.0 (0.33)	23	25 (13-35)	43% (26%)	0.45 (0.30)
Feeling well (0)-Feeling poor (100)	24	13 (0-25)	21% (33%)	0.58 (0.25)	23	13 (0-25)	43% (22%)	0.30 (0.13)

* Sign test; * if p≤0.05, † if 0.05<p≤0.10; ** Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10

Table 6.9.7. Results of subjective evaluations of classroom conditions and well-being. The evaluations were performed during the non-heating season by the pupils in the classroom with a decentralized mechanical ventilation system and in the control classroom with manual window opening, where no intervention was made.

Question	Intervention (system idled vs. system activated)				Control (no system installed)			
	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)
Perceptions								
Not too warm (0)-Too warm (100)	22	25 (25-50)	32% (18%)	0.55 (0.93)	23	25 (13-38)	48% (30%)	0.48 (0.32)
Not too cold (0)-Cold (100)	22	25 (0-25)	23% (18%)	1.0 (0.91)	23	25 (6-25)	39% (30%)	0.80 (0.33)
No draft (0)-Drafty (100)	22	25 (0-25)	36% (32%)	1.0 (0.53)	23	13 (0-25)	26% (30%)	1.0 (0.70)
Air fresh (0)-Air poor (100)	22	25 (25-50)	32% (27%)	1.0 (0.81)	23	38 (25-50)	39% (22%)	0.42 (0.36)
Not too much noise (0)-Too much noise (100)	22	38 (25-50)	23% (45%)	0.30 (0.12)	23	50 (31-63)	30% (22%)	0.77 (0.88)
Not too much light (0) -Too much light (100)	22	25 (0-25)	14% (14%)	0.68 (1.0)	23	13 (0-25)	52% (26%)	0.24 (0.12)
Not too dark (0)-Too dark (100)	22	25 (0-25)	27% (14%)	0.50 (*0.08†*)	23	13 (0-25)	35% (35%)	0.80 (0.98)
Symptoms, general well-being, readiness to learn								
Thermally pleasant (0)-Thermally not pl. (100)	22	25 (0-47)	45% (23%)	0.30 (0.26)	23	25 (13-35)	26% (26%)	0.77 (0.50)
Able to breathe easily (0)-Blocked nose (100)	22	25 (0-34)	50% (14%)	*0.06†* (**0.03***)	23	25 (13-44)	30% (30%)	0.79 (0.90)
Not dry skin (0)-Dry skin (100)	22	25 (0-25)	36% (18%)	0.39 (0.48)	23	13 (6-25)	39% (35%)	1.0 (0.91)
Not dry throat (0)-Dry throat (100)	22	25 (6-50)	45% (18%)	0.18 (0.26)	23	13 (0-25)	30% (17%)	0.55 (0.37)
Not tired eyes (0)-Tired eyes (100)	22	25 (25-50)	36% (27%)	0.79 (0.55)	23	25 (25-44)	52% (17%)	*0.08†* (**0.014***)
Not at all tired (0)-Feeling very tired (100)	22	50 (25-69)	41% (32%)	0.80 (0.55)	23	38 (25-50)	39% (17%)	0.27 (0.35)
No headache (0)-Headache (100)	22	25 (0-50)	36% (23%)	0.58 (0.33)	23	13 (0-25)	43% (22%)	0.30 (0.11)
Easy to concentrate (0)-Difficult to conc. (100)	22	38 (25-50)	14% (32%)	0.34 (0.15)	23	25 (25-44)	48% (22%)	0.21 (0.37)
Awake (0)-Very sleepy (100)	22	25 (25-50)	36% (36%)	0.80 (0.30)	23	25 (13-31)	48% (35%)	0.65 (0.26)
Feel like working (0)-Unwilling to work (100)	22	25 (3-50)	36% (23%)	0.58 (0.33)	23	25 (13-35)	43% (26%)	0.45 (0.30)
Feeling well (0)-Feeling poor (100)	22	0 (0-25)	32% (5%)	*0.08†* (**0.04***)	23	13 (0-25)	43% (22%)	0.30 (0.13)

* Sign test; * if p≤0.05, † if 0.05<p≤0.10; ** Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10

Table 6.9.8. Results of subjective evaluations of classroom conditions and well-being. The evaluations were performed during the non-heating season by the pupils in the classroom with CO_2 based control of automatic window opening and fan assisted exhaust and in the control classroom with manual window opening, where no intervention was made

Question	Intervention (system idled vs. system activated)				Control (no system installed)			
	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)
Perceptions								
Not too warm (0)-Too warm (100)	22	25 (13-47)	59% (18%)	*0.052†* (**0.03***)	23	25 (13-38)	48% (30%)	0.48 (0.32)
Not too cold (0)-Cold (100)	22	25 (13-47)	32% (23%)	0.77 (0.66)	23	25 (6-25)	39% (30%)	0.80 (0.33)
No draft (0)-Drafty (100)	22	38 (13-50)	18% (55%)	*0.08†* (**0.02***)	23	13 (0-25)	26% (30%)	1.0 (0.70)
Air fresh (0)-Air poor (100)	22	25 (25-50)	32% (23%)	0.77 (0.41)	23	38 (25-50)	39% (22%)	0.42 (0.36)
Not too much noise (0)-Too much noise (100)	22	25 (25-48)	41% (36%)	1.0 (0.32)	23	50 (31-63)	30% (22%)	0.77 (0.88)
Not too much light (0) -Too much light (100)	22	25 (13-47)	23% (27%)	1.0 (0.82)	23	13 (0-25)	52% (26%)	0.24 (0.12)
Not too dark (0)-Too dark (100)	22	25 (13-50)	32% (41%)	0.80 (0.45)	23	13 (0-25)	35% (35%)	0.80 (0.98)
Symptoms, general well-being, readiness to learn								
Thermally pleasant (0)-Thermally not pl. (100)	22	25 (13-38)	41% (27%)	0.61 (0.59)	23	25 (13-35)	26% (26%)	0.77 (0.50)
Able to breathe easily (0)-Blocked nose (100)	22	25 (13-50)	41% (18%)	0.27 (0.40)	23	25 (13-44)	30% (30%)	0.79 (0.90)
Not dry skin (0)-Dry skin (100)	22	25 (13-50)	36% (18%)	0.38 (0.14)	23	13 (6-25)	39% (35%)	1.0 (0.91)
Not dry throat (0)-Dry throat (100)	22	31 (13-50)	36% (27%)	0.79 (0.59)	23	13 (0-25)	30% (17%)	0.55 (0.37)
Not tired eyes (0)-Tired eyes (100)	22	44 (16-50)	32% (18%)	0.55 (0.72)	23	25 (25-44)	52% (17%)	*0.08†* (**0.014***)
Not at all tired (0)-Feeling very tired (100)	22	50 (28-50)	36% (18%)	0.39 (0.50)	23	38 (25-50)	39% (17%)	0.27 (0.35)
No headache (0)-Headache (100)	22	25 (13-49)	45% (41%)	0.63 (0.81)	23	13 (0-25)	43% (22%)	0.30 (0.11)
Easy to concentrate (0)-Difficult to conc. (100)	22	38 (16-50)	27% (36%)	0.79 (0.66)	23	25 (25-44)	48% (22%)	0.21 (0.37)
Awake (0)-Very sleepy (100)	22	38 (25-50)	36% (18%)	0.39 (0.39)	23	25 (13-31)	48% (35%)	0.65 (0.26)
Feel like working (0)-Unwilling to work (100)	22	25 (25-50)	18% (41%)	0.27 (0.55)	23	25 (13-35)	43% (26%)	0.45 (0.30)
Feeling well (0)-Feeling poor (100)	22	25 (3-38)	32% (18%)	0.55 (0.33)	23	13 (0-25)	43% (22%)	0.30 (0.13)

* Sign test; * if $p \leq 0.05$, † if $0.05 < p \leq 0.10$; ** Wilcoxon signed-rank test: * if $p \leq 0.05$, † if $0.05 < p \leq 0.10$

Table 6.9.9. Results of subjective evaluations of the classroom conditions and well-being. The evaluations were performed during the heating season by the pupils in the classroom with CO_2 based control of automatic window opening and heat recovery units and in the control classroom with manual window opening, where no intervention was made

Question	Intervention (system idled vs. system activated)				Control (no system installed)			
	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)	Obs.	Median-baseline (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (p**)
Perceptions								
Not too warm (0)-Too warm (100)	27	38 (19-50)	7% (52%)	**0.01*** (**0.01***)	26	25 (25-50)	12% (35%)	0.15 (0.31)
Not too cold (0)-Cold (100)	27	25 (13-38)	33% (30%)	1.0 (0.69)	26	25 (0-25)	35% (8%)	*0.07†* (*0.06†*)
No draft (0)-Drafty (100)	27	25 (13-38)	19% (52%)	*0.07†* (0.10)	26	25 (3-25)	27% (35%)	0.80 (0.29)
Air fresh (0)-Air poor (100)	27	38 (25-50)	22% (44%)	0.24 (0.10)	26	50 (25-72)	27% (19%)	0.77 (0.69)
Not too much noise (0)-Too much noise (100)	27	25 (25-50)	15% (33%)	0.27 (0.29)	26	50 (25-50)	19% (8%)	0.45 (0.39)
Not too much light (0) -Too much light (100)	27	13 (0-31)	30% (15%)	0.39 (0.27)	26	25 (0-25)	19% (19%)	0.75 (0.80)
Not too dark (0)-Too dark (100)	27	13 (0-25)	22% (41%)	0.33 (0.59)	26	25 (0-25)	31% (12%)	0.23 (0.25)
Symptoms, general well-being, readiness to learn								
Thermally pleasant (0)-Thermally not pl. (100)	27	25 (13-38)	19% (52%)	*0.07†* (**0.04***)	26	25 (25-50)	27% (19%)	0.77 (0.27)
Able to breathe easily (0)-Blocked nose (100)	27	25 (13-50)	26% (41%)	0.48 (0.51)	26	25 (6-50)	46% (19%)	0.15 (0.31)
Not dry skin (0)-Dry skin (100)	27	25 (25-44)	22% (44%)	0.24 (*0.09†*)	26	25 (3-50)	27% (23%)	1.0 (0.65)
Not dry throat (0)-Dry throat (100)	27	25 (13-38)	26% (52%)	0.19 (0.92)	26	25 (6-50)	27% (19%)	0.77 (0.48)
Not tired eyes (0)-Tired eyes (100)	27	25 (13-50)	30% (33%)	1.0 (0.89)	26	25 (25-50)	35% (23%)	0.61 (0.50)
Not at all tired (0)-Feeling very tired (100)	27	38 (25-50)	33% (37%)	1.0 (0.64)	26	25 (25-50)	27% (12%)	0.34 (0.33)
No headache (0)-Headache (100)	27	25 (0-38)	19% (37%)	0.30 (0.41)	26	25 (0-25)	31% (15%)	0.39 (0.24)
Easy to concentrate (0)-Difficult to conc. (100)	27	25 (25-38)	22% (41%)	0.33 (0.51)	26	25 (25-50)	27% (12%)	0.12 (0.26)
Awake (0)-Very sleepy (100)	27	25 (13-38)	22% (41%)	0.45 (0.35)	26	25 (25-50)	19% (23%)	1.0 (1.0)
Feel like working (0)-Unwilling to work (100)	27	25 (13-38)	19% (37%)	0.30 (0.28)	26	25 (16-47)	15% (12%)	1.0 (0.67)
Feeling well (0)-Feeling poor (100)	27	25 (0-25)	11% (37%)	*0.10†* (*0.05†*)	26	25 (25-25)	8% (19%)	0.45 (0.40)

* Sign test; * if p≤0.05, † if 0.05<p≤0.10; ** Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10

Table 6.9.10. Results of subjective evaluations of classroom conditions and well-being. The evaluations were performed during the heating season by the students in the classroom with a sorbent type gas-phase air cleaner.

Question	Intervention (system idled vs. system activated)				
	Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (d**)
Perceptions					
Too cold (0)-Too warm (100)	21	29 (24-48)	-2 (-17-3)	38% (62%)	*0.099†* (0.38)
Air fresh (0)-Air Poor (100)	21	26 (19-50)	-1 (-7-11)	48% (52%)	0.72 (0.06)
Too quiet (0)-Too noisy (100)	21	60 (50-69)	0 (-12-0)	24% (43%)	0.43 (0.47)
Too dry (0)-Too humid (100)	21	50 (48-51)	-3 (-10--1)	14% (76%)	**0.004*** (0.67)
Symptoms, general well being, readiness to learn					
Eyed do not ache (0)-Eyes ache(100)	21	29 (4-53)	2 (-8-21)	52% (48%)	0.37 (0.25)
Easy to breathe (0) –Difficult to breathe (100)	21	27 (10-50)	-2 (-5-8)	38% (62%)	0.58 (0.14)
No headache (0)-Headache (100)	21	20 (10-40)	2 (-15-15)	57% (43%)	0.77 (0.07)
Easy to concentrate (0)-Difficult to conc. (100)	21	50 (31-70)	-9 (-19-6)	33% (62%)	0.35 (0.21)
Awake (0)-Very sleepy (100)	21	52 (30-72)	-10 (-18-8)	38% (62%)	0.30 (0.16)
Relaxed (0)-Tense (100)	21	49 (29-66)	-8 (-21-10)	43% (57%)	0.15 (0.51)
Feeling well (0)-Feeling poor (100)	21	47 (22-60)	-4 (-27-9)	43% (57%)	0.30 (0.22)
Easy to think (0).Difficult to think (100)	21	40 (30-60)	1 (-13-16)	52% (48%)	0.75 (0.09)
Not at all tired (0)-Feeling very tired (100)	21	64 (32-70)	-2 (-22-11)	38% (57%)	0.30 (0.22)
Effort is low (0)-Effort is high (100)	21	42 (25-54)	7 (-2-19)	62% (38%)	*0.099†* (0.36)
Learnt a lot (0)-Learnt very little (100)	20	40 (28-57)	-0.5 (-16-25)	50% (50%)	0.49 (0.16)

*Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

Table 6.9.11. Summary of subjective ratings during the heating season (HS) and non-heating season (NHS) in the classrooms with the different retrofitted systems; ↑ and ↓ indicate the direction of the change ($p \leq 0.10$): ↑ shows a change toward the right end of the scale and ↓ shows a change towards the left end of the scale as a result of the intervention; a change for the better is shaded ( ); n.a. – no experiments were performed

Subjective ratings	Manual window opening (Control)		Manual window opening in response to visual feedback on CO_2		CO_2 based control of automatic window opening		CO_2 based control of automatic window opening and a heat recuperator		CO_2 based control of automatic window opening and fan assisted exhaust		Decentralized mechanical ventilation system		Sorbent type gas-phase air cleaner	
	HS	NHS	HS	NHS	HS	NHS	HS	NHS	HS	NHS	HS	NHS	HS	NHS
Perceptions														
Too cold-Too warm			↑					↓ (shaded)	↓ (shaded)	↑	↓ (shaded)		↓ (shaded)	
Air fresh-Air poor									↓ (shaded)					
No draft-Drafty			↑				n.a.			↓ (shaded)			n.a.	n.a.
Too much noise-Too little noise														
Too humid-Too dry														
Too little light-Too much light				↓								↓	n.a	
Symptoms, general well being, readiness to learn														
Thermally pleasant-Thermally not pleasant										↓ (shaded)			n.a.	
Able to breathe easily-Blocked nose			↓ (shaded)		↑						↑	↑		
Feeling well-Feeling poor	↑		↓ (shaded)		↓ (shaded)					↓ (shaded)		↑		
Not dry skin-Dry skin										↓ (shaded)				
Not dry lips-Dry lips													n.a.	
Not dry throat-Dry throat						↑	n.a.							n.a.
No tired or pain in eyes-Eyes aching or tired	↑	↑												
No headache-Headache														
Easy to concentrate-Difficult to concentrate			↑											
Not at all tired-Feeling very tired						↑								
Awake-Very sleepy				↑										

Feel like working-Unwilling to work					↓								↑	

Table 6.9.12. Results of subjective evaluations of classroom conditions and well-being - heating season. The evaluations were performed by the students in the classroom where the intervention with sorbent type gas-phase air cleaner was performed during two weeks when the sorbent air cleaner was inactivated and the CO_2 concentration indicating the ventilation effectiveness was different: 2150 ppm at baseline and 1100 ppm the other week.

Question	CO2 concentration: 2,150 ppm vs. 1,100 ppm				
	Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	% resp. >baseline (% resp. <baseline)	Effect P* (d**)
Perceptions					
Too cold (0)-Too warm (100)	18	28 (24-42)	9,5 (-4-20)	67% (33%)	**0.028*** (0.43)
Air fresh (o)-Air Poor (100)	18	24,5 (19-30)	32,5 (14-47)	89% (11%)	**<0.001*** (1.28)
Too quiet (0)-Too noisy (100)	18	56,5 (49-70)	-6 (-21-8)	28% (67%)	0.20 (0.38)
Too dry (0)-Too humid (100)	18	50 (48-51)	0.5 (-2-0.8)	50% (39%)	0.21 (0.32)
Symptoms, general well-being, readiness to learn					
Eyed do not ache (0)-Eyes ache(100)	18	16 (4-46)	5.5 (0-26)	72% (22%)	**0.024*** (0.38)
Easy to breathe (0) –Difficult to breathe (100)	18	20,5 (6-41)	0 (-1-11)	44% (39%)	0.71 (0.15)
No headache (0)-Headache (100)	18	19 (6-46)	0.5 (-4-7)	50% (44%)	0.92 (0.13)
Easy to concentrate (0)-Difficult to conc. (100)	18	32 (24-66)	15.5 (-3-26)	61% (39%)	**0.037*** (0.39)
Awake (0)-Very sleepy (100)	18	51 (28-71)	11 (-4-19)	61% (28%)	0.26 (0.25)
Relaxed (0)-Tense (100)	18	43,5 (25-58)	1 (-19-7)	50% (44%)	0.89 (0.33)
Feeling well (0)-Feeling poor (100)	18	31,5 (20-58)	2 (-4-15)	50% (39%)	0.42 (0.03)
Easy to think (0).Difficult to think (100)	18	37 (29-53)	11 (-4-33)	72% (28%)	**0.035*** (0.59)
Not at all tired (0)-Feeling very tired (100)	18	56,5 (31-69)	1.5 (-9-21)	56% (44%)	0.46 (0.20)
Effort is low (0)-Effort is high (100)	18	41,5 (29-53)	0.5 (-14-9)	50% (44%)	0.91 (0.06)
Learnt a lot (0)-Learnt very little (100)	18	31,5 (21-50)	15.5 (-1-34)	61% (33%)	**0.059*** (0.57)

*Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

6.10 Performance

6.10.1 Association between interventions and test performance

Table 6.10.1 to Table 6.10.5 show the results of the tests performed by the pupils under the different intervention conditions. The performance metrics were speed, percentage of errors and the product of speed and errors, indicating how quickly the tests were performed without errors. The tables show median performance during weeks when the retrofit was idled and the change in performance to when it was activated, together with the results of statistical analyses. They also show the median performance of the pupils in the reference classroom and whether their performance changed on the weeks when the retrofit was activated in the parallel classrooms where the interventions took place.

Table 6.10.10 shows the results of the logical reasoning test performed by the students when the sorbent air cleaner was idled and when it was activated. Increased speed and an increased product of speed and errors, and reduced percentage of errors indicate improved performance.

Table 6.10.11 summarizes all results; two arrows in case of some tests in the heating season indicate that two types of tests were performed. For comparison, Table 6.10.11 shows also the results from the reference classroom. Table 6.10.12 shows Cohen's d for the differences that were at least approaching statistical significance ($P<0.10$).

Table 6.10.12 shows that many significant effects occurred in the classrooms where windows were opened only manually to ventilate the classrooms. However, in these classrooms the effects were also least systematic. In the reference classroom, the performance of the math and logical reasoning tests improved in one heating season, whereas it decreased in the other heating season. In the non-heating season, the performance was generally reduced in this classroom. The observed effects could be caused by uncontrollable external factors, i.e. were occurring at random. In the classroom with the visual feedback device, the use of the feedback resulted in improved performance of all tests (at least for some of their performance measures) in the heating season, but generally reduced performance in the non-heating season. These effects were thus inconsistent across seasons. But in the non-heating season it may be assumed that the windows were opened and stayed open more frequently because of favorable weather conditions, and the contrast between the system idled or activated would be smaller. Consequently, the results from the non-heating season may be regarded as random and should not be attributed to the use of the retrofit. Automatic window opening either with or without heat recovery units also had inconsistent effects on performance; in some cases the performance increased and in some cases it was reduced. This effect was similar to the classroom with the visual feedback device and in the reference classroom.

The most consistent effects, though not for all performance tests used, were seen for the retrofits with automatically operable windows assisted by an exhaust fan and the decentralized ventilation system. With the decentralized ventilation system, the performance of the math test was improved in both seasons, while the performance of the graphical logical test and the d2-test improved only in the non-heating season. With automatically operable windows assisted by the exhaust fan, the performance of the d2-test improved, but not consistently during both the heating and non-heating seasons. With this system, the performance of the logical reasoning test also improved. These results suggest that increased ventilation improves the performance of tasks requiring logical thinking, concentration and attention. They are consistent with the data reported in the literature (Wargocki and Wyon, 2012; 2017).

The use of the sorbent air cleaner improved the performance of the logical reasoning task. However, this effect could also be ascribed the learning effect as this result is based on two measurements under two conditions in a non-balanced order of presentation. Additional analysis of the results from the classroom showed that the performance of the logical reasoning test was reduced when the CO_2 concentration was higher (Table 6.10.13), 2250 ppm during one week and 1100 ppm during the other. Even in this case, the observed effect could be caused by gradual improvement in performance due to learning with repeated use of the test.

Table 6.10.1. Performance of school tasks and cognitive tests performed during the heating season in the classroom with CO_2 based control of automatic window opening and in the control classroom with manual window opening where no intervention was made.

Test	Metric	Intervention (system idled vs. system activated)				Control (no system installed)			
		Obs.	Median-baseline (25^{th}-75^{th} percentile)	Median-change (25th-75th percentile)	Effect P* (d**)	Obs.	Median-baseline (25^{th}-75^{th} percentile)	Median-change (25th-75th percentile)	Effect P* (d**)
Subtraction	Speed	26	3.09 (2.61-3.89)	-0.31 (-0.99-0.05)	**0.038*** **(0.22)**	24	2.96 (2.40-3.71)	-0.23 (-0.81-0.25)	0.12 (0.40)
	% Errors	26	15.84 (10.18-37.27)	5.39 (0.37-9.08)	**0.006*** **(0.60)**	24	14.73 (9.22-21.47)	2.78 (-1.63-10.88)	*0.059†* (0.37)
	SpeedxErrors	26	2.36 (1.96-2.90)	-0.36 (-0.91-0.06)	**0.009*** **(0.59)**	24	2.42 (2.03-3.00)	-0.25 (-0.85-0.07)	*0.056†* (0.44)
Logical reasoning	Speed	26	8.73 (7.16-10.52)	0.04 (-1.73-1.83)	0.83 (0.12)	24	5.40 (4.36-6.40)	1.66 (0.37-2.97)	**0.001*** **(0.65)**
	% Errors	26	52.15 (24.65-55.10)	0.33 (-3.14-3.14)	0.97 (0.13)	24	14.99 (8.72-25.44)	-1.02 (-6.59-5.45)	0.86 (0.06)
	SpeedxErrors	26	4.80 (3.63-6.99)	-0.17 (-0.74-0.76)	0.99 (0.03)	24	4.30 (2.61-5.61)	1.38 (0.46-2.57)	**0.001*** **(0.71)**
d2-test	dTS	26	390.0 (340.5-452.8)	-6.5 (-27.5-23.5)	0.81 (0.02)	25	419.0 (384.0-454.0)	-8.0 (-61.0-35.0)	0.77 (0.07)
	Total Errors	26	11.00 (7.00-22.63)	-0.50 (-4.00-2.00)	0.35 (0.28)	25	10.00 (7.00-17.00)	0.0 (-4.0-2.0)	0.23 (0.09)
	% Errors	26	3.08 (1.85-5.27)	-0.29 (-1.37-0.60)	0.20 (0.30)	25	2.43 (1.62-4.04)	-0.45 (-1.01-0.54)	0.34 (0.16)
	Conc. Perfor.	26	376.0 (331.0-440.0)	3.00 (-27.63-28.00)	0.86 (0.03)	25	412.0 (373.0-443.0)	-6.0 (-55.0-21.0)	0.54 (0.10)
	Fluct. Rate	26	15.0 (13.0-16.0)	2.00 (-1.00-3.88)	*0.08†* (0.37)	25	19.0 (15.0-27.0)	-2.50 (-7.0-0.0)	*0.057†* (0.44)
Multiplication	Speed	19	15.72 (12.62-19.15)	12.60 (5.97-18.69)	**0.0001*** **(1.46)**	17	11.97 (10.09-13.68)	-2.23 (-3.41--1.71)	0.22 (0.30)
	% Errors	19	6.41 (1.68-11.19)	1.25 (-0.69-4.98)	0.14 (0.28)	17	5.00 (2.50-6.56)	0.42 (-1.25-5.77)	**0.023*** **(0.33)**
	SpeedxErrors	19	14.39 (10.41-17.60)	10.99 (6.43-14.08)	**0.0002*** **(1.40)**	17	11.79 (9.40-13.33)	-2.10 (-3.39--1.21)	0.22 (0.33)

*Wilcoxon signed-rank test: * if $p \leq 0.05$, † if $0.05 < p \leq 0.10$; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

Table 6.10.2. Performance of school tasks and cognitive tests performed during the heating season in the classroom with manual window opening in response to visual feedback on CO_2 and in the control classroom with manual window opening where no intervention was made.

Test	Metric	Intervention (system idled vs. system activated)				Control (no system installed)			
		Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)	Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)
Subtraction	Speed	25	3.44 (2.14-4.05)	-0.15 (-0.31-0.33)	0.88 (0.03)	24	2.52 (1.93-3.88)	0.23 (-0.25-0.81)	0.12 (0.40)
	% Errors	25	11.90 (7.89-21.54)	-0.01 (-7.46-5.14)	0.70 (0.09)	24	21.32 (6.93-29.07)	-2.78 (-10.88-1.63)	*0.059†* (0.37)
	SpeedxErrors	25	3.06 (1.68-3.60)	-0.14 (-0.46-0.43)	0.51 (0.10)	24	1.82 (1.47-2.98)	0.25 (-0.07-0.85)	*0.056†* (0.44)
Logical reasoning	Speed	22	7.07 (5.86-8.54)	0.79 (-0.23-1.71)	**0.019*** **(0.50)**	24	6.83 (5.32-8.54)	-1.66 (-2.97--0.37)	**0.001*** **(0.65)**
	% Errors	22	6.58 (2.85-13.85)	-0.10 (-3.39-4.45)	0.64 (0.18)	24	15.69 (5.07-33.00)	1.02 (-5.45-6.59)	0.86 (0.06)
	SpeedxErrors	22	6.54 (5.41-7.82)	0.68 (-0.26-1.35)	*0.062†* (0.41)	24	5.35 (3.22-7.77)	-1.38 (-2.57--0.46)	**0.001*** **(0.71)**
d2-test	dTS	23	411.0 (395.3-475.0)	35.0 (0.0-63.5)	**0.003*** **(0.81)**	25	421.0 (361.0-454.0)	5.0 (-64.0-37.5)	0.77 (0.07)
	Total Errors	23	4.0 (2.0-6.5)	0.0 (-1.5-2.0)	0.65 (0.15)	25	11.0 (5.0-14.0)	1.0 (-2.5-5.0)	0.23 (0.09)
	% Errors	23	0.91 (0.42-1.33)	0.01 (-0.14-0.35)	0.63 (0.16)	25	2.26 (1.10-3.80)	0.47 (-0.61-1.01)	0.34 (0.16)
	Conc. Perfor.	23	409.0 (389.5-465.3)	35.0 (-1.75-65.75)	**0.003*** **(0.81)**	25	416.0 (359.0-445.0)	-8.0 (-60.0-33.0)	0.54 (0.10)
	Fluct. Rate	23	16.0 (13.5-19.5)	0.0 (-5.0-3.0)	0.96 (0.01)	25	16.0 (14.0-20.0)	4.0 (-2.0-9.0)	*0.057†* (0.44)
Multiplication	Speed	22	9.05 (7.21-13.24)	1.56 (-0.04-2.82)	**0.003*** **(0.82)**	14	9.87 (6.80-10.67)	3.41 (-0.58-4.40)	0.22 (0.30)
	% Errors	22	5.00 (1.62-11.73)	-3.01 (-6.05-1.02)	**0.023*** **(0.53)**	14	7.50 (5.63-12.33)	-5.19 (-9.80--2.50)	**0.023*** **(0.33)**
	SpeedxErrors	22	8.38 (6.70-12.61)	1.79 (0.37-2.46)	**0.0002*** **(1.00)**	14	8.53 (6.13-10.40)	3.71 (-2.66-5.00)	0.22 (0.33)

*Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

Table 6.10.3. Performance of school tasks and cognitive tests performed during the heating season in the classroom with a <u>decentralized mechanical ventilation system</u> and in the control classroom with manual window opening where no intervention was made.

Test	Metric	Intervention (system idled vs. system activated)				Control (no system installed)			
		Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)	Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)
Subtraction	Speed	22	5.18 (4.09-7.19)	-0.25 (-0.69-0.49)	0.43 (0.13)	24	2.52 (1.93-3.88)	0.23 (-0.25-0.81)	0.12 (0.40)
	% Errors	22	4.40 (2.69-6.90)	2.19 (0.60-5.03)	**0.002*** **(0.82)**	24	21.32 (6.93-29.07)	-2.78 (-10.88-1.63)	*0.059†* (0.37)
	SpeedxErrors	22	4.85 (3.91-6.76)	-0.34 (-0.71-0.28)	0.16 (0.29)	24	1.82 (1.47-2.98)	0.25 (-0.07-0.85)	*0.056†* (0.44)
Logical reasoning	Speed	22	10.39 (8.60-16.19)	-0.59 (-3.55-1.58)	0.35 (0.19)	24	6.83 (5.32-8.54)	-1.66 (-2.97--0.37)	**0.001*** **(0.65)**
	% Errors	22	11.68 (7.10-18.55)	-0.37 (-4.66-2.22)	0.47 (0.19)	24	15.69 (5.07-33.00)	1.02 (-5.45-6.59)	0.86 (0.06)
	SpeedxErrors	22	9.33 (7.82-11.02)	-0.88 (-2.04-0.97)	0.34 (0.10)	24	5.35 (3.22-7.77)	-1.38 (-2.57--0.46)	**0.001*** **(0.71)**
d2-test	dTS	22	547.8 (455.8-589.4)	14.25 (-19.75-47.25)	0.27 (0.29)	25	421.0 (361.0-454.0)	5.0 (-64.0-37.5)	0.77 (0.07)
	Total Errors	22	9.25 (5.00-31.88)	0.75 (-3.88-5.38)	0.67 (0.10)	25	11.0 (5.0-14.0)	1.0 (-2.5-5.0)	0.23 (0.09)
	% Errors	22	2.39 (1.09-5.83)	0.21 (-0.71-0.93)	0.61 (0.12)	25	2.26 (1.10-3.80)	0.47 (-0.61-1.01)	0.34 (0.16)
	Conc. Perfor.	22	502.3 (443.3-562.4)	13.50 (-17.75-29.50)	0.28 (0.29)	25	416.0 (359.0-445.0)	-8.0 (-60.0-33.0)	0.54 (0.10)
	Fluct. Rate	22	15.00 (10.63-19.00)	0.00 (-4.38-2.13)	**0.01*** **(0.28)**	25	16.0 (14.0-20.0)	4.0 (-2.0-9.0)	*0.057†* (0.44)
Multiplication	Speed	19	6.30 (6.00-8.25)	0.90 (0.15-1.50)	**0.003*** **(0.87)**	14	9.87 (6.80-10.67)	3.41 (-0.58-4.40)	0.22 (0.30)
	% Errors	19	6.15 (2.36-11.89)	-0.05 (-3.74-1.76)	0.57 (0.29)	14	7.50 (5.63-12.33)	-5.19 (-9.80--2.50)	**0.023*** **(0.33)**
	SpeedxErrors	19	6.00 (5.35-7.90)	1.10 (0.45-1.55)	**0.003*** **(0.92)**	14	8.53 (6.13-10.40)	3.71 (-2.66-5.00)	0.22 (0.33)

*Wilcoxon signed- rank test: * if p≤0.05, † if 0.05<p≤0.10; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

Table 6.10.4. Performance of school tasks and cognitive tests performed during the heating season in the classroom with <u>CO_2 based control of automatic window opening and fan assisted exhaust</u> and in the control classroom with manual window opening where no intervention was made.

Test	Metric	Intervention (system idled vs. system activated)				Control (no system installed)			
		Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)	Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)
Subtraction	Speed	20	2.79 (2.50-3.68)	-0.01 (-0.18-1.03)	0.63 (0.10)	24	2.96 (2.40-3.71)	-0.23 (-0.81-0.25)	0.12 (0.40)
	% Errors	20	15.00 (11.43-20.89)	1.60 (-6-.08-5.33)	0.97 (0.06)	24	14.73 (9.22-21.47)	2.78 (-1.63-10.88)	*0.059†* (0.37)
	SpeedxErrors	20	2.47 (2.08-3.16)	-0.03 (-0.45-0.54)	0.94 (0.02)	24	2.42 (2.03-3.00)	-0.25 (-0.85-0.07)	*0.056†* (0.44)
Logical reasoning	Speed	23	6.49 (4.70-8.33)	2.40 (0.23-3.53)	**0.002*** (0.78)	24	5.40 (4.36-6.40)	1.66 (0.37-2.97)	**0.001*** **(0.65)**
	% Errors	23	18.41 (11.78-51.90)	-1.44 (-5.23-1.19)	0.15 (0.21)	24	14.99 (8.72-25.44)	-1.02 (-6.59-5.45)	0.86 (0.06)
	SpeedxErrors	23	4.50 (3.28-5.26)	1.35 (0.40-2.96)	**0.001*** (0.85)	24	4.30 (2.61-5.61)	1.38 (0.46-2.57)	**0.001*** **(0.71)**
d2-test	dTS	23	415.0 (349.5-456.0)	5.00 (-10.00-26.50)	0.17 (0.32)	25	419.0 (384.0-454.0)	-8.0 (-61.0-35.0)	0.77 (0.07)
	Total Errors	23	8.00 (6.25-27.25)	-3.00 (-5.50-1.00)	**0.007*** (0.19)	25	10.00 (7.00-17.00)	0.0 (-4.0-2.0)	0.23 (0.09)
	% Errors	23	2.14 (1.69-8.77)	-0.51 (-2.34-0.30)	**0.04*** (0.21)	25	2.43 (1.62-4.04)	-0.45 (-1.01-0.54)	0.34 (0.16)
	Conc. Perfor.	23	349.0 (338.3-420.0)	13.00 (-11.00-27.50)	0.16 (0.38)	25	412.0 (373.0-443.0)	-6.0 (-55.0-21.0)	0.54 (0.10)
	Fluct. Rate	23	13.00 (7.75-16.25)	4.00 (1.00-7.00)	**0.005*** (0.68)	25	19.0 (15.0-27.0)	-2.50 (-7.0-0.0)	*0.057†* (0.44)
Multiplication	Speed	18	2.35 (2.00-4.30)	0.05 (-0.45-1.23)	0.96 (0.00)	17	11.97 (10.09-13.68)	-2.23 (-3.41--1.71)	0.22 (0.30)
	% Errors	18	51.14 (41.25-62.94)	2.26 (-14.18-7.63)	0.56 (0.21)	17	5.00 (2.50-6.56)	0.42 (-1.25-5.77)	**0.023*** **(0.33)**
	SpeedxErrors	18	1.25 (1.00-2.40)	0.10 (-0.38-0.80)	0.41 (0.10)	17	11.79 (9.40-13.33)	-2.10 (-3.39--1.21)	0.22 (0.33)

*Wilcoxon signed- rank test: * if p≤0.05, † if 0.05<p≤0.10; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

Table 6.10.5. Performance of school tasks and cognitive tests performed during the heating season in the classroom with CO2 based control of automatic window opening and heat recovery units and in the control classroom with manual window opening where no intervention was made.

Test	Metric	Intervention (system idled vs. system activated)				Control (no system installed)			
		Obs.	Median-baseline (25^{th}-75^{th} percentile)	Median-change (25th-75th percentile)	Effect P^{*} (d^{**})	Obs.	Median-baseline (25^{th}-75^{th} percentile)	Median-change (25th-75th percentile)	Effect P^{*} (d^{**})
Subtraction & multiplication	Speed	27	2.56 (1.81-2.94)	0.20 (-0.22-0.61)	0.17 (0.26)	26	3.09 (2.06-3.94)	-0.13 (-0.72-0.36)	0.33 (0.18)
	% Errors	27	15.38 (8.02-38.75)	4.17 (-5.58-7.34)	0.69 (0.03)	26	22.47 (8.94-33.45)	-0.14 (-8.09-13.68)	0.79 (0.10)
	SpeedxErrors	27	1.63 (1.19-2.41)	0.18 (-0.38-0.71)	0.25 (0.25)	26	2.13 (1.39-3.22)	-0.25 (-0.72-0.36)	0.12 (0.19)
Graph. logical reasoning	Speed	27	9.30 (6.45-11.30)	0.60 (-0.75-1.15)	0.58 (0.05)	26	8.80 (6.72-10.67)	-0.75 (-1.58-0.30)	*0.054†* (0.15)
	% Errors	27	7.60 (1.41-12.05)	-0.21 (-1.29-2.84)	0.81 (0.05)	26	4.58 (0.00-17.32)	0.50 (-1.19-2.98)	0.29 (0.25)
	SpeedxErrors	27	8.30 (6.10-10.25)	0.40 (-1.05-0.95)	0.99 (0.11)	26	7.78 (6.10-9.17)	-0.80 (-1.05-0.27)	**0.03* (0.30)**
d2-test	dTS	27	503.0 (438.0-563.0)	61.0 (25.5-103.0)	**0.001* (0.69)**	26	537.5 (487.9-596.5)	0.00 (-12.88-19.75)	0.93 (0.17)
	Total Errors	27	12.00 (6.50-21.00)	1.00 (-7.00-5.50)	0.92 (0.03)	26	10.50 (5.00-21.75)	0.50 (-3.00-3.00)	0.95 (0.17)
	% Errors	27	2.80 (1.30-3.97)	0.04 (-1.31-0.59)	0.61 (0.06)	26	2.24 (0.89-4.26)	0.07 (-0.56-0.63)	0.85 (0.17)
	Conc. Perfor.	27	480.0 (422.5-519.5)	52.00 (23.25-97.50)	**0.001* (0.78)**	26	516.0 (450.0-555.0)	1.75 (-12.38-15.50)	0.77 (0.04)
	Fluct. Rate	27	18.0 (14.0-21.0)	-2.00 (-8.00-1.25)	0.12 (0.30)	26	18.00 (10.75-22.63)	-1.00 (-4.38-3.50)	0.87 (0.14)

*Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

Table 6.10.6. Performance of school tasks and cognitive tests performed during the non-heating season in the classroom with CO_2 based control of automatic window opening and in the control classroom with manual window opening where no intervention was made.

Test	Metric	Intervention (system idled vs. system activated)				Control (no system installed)			
		Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)	Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)
Subtraction & multiplication	Speed	26	3.81 (2.91-5.03)	-0.31 (-0.81-0.34)	0.14 (0.26)	25	3.38 (2.63-4.56)	-0.25 (-0.63-0.19)	0.15 (0.12)
	% Errors	26	9.52 (5.42-19.76)	1.32 (-2.10-7.51)	*0.054†* (0.47)	25	14.71 (10.53-20.00)	0.00 (-5.61-4.26)	0.72 (0.00)
	SpeedxErrors	26	3.13 (2.44-4.09)	-0.34 (-0.72-0.16)	*0.088†* (0.26)	25	2.81 (1.88-4.13)	-0.25 (-0.63-0.13)	**0.05*** (0.40)
Graph. logical reasoning	Speed	26	7.69 (5.41-9.30)	0.29 (-1.24-1.29)	0.64 (0.13)	25	7.60 (5.40-10.00)	-0.90 (-2.00-0.80)	*0.09†* (0.35)
	% Errors	26	9.00 (3.17-20.42)	-0.48 (-3.24-2.00)	0.53 (0.19)	25	7.50 (2.78-16.23)	0.42 (-3.72-2.63)	0.60 (0.21)
	SpeedxErrors	26	7.20 (4.56-8.12)	-0.01 (-0.92-1.20)	0.66 (0.15)	25	7.20 (4.80-9.40)	-0.90 (-1.80-0.30)	*0.10†* (0.34)
d2-test	dTS	26	481.0 (438.3-530.5)	-33.50 (-50.88--1.00)	**0.004*** (0.71)	25	493.5 (447.0-541.0)	-32.0 (-57.5--1.0)	**0.004*** (0.68)
	Total Errors	26	11.50 (6.50-17.75)	-1.25 (-4.00-2.75)	0.35 (0.22)	25	13.50 (10.00-24.00)	-1.50 (-9.00-3.50)	0.54 (0.13)
	% Errors	26	2.29 (1.29-4.11)	-0.26 (-0.67-0.49)	0.55 (0.08)	25	2.76 (2.09-4.83)	-0.53 (-1.03-0.83)	0.56 (0.04)
	Conc. Perfor.	26	474.0 (410.25-496.75)	-34.50 (-51.88--8.25)	**0.002*** (0.64)	25	468.0 (415.0-491.0)	-25.0 (-42.0-3.50)	**0.015*** (0.57)
	Fluct. Rate	26	18.50 (14.25-24.75)	-2.00 (-4.75-0.00)	**0.013*** (0.46)	25	19.0 (13.0-23.0)	3.00 (-0.50-5.00)	0.24 (0.20)

*Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

Table 6.10.7. Performance of school tasks and cognitive tests performed during the non-heating season in the classroom with manual window opening in response to visual feedback on CO_2 and in the control classroom with manual window opening where no intervention was made.

Test	Metric	Intervention (system idled vs. system activated)				Control (no system installed)			
		Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)	Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)
Subtraction & multiplication	Speed	23	3.63 (2.44-5.06)	-0.13 (-0.75-0.28)	0.23 (0.30)	25	3.38 (2.63-4.56)	-0.25 (-0.63-0.19)	0.15 (0.12)
	% Errors	23	11.43 (6.43-18.00)	5.75 (-3.06-11.23)	*0.09†* (0.39)	25	14.71 (10.53-20.00)	0.00 (-5.61-4.26)	0.72 (0.00)
	SpeedxErrors	23	3.13 (2.13-4.50)	-0.44 (-0.91-0.09)	*0.053†* (0.44)	25	2.81 (1.88-4.13)	-0.25 (-0.63-0.13)	**0.05*** (0.40)
Graph. logical reasoning	Speed	23	8.80 (7.40-11.90)	-1.00 (-1.95--0.50)	**0.001*** (1.02)	25	7.60 (5.40-10.00)	-0.90 (-2.00-0.80)	*0.09†* (0.35)
	% Errors	23	4.55 (2.43-8.76)	-1.23 (-3.01-2.35)	0.39 (0.25)	25	7.50 (2.78-16.23)	0.42 (-3.72-2.63)	0.60 (0.21)
	SpeedxErrors	23	8.20 (6.70-11.55)	-1.20 (-1.55--0.50)	**0.001*** (1.26)	25	7.20 (4.80-9.40)	-0.90 (-1.80-0.30)	*0.10†* (0.34)
d2-test	dTS	23	533.5 (509.3-602.3)	-34.50 (-59.50-1.75)	**0.002*** (0.86)	25	493.5 (447.0-541.0)	-32.0 (-57.5--1.0)	**0.004*** (0.68)
	Total Errors	23	6.50 (5.00-11.75)	-1.00 (-4.25-0.25)	**0.04*** (0.44)	25	13.50 (10.00-24.00)	-1.50 (-9.00-3.50)	0.54 (0.13)
	% Errors	23	1.40 (0.86-2.17)	-0.16 (-0.65-0.04)	**0.045*** (0.33)	25	2.76 (2.09-4.83)	-0.53 (-1.03-0.83)	0.56 (0.04)
	Conc. Perfor.	23	521.5 (503.0-596.8)	-32.00 (-57.50-3.75)	**0.002*** (0.81)	25	468.0 (415.0-491.0)	-25.0 (-42.0-3.50)	**0.015*** (0.57)
	Fluct. Rate	23	13.00 (9.75-17.75)	2.00 (-3.75-3.50)	0.66 (0.04)	25	19.0 (13.0-23.0)	3.00 (-0.50-5.00)	0.24 (0.20)

*Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

Table 6.10.8. Performance of school tasks and cognitive tests performed during the non-heating season in the classroom with a decentralized mechanical ventilation system and in the control classroom with manual window opening where no intervention was made.

Test	Metric	Intervention (system idled vs. system activated)				Control (no system installed)			
		Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)	Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)
Subtraction & multiplication	Speed	22	4.63 (3.53-5.75)	0.34 (0.06-1.06)	**0.03*** (0.45)	25	3.38 (2.63-4.56)	-0.25 (-0.63-0.19)	0.15 (0.12)
	% Errors	22	7.14 (3.60-10.39)	1.50 (-2.07-5.46)	0.20 (0.39)	25	14.71 (10.53-20.00)	0.00 (-5.61-4.26)	0.72 (0.00)
	SpeedxErrors	22	4.19 (3.00-5.09)	0.28 (-0.02-0.72)	*0.064†* (0.29)	25	2.81 (1.88-4.13)	-0.25 (-0.63-0.13)	**0.05*** (0.40)
Graph. logical reasoning	Speed	22	8.82 (7.45-11.70)	0.73 (0.24-2.06)	**0.013*** (0.54)	25	7.60 (5.40-10.00)	-0.90 (-2.00-0.80)	*0.09†* (0.35)
	% Errors	22	8.14 (4.32-15.18)	1.57 (-1.64-4.74)	*0.094†* (0.43)	25	7.50 (2.78-16.23)	0.42 (-3.72-2.63)	0.60 (0.21)
	SpeedxErrors	22	8.15 (6.06-10.10)	0.78 (-0.05-1.88)	**0.012*** (0.59)	25	7.20 (4.80-9.40)	-0.90 (-1.80-0.30)	*0.10†* (0.34)
d2-test	dTS	22	591.0 (502.3-647.0)	15.25 (0.13-60.75)	**0.002*** (0.80)	25	493.5 (447.0-541.0)	-32.0 (-57.5--1.0)	**0.004*** (0.68)
	Total Errors	22	11.50 (5.50-25.00)	-1.00 (-3.88-2.00)	0.49 (0.17)	25	13.50 (10.00-24.00)	-1.50 (-9.00-3.50)	0.54 (0.13)
	% Errors	22	2.18 (1.13-5.03)	-0.22 (-0.81-0.22)	0.15 (0.31)	25	2.76 (2.09-4.83)	-0.53 (-1.03-0.83)	0.56 (0.04)
	Conc. Perfor.	22	547.0 (484.8-618.4)	21.25 (9.38-62.50)	**0.001*** (1.05)	25	468.0 (415.0-491.0)	-25.0 (-42.0-3.50)	**0.015*** (0.57)
	Fluct. Rate	22	13.50 (3.25-18.00)	-0.25 (-4.75-0.38)	0.11 (0.35)	25	19.0 (13.0-23.0)	3.00 (-0.50-5.00)	0.24 (0.20)

*Wilcoxon signed- rank test: * if p≤0.05, † if 0.05<p≤0.10; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

Table 6.10.9. Performance of school tasks and cognitive tests performed during the non-heating season in the classroom with CO_2 based control of automatic window opening and fan assisted exhaust and in the control classroom with manual window opening where no intervention was made.

Test	Metric	Intervention (system idled vs. system activated)				Control (no system installed)			
		Obs.	Median-baseline (25^{th}-75^{th} percentile)	Median-change (25th-75th percentile)	Effect P^* (d^{**})	Obs.	Median-baseline (25^{th}-75^{th} percentile)	Median-change (25th-75th percentile)	Effect P^* (d^{**})
Subtraction & multiplication	Speed	22	3.38 (2.53-4.31)	0.00 (-0.84-0.48)	0.73 (0.12)	25	3.38 (2.63-4.56)	-0.25 (-0.63-0.19)	0.15 (0.12)
	% Errors	22	9.25 (3.46-14.05)	3.18 (-0.30-6.34)	0.101 (0.26)	25	14.71 (10.53-20.00)	0.00 (-5.61-4.26)	0.72 (0.00)
	SpeedxErrors	22	2.63 (2.16-4.19)	-0.19 (-0.59-0.52)	0.83 (0.01)	25	2.81 (1.88-4.13)	-0.25 (-0.63-0.13)	**0.05*** (0.40)
Graph. logical reasoning	Speed	21	7.80 (5.60-9.80)	0.60 (-0.40-1.80)	0.102 (0.23)	25	7.60 (5.40-10.00)	-0.90 (-2.00-0.80)	*0.09†* (0.35)
	% Errors	21	8.22 (4.17-14.29)	0.98 (-1.64-4.37)	0.25 (0.23)	25	7.50 (2.78-16.23)	0.42 (-3.72-2.63)	0.60 (0.21)
	SpeedxErrors	21	7.60 (3.90-8.80)	0.80 (-0.20-1.60)	*0.08†* (0.28)	25	7.20 (4.80-9.40)	-0.90 (-1.80-0.30)	*0.10†* (0.34)
d2-test	dTS	20	477.5 (364.8-587.5)	22.50 (6.50-69.75)	*0.05†* (0.49)	25	493.5 (447.0-541.0)	-32.0 (-57.5--1.0)	**0.004*** (0.68)
	Total Errors	20	5.00 (2.00-19.25)	67.50 (46.75-84.75)	**0.001*** (2.13)	25	13.50 (10.00-24.00)	-1.50 (-9.00-3.50)	0.54 (0.13)
	% Errors	20	1.37 (0.54-3.76)	12.90 (10.62-13.93)	**0.001*** (2.84)	25	2.76 (2.09-4.83)	-0.53 (-1.03-0.83)	0.56 (0.04)
	Conc. Perfor.	20	475.5 (359.0-579.8)	-35.00 (-76.00--3.63)	**0.048*** (0.34)	25	468.0 (415.0-491.0)	-25.0 (-42.0-3.50)	**0.015*** (0.57)
	Fluct. Rate	20	13.00 (9.75-17.25)	0.50 (-4.00-4.25)	0.71 (0.17)	25	19.0 (13.0-23.0)	3.00 (-0.50-5.00)	0.24 (0.20)

*Wilcoxon signed- rank test: * if p≤0.05, † if 0.05<p≤0.10; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

Table 6.10.10. Performance of tasks and cognitive tests performed during the heating season in the classroom with a sorbent type gas-phase air cleaner.

Test	Metric	Intervention (system idled vs. system activated)			
		Obs.	Median-baseline (25^{th}-75^{th} percentile)	Median-change (25th-75th percentile)	Effect P* (d**)
Logical reasoning	Speed	22	9.2 (6.1-11.3)	0.5 (-0.7-1.9)	**0.0001*** (0.32)
	% Errors	22	16.2 (7.7-38.8)	-2.2 (-6.9-4.7)	**0.0001*** (0.13)
	SpeedxErrors	22	6.3 (4.3-9.6)	0.3 (-0.3-1.3)	**0.002*** (0.31)

*Wilcoxon signed-rank test: * if p≤0.05, † if 0.05<p≤0.10; **Cohen's d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

Table 6.10.11. Summary of results of the effects on performance of school tasks and cognitive tests performed during the heating season (HS) and non-heating season (NHS) in all elementary school classrooms; ↑ indicates improved performance and ↓ indicates reduced performance ($p \leq 0.10$); consistent findings ( ) and somewhat consistent ( ) are shaded; Empty cells indicate no consistent effect. n.a. – no experiments were performed

Test	Performance	Manual window opening (Control)		Manual window opening in response to visual feedback on CO_2		CO_2 based control of automatic window opening		CO_2 based control of automatic window opening and a heat recuperator		CO_2 based control of automatic window opening and fan assisted exhaust		Decentralized mechanical ventilation system		Sorbent type gas-phase air cleaner	
		HS	NHS	HS	NHS	HS	NHS	HS	NHS	HS	NHS	HS	NHS	HS	NHS
Math (subtraction, multiplication or both)	Speed			↑		↑↓						↑	↑		
	%Errors	↑↓		↑	↓	↓	↓		n.a.			↓		n.a.	
	SpeedxErrors	↑↓	↓	↑	↓	↑↓	↓					↑	↑		
Logical reasoning (traditional or graphical)	Speed	↑↓	↓↓	↑	↓					↑			↑	↑	
	% Errors								n.a.				↓	↓	n.a.
	SpeedxErrors	↑↓	↓↓	↑	↓					↑	↑		↑	↑	
d2-test	dTS		↓	↑	↓		↓	↑			↑		↑		
	Total Errors				↑				n.a.	↑	↓			n.a.	
	% Errors				↑					↑	↓				
	Conc. Perfor.		↓	↑	↓		↓	↑			↓		↑		

Table 6.10.12. Summary of results of the effects on performance of school tasks and cognitive tests performed during the heating season (HS) and non-heating season (NHS) in all elementary school classrooms. The table shows Cohen's d values for the differences in performance that reached statistical significance (P<0.05) or were approaching significance (P<0.10); the d value in brackets suggest that the performance got better when the retrofit was idled.

Test	Performance	Manual window opening (Control)		Manual window opening in response to visual feedback on CO_2		CO_2 based control of automatic window opening		CO_2 based control of automatic window opening and a heat recuperator		CO_2 based control of automatic window opening and fan assisted exhaust		Decentralized mechanical ventilation system		Sorbent type gas-phase air cleaner	
		HS	NHS	HS	NHS	HS	NHS	HS	NHS	HS	NHS	HS	NHS	HS	NHS
Math (subtraction, multiplication or both)	Speed			0.82		(0.22) 1.46						0.87	0.45		
	%Errors	(0.37) (0.33)		0.53	(0.39)	(0.60)	(0.47)		n.a.			(0.82)		n.a.	
	SpeedxErrors	(0.44)	(0.40)	1.00	(0.44)	(0.59) 1.40	(0.26)					0.92	0.29		
Logical reasoning (traditional or graphical)	Speed	(0.65) (0.15)	(0.35)	0.50	(1.02)					0.78			0.54	0.32	
	% Errors								n.a.				(0.43)	0.13	n.a.
	SpeedxErrors	(0.71) (0.30)	(0.34)	0.41	(1.26)					0.85	0.28		0.59	0.31	
d2-test	dTS		(0.68)	0.81	(0.86)		(0.71)	0.69			0.49		0.80		
	Total Errors				(0.33)				n.a.	0.19	(2.13)			n.a.	
	% Errors				(0.33)					0.21	(2.84)				
	Conc. Perfor.		(0.57)	0.81	(0.81)		(0.64)	0.78			(0.34)		1.05		

Table 6.10.13. Performance of the cognitive tests performed during the heating season in the classroom where the intervention with a sorbent type gas-phase air cleaner was performed.

Test	Metric	CO_2 concentration: 2150 ppm vs. 1100 ppm			
		Obs.	Median-baseline (25th-75th percentile)	Median-change (25th-75th percentile)	Effect P* (d**)
Logical reasoning	Speed	20	7.0 (5.6-8.9)	1.2 (0.3-2.5)	**0.038*** (0.52)
	% Errors	20	23.2 (11.3-38.1)	-5.2 (-12.4--0.1)	**0.040*** (0.50)
	SpeedxErrors	20	5.7 (3.3-7.2)	1.5 (0-2.8)	**0.004*** (0.82)

*Wilcoxon signed-rank test: * if p≤0.05, † if 0.0
5<p≤0.10; **Cohen’s d: 0.2=small effect; 0.5=medium effect; 0.8=large effect

6.10.2 Association between classroom exposures and test performance

Data on the performance of the d2, multiplication, subtraction, and combined multiplication/subtraction tests were pooled with CO_2 concentrations and temperatures measured during the three different intervention periods. The purpose was to analyze potential associations between the classroom environment and pupil performance of these tests. Mean values were calculated from instantaneous recordings of the CO_2 concentration and temperature during the lesson when pupils completed a test and aligned with the corresponding test outcome. Figure 6.10.1 shows the association between the mean of the CO_2 concentration and the mean of the temperature during the lessons when pupils completed the d2-test. Although the association was not entirely significant (P=0.07, linear regression), there was a tendency that high mean CO_2 concentration and high mean temperature occurred in the same lessons. A similar association between the CO_2 concentration and temperature was found in all the intervention periods that were used in these analyses.

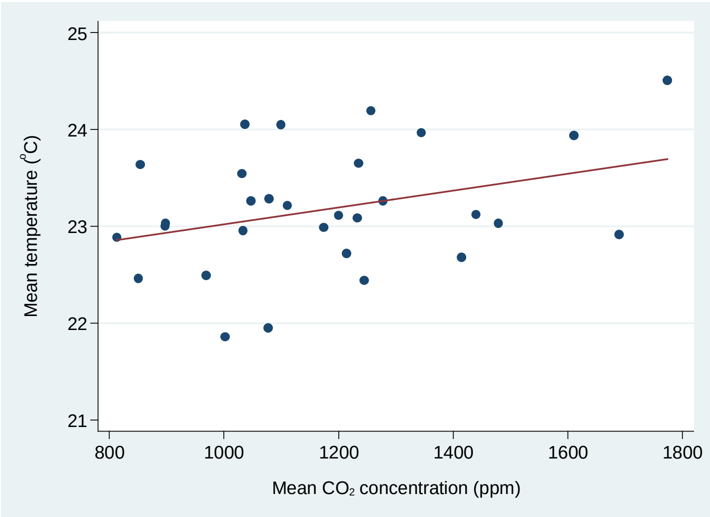


Figure 6.10.1. Association between the mean of the CO_2 concentration and the mean temperature during lessons when the d2 test was completed.

Figure 6.10.2 suggests that increasing CO_2 concentration or decreasing temperature resulted in decreased concentration performance measured with the d2 test. Table 6.10.14 confirms that the association was significant, although the direction of the temperature effect was not as could be expected.

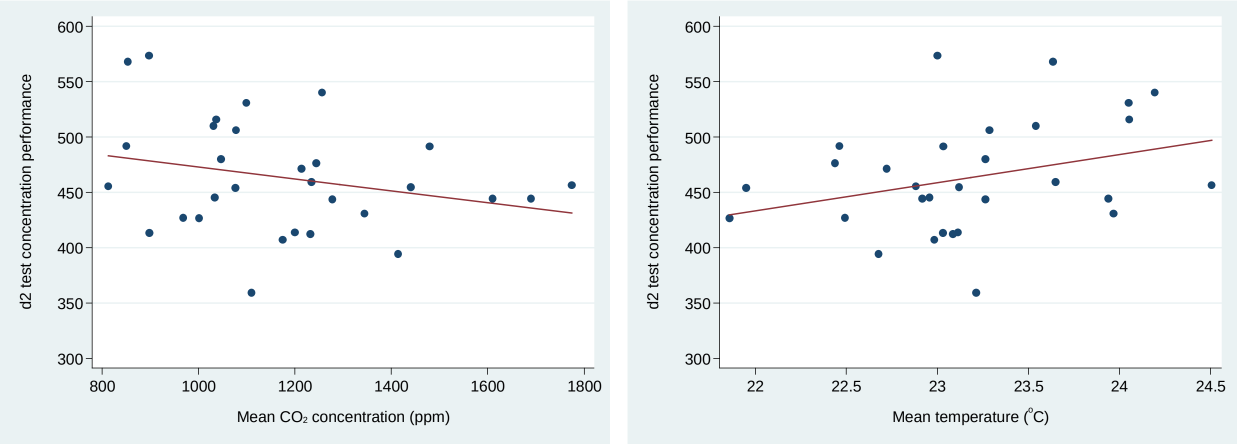


Figure 6.10.2. Association between the d2 concentration performance (mean for a class) and the mean CO_2 concentration (left) and mean temperature (right).

For the math test (combined multiplication and subtraction) applied during the non-heating season intervention in 2015 and the heating season intervention in 2016, Figure 6.10.3 and Figure 6.10.4 show associations between the speed and percent errors and the CO_2 concentration and temperature, respectively. With these tests, the scatter was smaller than with the d2 test. Although not significantly, the speed decreased and the error rate increased with increasing CO_2 concentration. The effect on test performance of the temperature was also non-significant. The simple linear regression in Figure 6.10.4 suggests that math speed decreased with increasing temperature, whereas the slope in Table 6.10.14 indicates the opposite association. However, the mixed effects analysis reported in Table 6.10.14 includes several other factors that were not accounted for in the simple linear regression in Figure 6.10.4.

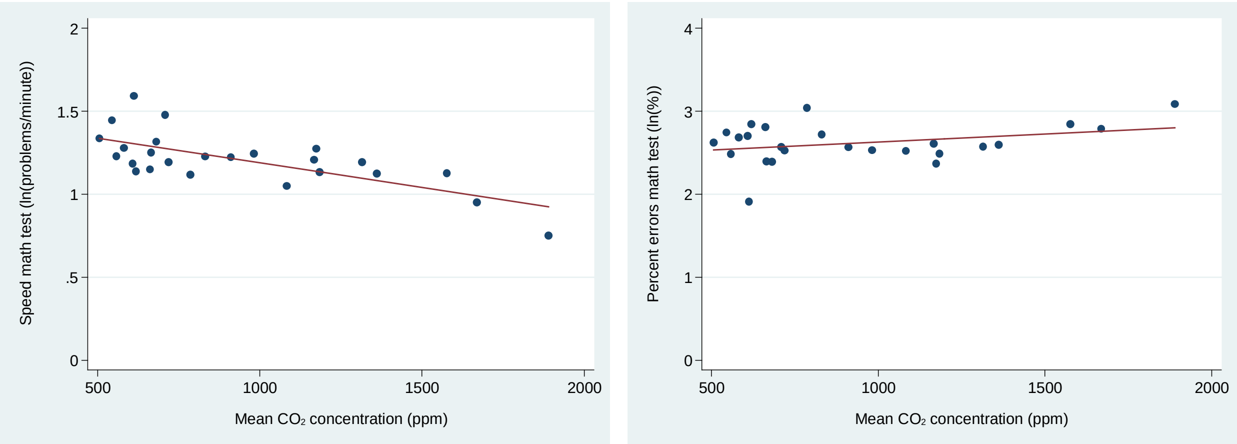


Figure 6.10.3. Association between the classroom CO_2 concentration and the speed (left) and percent errors (right) of the mathematics test.

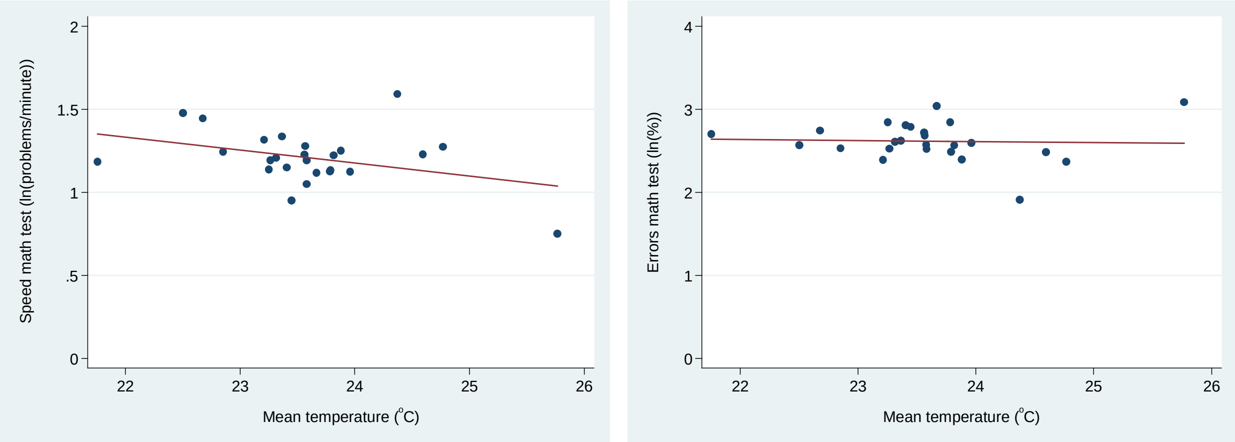


Figure 6.10.4. Association between the classroom temperature and the speed (left) and percent errors (right) of the mathematics test.

Table 6.10.14. Results of a linear mixed effects analysis of the association between performance outcomes and the CO_2 concentration and temperature. P-values and coefficients adjusted for pupil nested within class, for learning, and for differences in the sensitivity of the CO_2 concentration and temperature between pupils.

Performance metric	CO_2 concentration P-value Slope ± s.e.[1)]	Temperature P-value Slope ± s.e.	Data included in the analysis	N
d2 concentration performance	0.032 -0.009 ± 0.004	0.041 3.6 ± 1.7	Heating season 2015 Non-heating season 2016 Heating season 2016	1402
Subtraction speed[2)]	0.001 -0.0005 ± 0.0002	0.001 0.126 ± 0.038	Heating season 2014	288
Subtraction percent errors[2)]	0.579 0.00015 ± 0.0003	0.947 -0.005 ± 0.078	Heating season 2014	267
Multiplication speed[2)]	<0.001 -0.0091 ± 0.0002	0.116 0.141 ± 0.090	Heating season 2014	193
Multiplication percent errors[2)]	0.489 -0.00035 ± 0.0005	0.181 0.306 ± 0.228	Heating season 2014	171
Math speed[2)]	0.192 -0.000069 ± 0.00005	0.819 0.003 ± 0.017	Non-heating season 2015 Heating season 2016	776
Math percent errors[2)]	0.699 0.000042 ± 0.00011	0.093 -0.062 ± 0.037	Non-heating season 2015 Heating season 2016	707

1) Standard error of estimate
2) Analysis used logarithmic values of the performance metric

Table 6.10.14 summarizes the results of a linear mixed effects analysis of the association between the classroom CO_2 concentration and temperature and the performance outcomes of the d2 and mathematical tests. The effect of the CO_2 concentration and temperature was not consistent across tests, but the d2 concentration performance, the subtraction speed, and the multiplication speed decreased significantly with increasing CO_2 concentration. Surprisingly, the d2 concentration performance and the subtraction speed increased significantly with the temperature, which could be a result of the somewhat narrow temperature range that was measured during the lessons when the tests were completed. The error rate did not depend significantly on the CO_2 concentration or the temperature.

6.11 Energy use

Based on hourly measurements of the energy use during two full calendar years (2015 and 2016), Figure 6.11.1 compares the electricity and the heating energy use in classrooms S3, S4, and S5, averaged for the two years and normalized by the classroom area. In classroom S3, the heating energy use included both the radiators and convectors and the heating coil in the decentralized mechanical ventilation system; in classrooms S4 and S5, it included only radiators and convectors. No measurement of energy use was made in classrooms S7 and S8. Auxiliary electricity use (computer for central management of all systems, wiring closet, etc.) is not included in the values presented in Figure 6.11.1.

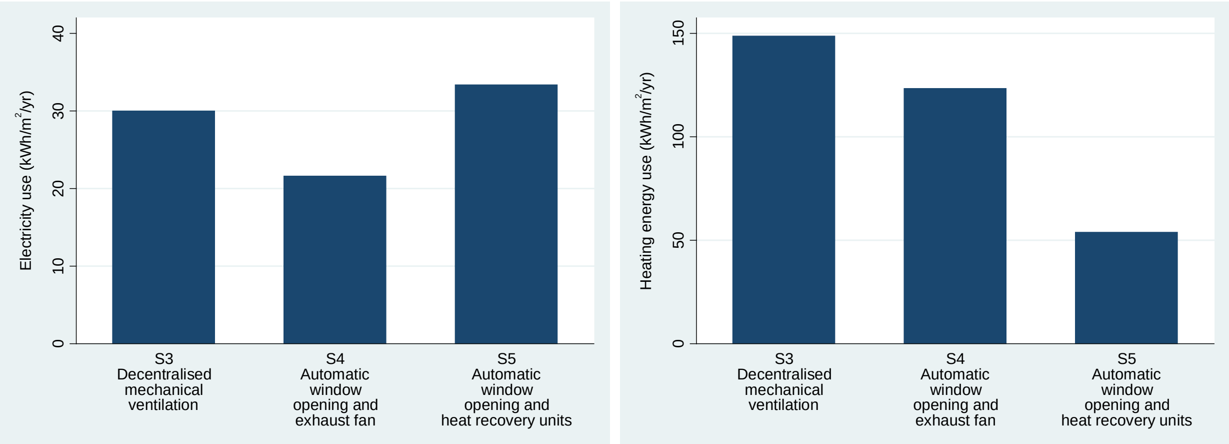


Figure 6.11.1. Yearly electricity (left) and heating energy use (right) based on measurements made during 2015 and 2016.

The average heating energy use was highest in classroom S3 with the decentralized mechanical ventilation system followed by classroom S4 with automatic window opening and an exhaust fan. In classroom S5 with automatic window opening and heat recovery units, the heating energy use was around 30% of that in classroom S3 with decentralized ventilation.

Figure 6.11.2 compares the monthly electricity and total heating energy use between classrooms S3, S4, and S5. Although the school was closed in July and the first part of August, the electricity use seemed to be highest in classroom S3 during the summer period, whereas in classrooms S4 and S5, the electricity use increased during the colder months. The heating energy use followed clearly the outdoor temperature in all three rooms.

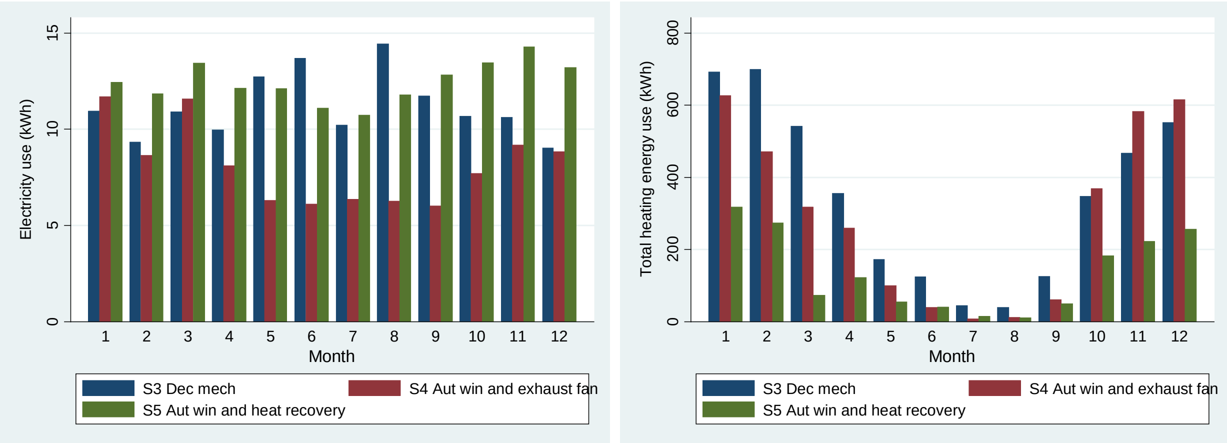


Figure 6.11.2. Monthly variation of the electricity use (left) and total heating energy use (right) determined as an average per month for 2015 and 2016.

Figure 6.11.3 shows that the CO_2 concentration was rarely above 1000 ppm during the occupied hours in classroom S3 and S4 when the system control was activated during the heating season. In comparison, the CO_2 concentration measured in classroom S5 was higher than 1000 ppm for around 25% of the occupied time. Thus, there was a clear trade-off between the heating energy consumption and the better air quality achieved by a higher air change rate in classroom S3 and S4 as compared with classroom S5. The decentralized mechanical ventilation system was equipped with a counter-current heat recovery unit, but this seemed to have had only minor influence on the heating energy consumption in classroom S3 as compared with classroom S4 with nearly the same air quality.

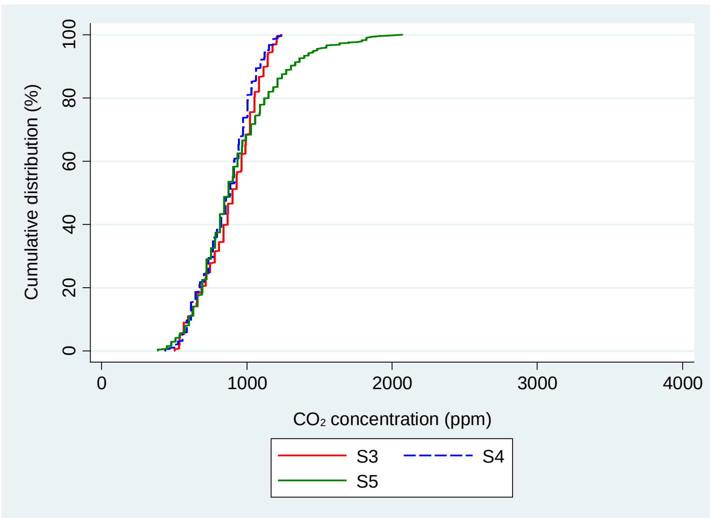


Figure 6.11.3. Cumulative distribution of the CO_2 concentration measured during the occupied lessons, cumulated for the three weeks with activated system control in the heating season.

Based on simple linear regression, Figure 6.11.4 compares the association between the monthly mean outdoor temperature and the monthly heating energy use. The figure also shows the slope of the regression line, which expresses the change in heating energy use per unit change in outdoor temperature. Figure 6.11.4 confirms that the heat recovery units in the decentralized mechanical ventilation system did not result in a heating energy consumption that was less dependent on the outdoor temperature than with automatic window opening and an exhaust fan.

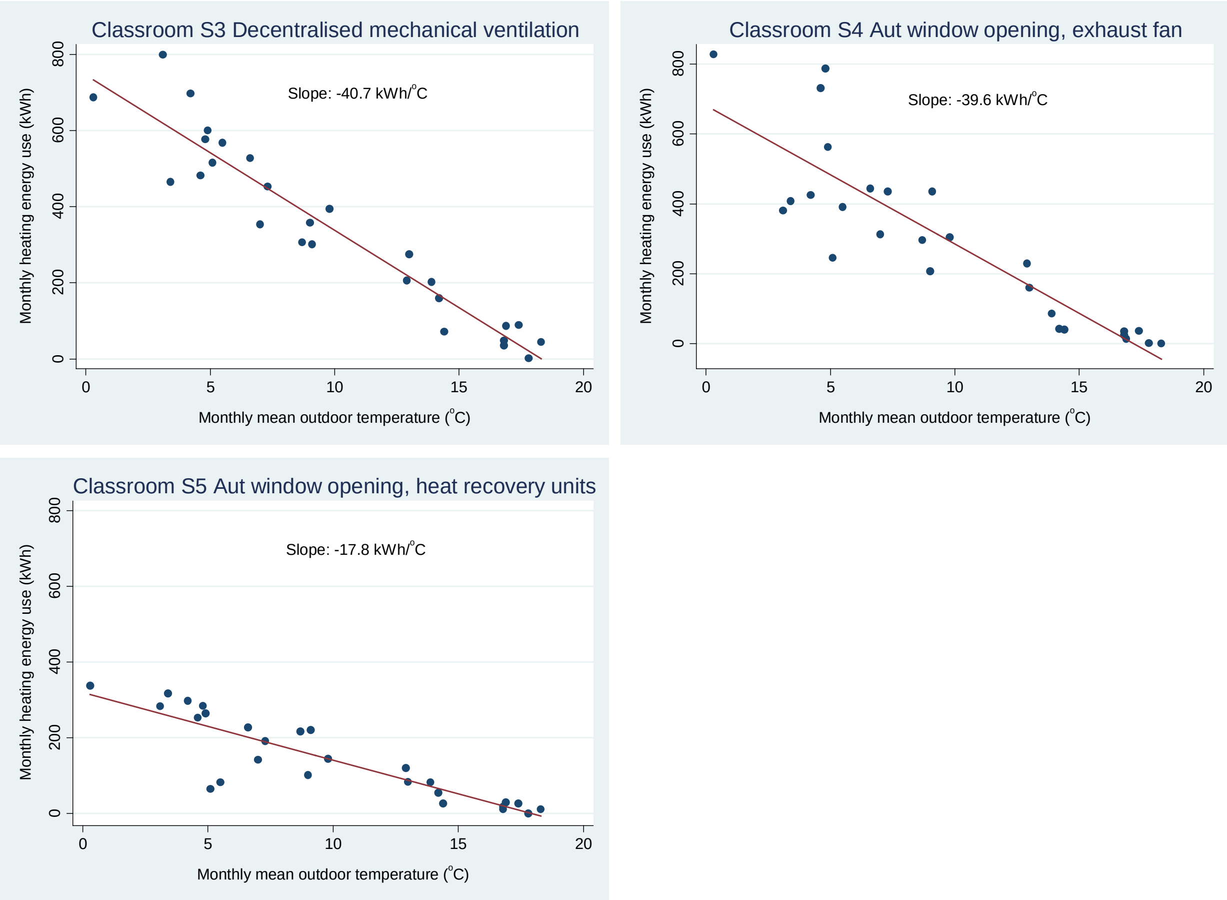


Figure 6.11.4. Association between monthly mean temperature and monthly heating energy use in S3 (top left), S4 (top right), and S5 (bottom). The period ranges from October 2014 to December 2016.

6.12 Investigation of the performance of the retrofit solutions in different climates

Table 6.12.1 and Table 6.12.2 show the simulated energy use (without cooling) and parameters indicating the quality of the indoor environment in the classrooms when the windows were opened manually or not when the retrofit solutions were activated. The minimum and the maximum accumulated number of hours with CO_2 concentrations higher than 1000 ppm or temperatures higher than 26°C indicate the range between classrooms in the south wing at which these conditions were likely to occur. The visual display unit with feedback on the classroom CO_2 concentration was not simulated as this solution would depend on the definition of the window and door opening behavior and not on the system performance. Instead, the reference classroom is included for comparison with the classrooms with dedicated ventilation systems.

Except for the retrofit solutions with automatic window opening and heat recovery units, the simulated energy use was considerably lower than the measured. The reasons for these differences were not investigated because the simulations were made mainly to show the relative impact of different climates. The influence of the outdoor climate on the simulation outcome was mostly visible when Copenhagen and Chicago were compared with New York and Los Angeles, where the heating energy use was considerably smaller due to the warm summers at these locations.

When windows were not opened manually, both the number of hours with high temperature and high CO_2 concentration were exceptionally high in the reference classroom, regardless of the location, as expected. All the retrofit solutions and in particular the decentralized and centralized mechanical systems provided better air quality than both systems with automatic window opening. Since no mechanical cooling was available and solar shading comprised only internal curtains, the number of hours with overheating was particularly high in Los Angeles.

When windows could be opened manually, which may occur also after installation of the retrofits, the indoor environment conditions improved in case of all retrofit solutions, but at the expense of an increased energy use. Being able to open windows manually improved both the thermal conditions and the air quality in Los Angeles in comparison with the condition when they were closed all the time. In Los Angeles, the heating energy use was less than 10% of that in Copenhagen and Chicago.

Table 6.12.1. Simulated energy use and indoor environment in classrooms where windows could not be opened manually for the school building located in Copenhagen, New York, Chicago, and Los Angeles. All numbers are averages/counts for a full year. Energy use is averaged both for the whole building including common areas and for the classrooms alone excluding the common areas.

		Heating energy use		Electricity use		Max no. hours	Min no. hours	Max no. hours	Min no. hours
		South wing (kWh/m^2)	Classroom (kWh/m^2)	South wing (kWh/m^2)	Classroom (kWh/m^2)	t > 26°C	t > 26°C	CO_2 > 1000 ppm	CO_2 > 1000 ppm
Copenhagen	Reference	52.9	43.1	0	0	2320	872	6010	5060
	Decentralized mechanical	58.4	54.4	1.4	3.1	1490	512	128	0
	Automatic window opening and exhaust fan	70.1	63.7	0.9	2	1550	529	662	136
	Automatic window opening and heat recovery units	60.2	52.7	0.4	0.9	1590	505	576	231
	Centralized mechanical	57.1	51.1	2.4	5.3	1540	638	117	0
New York	Reference	33.5	27	0	0	3890	3630	5720	4520
	Decentralized mechanical	37.7	36	1.4	3.1	3270	2790	67	0
	Automatic window opening and exhaust fan	46.3	42	0.9	2	3320	2860	708	254
	Automatic window opening and heat recovery units	38.3	33.8	0.4	0.9	3330	2810	627	342
	Centralized mechanical	36.8	33.6	2.4	5.3	3320	2810	61	0
Chicago	Reference	45.9	39.2	0	0	3590	2990	6310	5500
	Decentralized mechanical	51.9	52	1.4	3.1	3150	2580	108	0
	Automatic window opening and exhaust fan	62.2	59	1	2.2	3170	2640	750	346
	Automatic window opening and heat recovery units	52	47.7	0.4	0.9	3190	2610	694	382
	Centralized mechanical	51.1	49.8	2.4	5.3	3160	2590	95	0
Los Angeles	Reference	1.2	0.5	0	0	6650	5600	7070	6290
	Decentralized mechanical	2.5	3	1.4	3.1	4870	3460	150	0
	Automatic window opening and exhaust fan	2.1	0.9	1	2.2	5130	3980	794	446
	Automatic window opening and heat recovery units	1.5	0.7	0.4	0.9	5170	3920	838	462
	Centralized mechanical	1.5	0.7	2.5	5.5	4990	3570	142	0

Table 6.12.2. Simulated energy use and indoor environment with manual window opening in addition to the controlled systems and the school building located in Copenhagen, New York, Chicago, and Los Angeles. All numbers are averages/counts for a full year. Energy use is averaged both for the whole building including common areas and for the classrooms excluding the common areas.

		Heating energy use		Electricity use		Max no.	Min no.	Max no. hours	Min no. hours
		South wing (kWh/m^2)	Classroom (kWh/m^2)	South wing (kWh/m^2)	Classroom (kWh/m^2)	hours $t > 26^oC$	hours $t > 26^oC$	CO_2 > 1000 ppm	CO_2 > 1000 ppm
Copenhagen	Reference	67	54	0	0	67	10	2180	1520
	Decentralized mechanical	79	77.3	0.9	2	52	13	0	0
	Automatic window opening and exhaust fan	77.9	68.9	0.7	1.5	64	13	352	84
	Automatic window opening and heat recovery units	71	60.7	0.4	0.9	61	13	140	58
	Centralized mechanical	70.9	61	1.8	4	50	14	0	0
New York	Reference	44	37	0	0	1230	970	1280	870
	Decentralized mechanical	53	55.9	0.7	1.5	1040	882	0	0
	Automatic window opening and exhaust fan	51.7	46.8	0.5	1.1	1100	904	247	82
	Automatic window opening and heat recovery units	46.4	41.2	0.3	0.7	1100	905	93	47
	Centralized mechanical	47	42.8	1.5	3.3	1040	881	1	0
Chicago	Reference	58	50.8	0	0	944	746	1690	1170
	Decentralized mechanical	69	73.4	0.8	1.8	829	718	0	0
	Automatic window opening and exhaust fan	68.9	65	0.6	1.3	863	770	320	139
	Automatic window opening and heat recovery units	61.4	56.3	0.4	0.9	862	730	177	89
	Centralized mechanical	62.9	60.5	1.6	3.5	826	714	0	0
Los Angeles	Reference	5.1	3.6	0	0	280	46	505	159
	Decentralized mechanical	8.7	11.1	0.5	1.1	153	34	0	0
	Automatic window opening and exhaust fan	5.7	4.3	0.2	0.4	227	36	17	4
	Automatic window opening and heat recovery units	5.6	4.3	0.3	0.7	191	36	1	0
	Centralized mechanical	5.8	4.5	1	2.2	139	34	0	0

6.13 Influence of user behavior on the classroom environment and energy use

6.13.1 CO_2 concentration – calibration of the model

For each intervention classroom, Figure 6.13.1 compares the calibrated simulation model with the measurements of the classroom CO_2 concentration recorded during week 3 of the period from January 7, 2015 to February 2, 2015.

In classroom S3 with the decentralized mechanical system, the simulated CO_2 concentration rarely exceeded 1000 ppm, although some events with higher concentration occurred during this week.

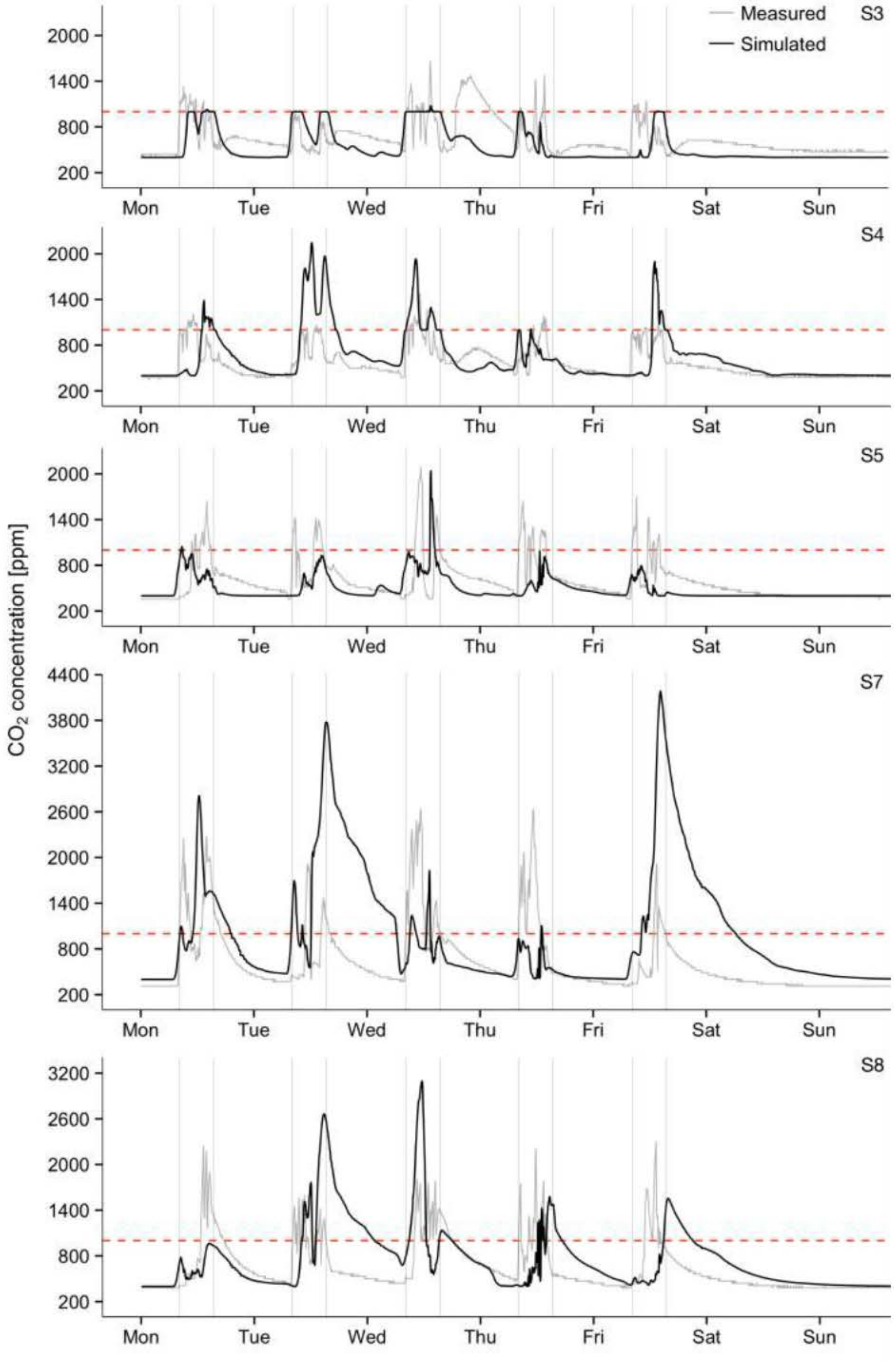


Figure 6.13.1. Measured and simulated CO_2 concentration in the intervention classrooms in week 3 (8:00 and 15:00 hrs are shown with vertical lines).

In S4 with automatic window control and an exhaust fan, the simulated CO_2 concentration reached more than 1800 ppm during most of the school days, indicating that the simulated ventilation flowrate was lower than the actual. In S5 with automatic window control and heat recovery units, the simulated CO_2 concentration was generally lower than the measured in classroom S7 (reference), the simulated CO_2 concentration reached high levels between 3800 ppm and 4300 ppm on some days, whereas the maximum measured CO_2 concentration was much lower (approximately 1800 ppm) on these days. In S8 with the visual feedback unit, the simulated CO_2 concentration reached levels considerably higher than the measured on Tuesday and Wednesday, but the correspondence was better on the other days. Overall, the comparison shows that it was difficult with a systematic and deterministic definition of occupant schedules and behaviors to match the measured CO_2 concentration, which depends on the occupants often random behavioral pattern.

Figure 6.13.2 shows the distribution of the measured and simulated CO_2 concentrations during the occupied time of the model calibration period. The simulated CO_2 concentration rarely deviated from the setpoint in classroom S3 with decentralized ventilation. The median CO_2 concentration in the classrooms with automatic window control was approximately 400 ppm higher and 200 ppm lower than the measured in classroom S4 with the exhaust fan and classroom S5 with heat recovery units, respectively. This confirms the concentration profiles shown in Figure 6.13.1. The large number of outliers in classrooms S7 and S8 corresponded well with the large variation of the simulated CO_2 concentration in these rooms as shown in Figure 6.13.1.

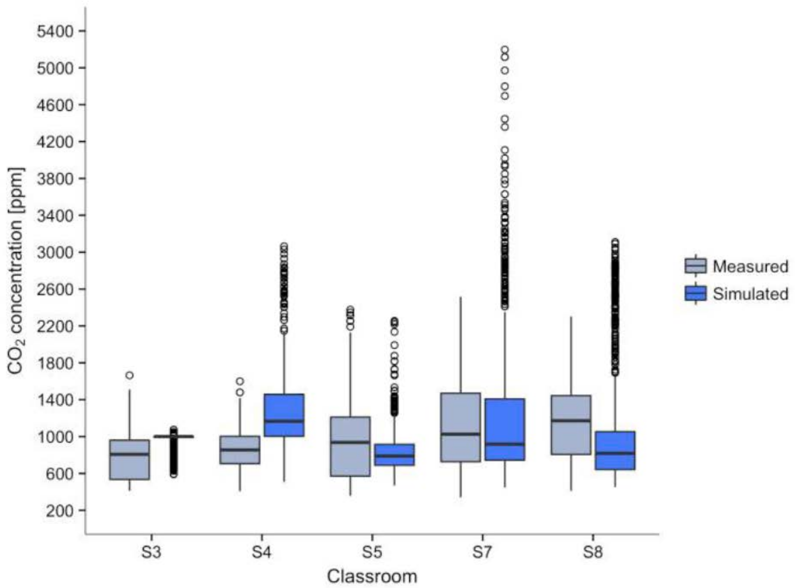


Figure 6.13.2. Boxplot of the measured and simulated CO_2 concentration during the occupied time of the calibration period.

Classroom temperature – calibration of the model

Figure 6.13.3 shows simulated and measured temperature profiles in classrooms S3, S4, and S5 during a school day in January along with the periods when windows were scheduled to be open in the simulations. Shaded areas indicate the number of windows open simultaneously.

The simulated temperature did not fluctuate in the same way in classroom S4 with automatic window opening and an exhaust fan as in classroom S3 with decentralized mechanical ventilation and in classroom S5 with automatic window opening and heat recovery units. In classroom S5 an event with several windows open during the afternoon clearly affected the simulated, but not the measured temperature.

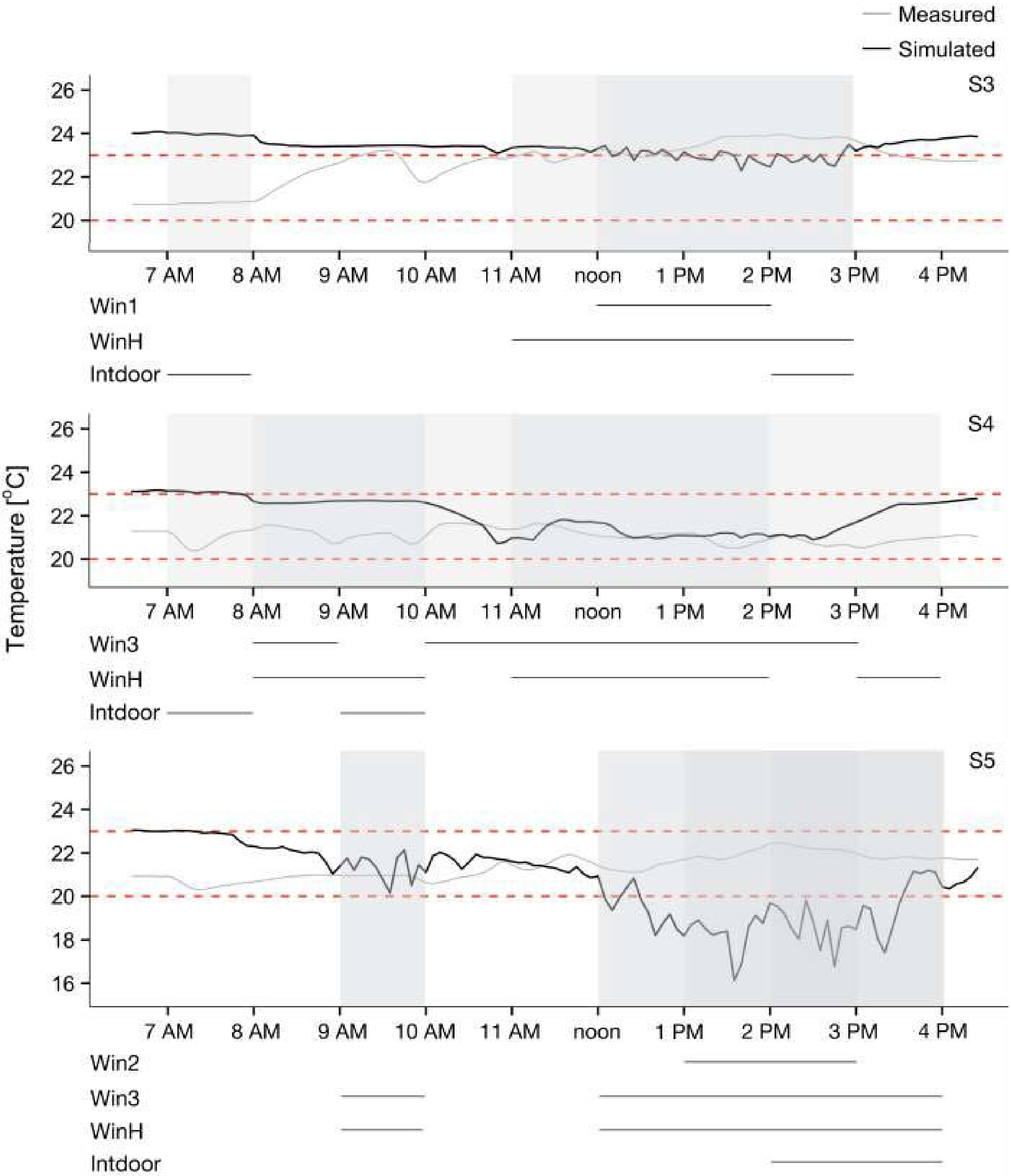


Figure 6.13.3. Temperature and open windows and doors in classrooms S3 and S4 on January 14th and in S5 on January 12th. Red dotted lines indicate the heating season comfort temperature interval.

Figure 6.13.4 shows that only the doors were opened during the 16th January in classroom S7. The simulated temperature decreased 2-3°C during the period when the doors were open. In classroom S8, the simulated temperature decreased approximately 10°C between 8:00 and 9:30 with both doors and one window open. The simulated temperature decreased 5°C around noon as the overhead window was opened. In general, the simulated temperature seemed much more affected by window and door opening events than the measured temperature.

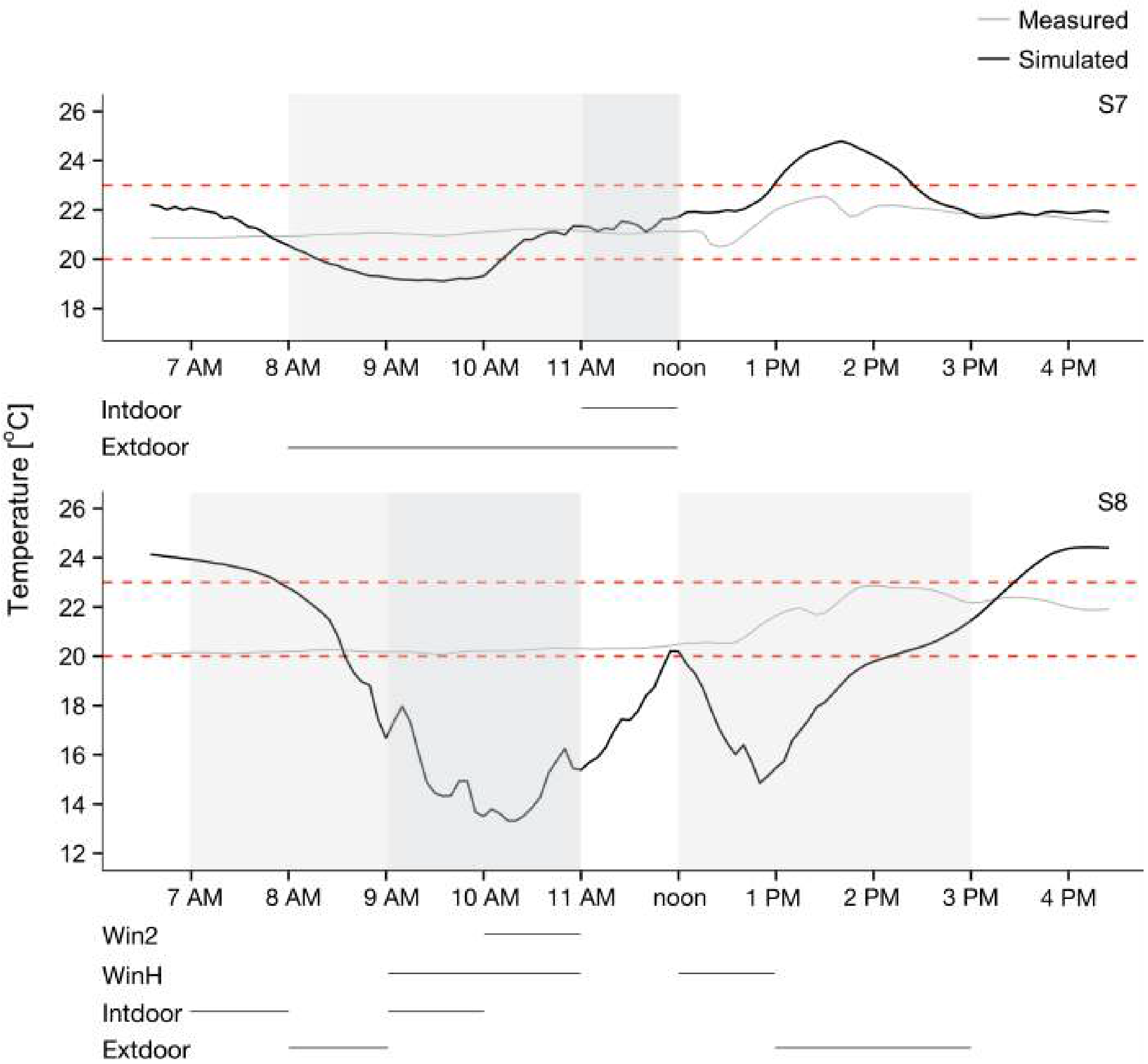


Figure 6.13.4. Temperature and open windows and doors in classroom S7 on January 16th and in S8 on January 12th.

Figure 6.13.5 shows that the median of simulated temperatures was quite similar to the median of the measured temperatures in the classrooms with dedicated ventilation systems. In classrooms S7 and S8 the median of the simulated temperature was approximately 2°C and 6°C below the median of the measured temperatures, respectively. In classrooms S3, S4, S5 and S7, there was a large number of outliers in the simulated temperatures compared with the measurements, which

corresponds well with the rapid decrease in the simulated temperature observed in the temperature profiles in
Figure 6.13.3 and Figure 6.13.4.

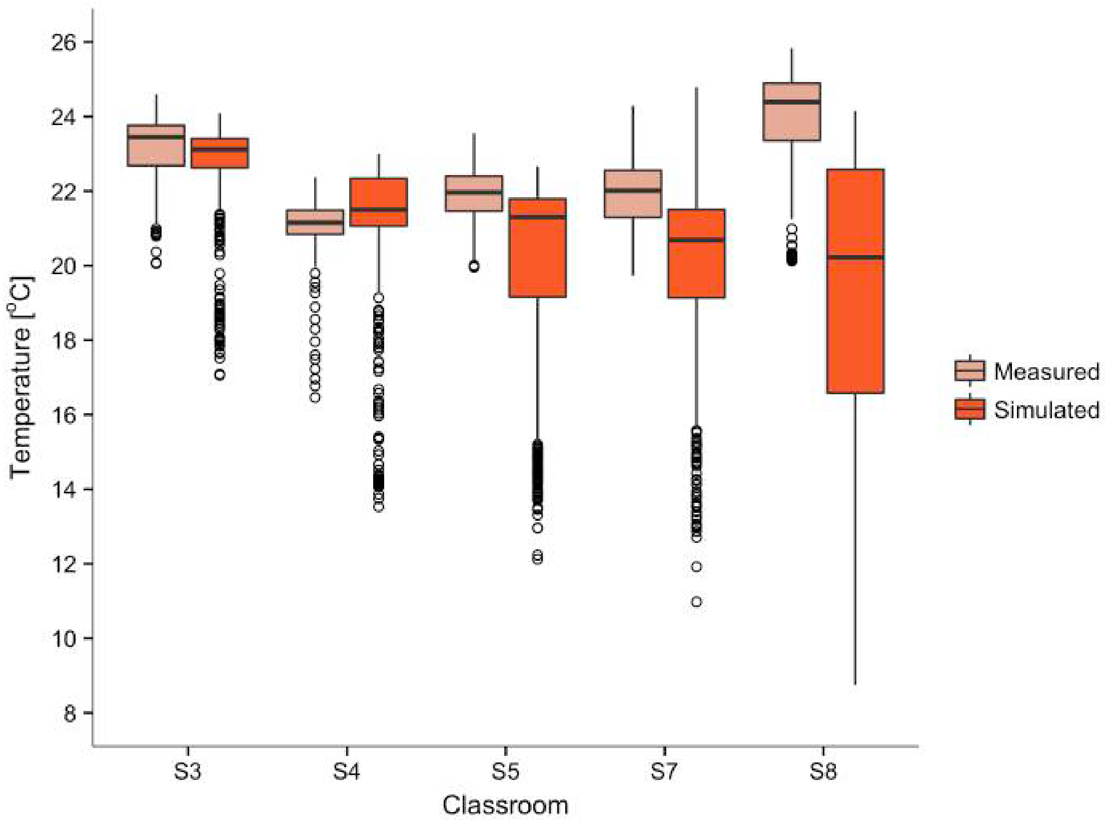


Figure 6.13.5. Boxplot of the measured and simulated temperature during the occupied time of the calibration period.

6.13.2 Annual performance

This section presents the results of annual simulations of the CO_2 concentration, temperature, and energy use.

6.13.2.1 CO_2 concentration

Figure 6.13.6 shows the distribution of the simulated CO_2 concentration in the occupied time in each month of the school year. As could be expected, the median CO_2 concentration was generally lower in all the classrooms in the simulation of the best-case behavior. In classroom S3, the worst-case behavior resulted in a median CO_2 concentration corresponding with the calibration settings. In the classrooms with automatic window control (classrooms S4 and S5), the median CO_2 concentration was approximately the same in the simulation of the worst-case and the best-case behavior, most likely because most of the windows in these classrooms were automatically controlled and the window settings thus were identical in the simulations of both behavior patterns. Generally, the CO_2 concentration did not vary considerably during the school year in any of the simulations, except in the simulation with calibration settings in classroom S5.

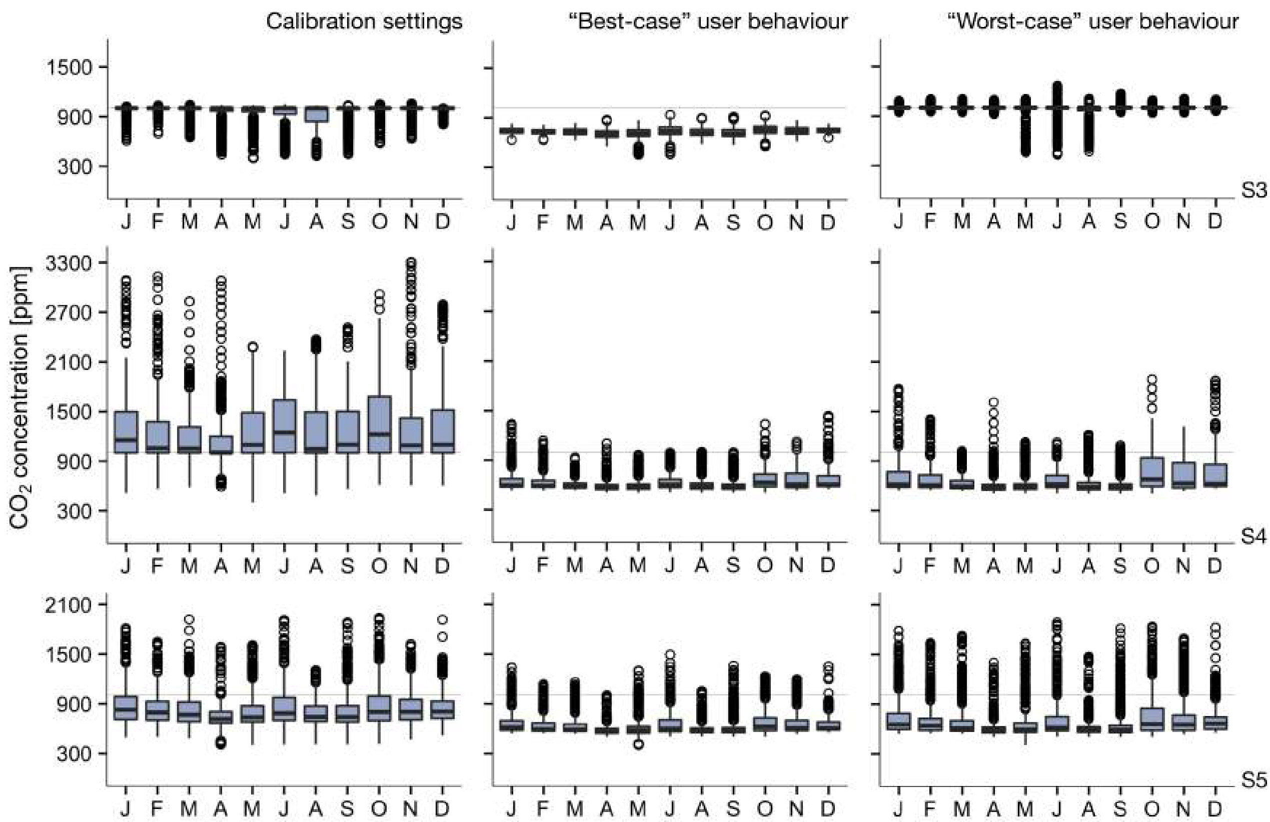


Figure 6.13.6. Boxplots of the CO_2 concentration in the occupied time (July not included) in the annual simulations of classrooms S3, S4 and S5.

Figure 6.13.7 shows that in classrooms S7 and S8 without dedicated ventilation systems where windows were only opened manually , the effect of the occupant behavior pattern was much more pronounced than in the other classrooms with automatic control of the ventilation. Surprisingly, the median CO_2 concentration was generally higher in the non-heating season compared to the heating season; this was not corresponding with the measurements. In the simulation of the worst-case behavior, the windows were set to open only when the outdoor temperature was above 19°C and therefore the CO_2 concentration was expected to be lower during the non-heating season compared to the heating season. Possibly, the calculation of the driving forces for natural ventilation that were smaller during the non-heating season compared with the heating season could be the reason for this unrealistic simulation result.

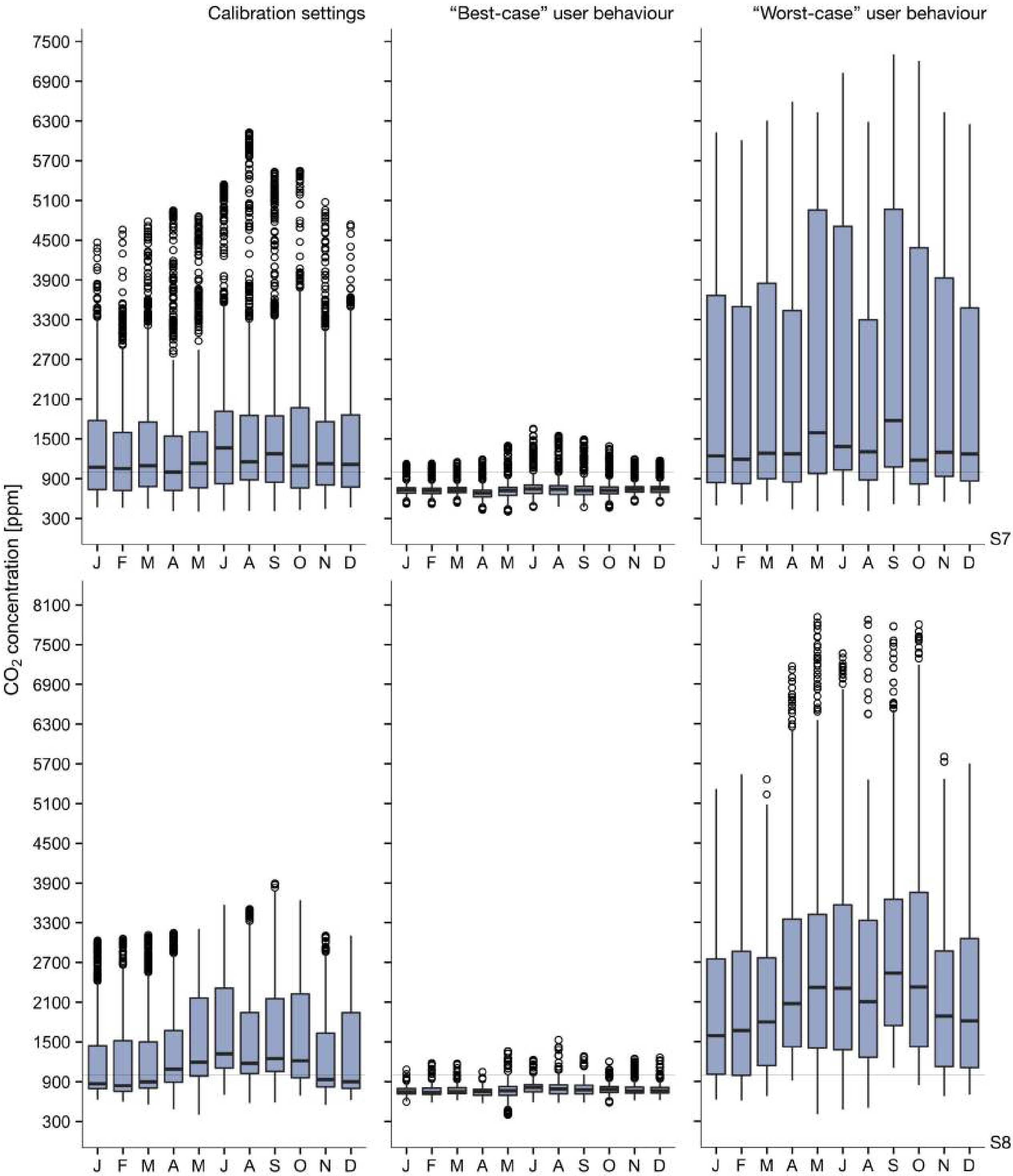


Figure 6.13.7. Boxplots of the CO_2 concentration in the occupied periods (July not included) in the annual simulations of conditions in classrooms S7 and S8.

6.13.2.2 Temperature

Figure 6.13.8 shows the distribution of the simulated temperatures in classrooms S3, S4, and S5 during the occupied periods in each month of the school year.

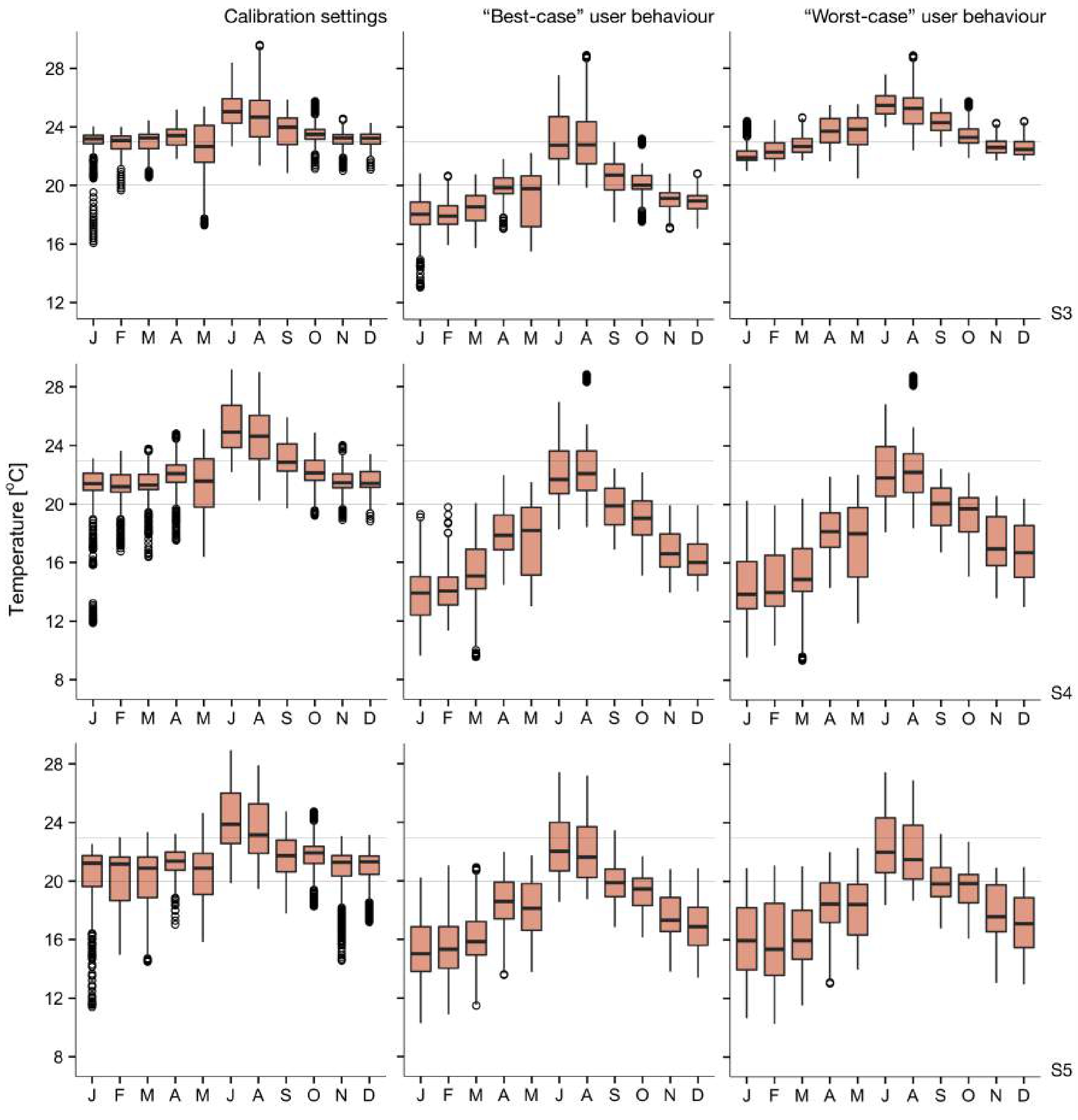


Figure 6.13.8. Boxplots of the temperature during the occupied time (July not included) in the annual simulations of classroom S3, S4 and S5.

In all annual simulations, the classroom temperature followed the outdoor conditions, although more so in classrooms S4 and S5 with automatic window opening. In the best-case and worst-case scenarios, temperatures were very low during most of the heating season and parts of the non-heating season due to the window control settings that used the CO_2 concentration as input. However, the more realistic calibration scenario resulted in a different temperature distribution that was closer in these rooms to the actually measured temperatures.

Figure 6.13.9 shows that in classrooms S7 and S8 without dedicated ventilation systems the temperatures were rather similar for each of the annual simulations. In addition, the median temperature was too high in June and August in the simulation with calibration settings in both classrooms.

In all classrooms, the best-case behavior resulted in too large variation in the temperature throughout the year and the temperatures were too low during most of the year. This was caused by the increased proportion of time with open windows to facilitate a low CO_2 concentration. The worst-case behavior resulted in too high temperatures during the non-heating season, especially in the classrooms without automatic window control.

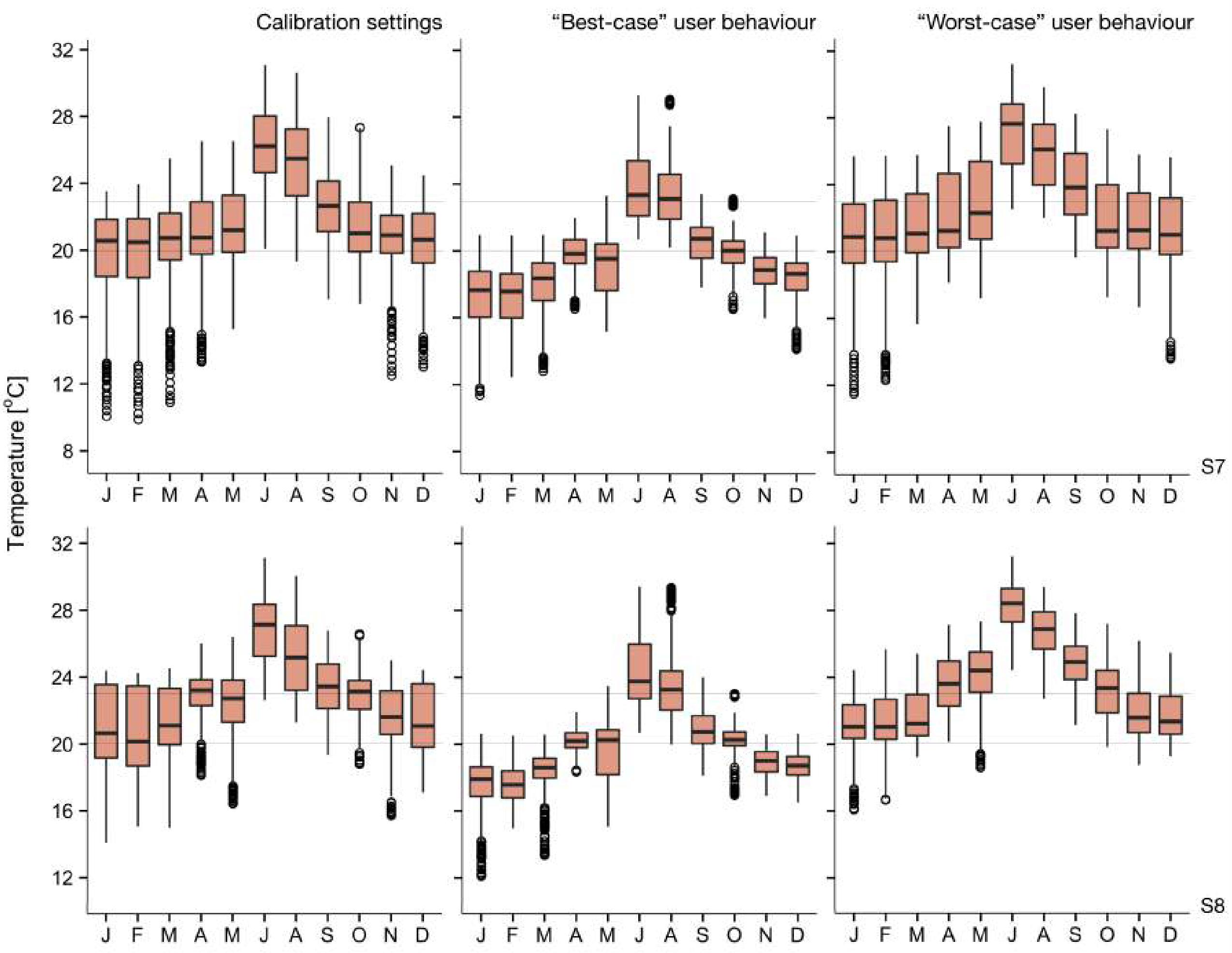


Figure 6.13.9. Boxplots of the temperatures in the occupied time (July not included) in the annual simulations of S7 and S8.

6.13.2.3 Energy use for ventilation and space heating

Table 6.13.1 shows the heating and electricity energy use of each of the annual simulations and compares these with the energy use measured during 2015 and 2016. In general, the measured energy use was considerably lower than the simulated for all systems, but in particular in the classroom with automatically controlled windows and heat recovery units. In this classroom, the simulated heating energy use was approximately three times higher than the measured. In the other two classrooms, the difference between the simulated and measured heating energy use was considerably smaller, when compared with the calibration setting or the best-case behavior. The simulated electricity use was generally much lower than the measured.

The heating energy use increased in most of the classrooms in the simulation of best-case behavior as compared with the calibration settings and worst-case behavior, since the windows were opened more frequently and for longer durations. The classrooms without automatically controlled windows (S3, S7 and S8) had the lowest space heating energy use in the simulation of worst-case behavior, since the windows in these classrooms were rarely opened.

Table 6.13.1. Annual electricity and heating energy use simulated for the retrofitted systems and the reference classroom. The measured energy use is included for comparison (mean for 2015 and 2016).

System		Decentralized mechanical ventilation	Automatic window opening and exhaust fan	Automatic window opening and heat recovery units	Reference	Visual display unit
Calibration settings	Electricity (kWh/(m^2 yr))	13	8	5	0	0
	Heating (kWh/(m^2 yr))	119	145	135	103	142
Best-case	Electricity (kWh/(m^2 yr))	8	5	3	0	0
	Heating (kWh/(m^2 yr))	123	152	148	134	148
Worst-case	Electricity (kWh/(m^2 yr))	15	5	5	0	0
	Heating (kWh/(m^2 yr))	60	169	164	86	91
Measured	Electricity (kWh/(m^2 yr))	30	21.6	33.4	-	-
	Heating (kWh/(m^2 yr))	148.7	123.4	53.9	-	-

6.14 Product, installation, and maintenance costs

Table 6.14.1 shows the estimated costs for product purchase, installation, and annual maintenance. The costs are without taxes and apply for retrofitting of a single classroom. No installation costs were included with the visual feedback device, since the Learn-O-Meter could be placed on a desk or hung on a nail on the wall.

Table 6.14.1. Estimated product, installation, and maintenance costs for the different retrofit solutions.

Room	Retrofit solution	Product cost [DKK (USD)]	Installation cost [DKK (USD)]	Maintenance cost [DKK (USD)]	Documentation in Appendix
S3	Decentralized mechanical ventilation	51790 (7463*)	7400 (1066)	814 (117)	G.1
S4	Automatic window control and exhaust fan	30000 (4322)	12000 (1729)	750 (108)	G.2
S5	Automatic window control and heat recovery units	40000 (5763)	17000 (2450)	750 (108)	G.2
S8	Visual feedback device	1.500 (216)	0	0	G.3

* With an exchange rate of 6.94 DKK/USD (20 April 2017)

The annual maintenance costs were quite similar in the case of the solutions with dedicated ventilation systems. The cost estimate for the decentralized ventilation system was based on the actual tender suggested to Ravnsholtskolen. The costs for the automatic window control and heat recovery units applied to the standard solution including six heat recovery units, the control system, and initial adjustment. Therefore, the costs of this solution did not match entirely the solution that was actually installed in classroom S5, but it was a very similar solution.

7 Discusssion

This study was first and foremost undertaken to evaluate the performance of different systems used to retrofit classroom ventilation during both the heating and non-heating seasons. Performance was evaluated by the classroom environment, including CO_2 concentration, temperature, and noise, the effect on pupils' perceptions of the classroom environment, their symptoms and learning performance, and the system energy use.

The retrofitted ventilation systems were installed and operated as they would be in any given school subject to a similar retrofit. This means that no special efforts were made to optimize the systems or achieve well-defined exposures in the classroom, as e.g. in the study by Wyon and Wargocki (2008). In their study, the contrasts in environmental conditions were included in the experimental design and carefully controlled, whereas in this study, focus was on the retrofit itself. The experimental design was therefore based merely on activated or idled control of the systems, which resulted in conditions during the two operation modes, which did not always facilitate clear and unambiguous findings. The measurements and observations therefore reflect the variation in indoor environment, occupant responses and behavior, and energy use that can be expected in any school with similar retrofits, when they are located in temperate climates, during the heating and non-heating seasons.

7.1 Ranking of retrofit solutions 1 to 5

Table 7.1.1 ranks the systems tested in the intervention studies at Ravnsholtskolen according to each of the listed performance metrics on a scale from 1 to 5; 1 for the best and 5 for the worst performance. Product, installation, and maintenance costs were not included in the ranking as this parameter is not associated with the performance of a system. No systematic difference between the systems was found for the temperature, noise, pupil perceptions or symptoms, and these parameters were therefore ranked equally between the systems. Details of the ranking of pupil performance are included in Appendix J.

With equal weighting of the different performance metrics, the decentralized system scored best, the system with automatic window opening and an exhaust fan scored second best, and third came the system with automatic window opening and heat recovery units. These systems were able to sustain a lower CO_2 concentration during a major part of the occupied time and although differences in pupil performance between retrofit systems were modest, these systems improved most consistently the performance of tasks requiring logical thinking, concentration and attention. The high performance of these systems was to some degree penalized by their higher energy use, which was not the case for the other retrofits. Energy use was only measured with three of the systems, but based on the distribution of the CO_2 concentration measured in the classrooms with manual window opening or the visual display unit it was assumed that energy use in these rooms would be comparable and lower than in the other rooms.

Table 7.1.1. Ranking of the retrofit solutions according to their performance evaluated by classroom environment parameters, pupil's perceptions and performance, and energy use.

System	CO_2	Temp.	Noise	Percept.	Sympt.	Performance	Energy	∑
Decentralized mechanical ventilation	1	-	-	-	-	1	5	7
Automatic window opening and exhaust fan	2	-	-	-	-	2	4	8
Automatic window opening and heat recovery units	3	-	-	-	-	3	3	9
Automatic window opening	4	-	-	-	-	5	1.5	10.5
Visual display unit	5	-	-	-	-	4	1.5	10.5

Obviously, the overall ranking was very sensitive to the weighting applied to each parameter as well as to the scoring itself. There is an infinite number of alternatives and the simplest scheme was selected, as each parameter in Table 7.1.1 was considered equally important. Yet, regardless of the detailed ranking, the findings of the intervention studies indicate that some means of mechanically supported system may be required to ventilate efficiently classrooms in moderate climates due to their generally high occupant density and the occupants' low motivation to open windows and doors when needed. The measurements during the heating season showed that manual opening of windows rarely took place unless the pupils were triggered to do so. Even with the visual display unit in the classroom urging the pupils and the teacher to open windows and doors when the CO_2 concentration was high, the median concentration remained higher than 1000 ppm. Therefore, manual opening of windows can be considered as less reliable to improve the classroom air quality compared with retrofits that allow automatic control of ventilation.

The school where the interventions were carried out was adjacent to a residential area on one side and a forest on the other. Thus, no obvious sources of outdoor air pollution were identified. During a few of the many visits that were paid to the school, but not systematically, the concentration of ultrafine particles were measured in the classrooms. These measurements generally showed levels corresponding with very clean outdoor air, which did not cause concerns for the indoor air quality in the school classrooms. At other locations, traffic, industry or energy production may cause higher outdoor pollution levels that need to be taken into account when selecting the most appropriate ventilation retrofit solution.

7.2 Sorbent type gas-phase air cleaner

The system with the sorption air cleaner that was tested in a classroom at the Technical University of Denmark was not included in the ranking, as the technology does not yet seem to be ready for practical application. Nevertheless, operation of the sorption air cleaner resulted in improved performance of the logical reasoning test. No changes in the reported intensity of symptoms were seen, except for the perceived dryness of the air. The students also reported that they put more effort into performing the task and that they felt slightly cooler. The air quality and odor intensity assessed by the students did not change with different operation modes of the air cleaner. The assessments of air quality were consistent with the chemical measurements performed in the classroom, which also were comparable between operation modes.

The improved performance could not be explained by a reduction of the pollutant concentrations. They were most likely a consequence of the learning effect, i.e. gradual improvement in performance when a task is repeated. The order of presentation of conditions with the air cleaner activated and idled was not properly balanced, even though it was originally planned to do so. The students performed the task twice with the air cleaner activated, but the first result of the performance task was not included in the analysis. A higher CO_2 concentration and temperature in the classroom during one exposure suggested that the supply of outdoor air was lower. Inclusion of this condition would bias the comparison as the lower ventilation rate could result in increased intensity of symptoms and reduced performance because the air quality was poorer. Consequently, only two conditions were analyzed and these were not balanced.

The doubled CO_2 concentration under one condition with the air cleaner idled caused increased difficulty to concentrate and think clearly. The students also indicated that they learnt less under this condition. It is likely that as a consequence of these symptoms, the students performed worse in the logical reasoning task when the CO_2 concentration was higher. Even in this case, the learning effect cannot be ruled out because the order of presentation of the logical reasoning task was confounded with the CO_2 concentration, the lower followed the higher concentration.

7.3 Study design and analysis

The crude analyses of pupil perceptions, symptoms, and performance included the operation mode as the only independent variable and neglected the actual environmental exposures during the interventions. It was observed that during some lessons when a system was idled and the pupils completed questionnaires or tasks, the CO_2 concentration was lower than in other weeks when the systems were activated. This could be due to less intense use of the classroom in the lessons leading up to the performance measurement or different window or door settings. Thus, the analyses of the system operation mode should be supplemented by additional analyses that as far as possible account for co-varying factors, including the actual environmental exposures.

A first attempt was made in the analyses that across systems and seasons merged available data on pupil performance of the mathematical tasks and the concentration ability task. The results of these analyses showed significant effects of the CO_2 concentration on the concentration ability (d2 test) and the speed by which pupils completed the subtraction and multiplication tests, whereas there was no significant effect on the error rate. This effect was not that obvious from the crude analyses, when the independent variable was activation or idling of the retrofit solutions. This result suggests that to provide the expected benefits for learning, the ventilation retrofit solutions should sustain improved conditions at any time during their operation and should therefore have sufficient capacity and be responsive to changes in the demand.

Surprisingly, increasing temperature seemed to increase the speed of some tasks, although this effect was only significant with the subtraction speed. This finding contradicts somewhat the findings of Wyon and Wargocki (2008) who in their controlled intervention study found that each reduction of classroom air temperature by 1^{o}C during warm weather would result in an increase of 2% in the performance of schoolwork. However, even though tests in this study were also completed during the non-heating season, intervention weeks included the late spring/early summer when temperatures during school hours were only moderate (up to a maximum of 22.4^{o}C). Further and more detailed analyses are needed to explore this unexplained finding, e.g. by taking into account the time of day when the test was completed and the pupils' history of exposure in the classroom during the day.

To compensate the analyses for external factors, the pupils repeated the tests three times under each condition during a six week period. The results were then averaged across experimental weeks. To keep the realism of the experiments and the schedule of the classes unchanged, the performance testing was made on different days during the school week and at different times during the day. Ideally, all tasks should have been performed towards the end of the week or at least in the afternoon, which was literally not possible due to class activities. Consequently, there were inevitable differences in the actual levels of air quality in the classrooms, when the performance tests were presented to the pupils. These differences could for example cause that the air quality during performance testing was better than anticipated, e.g. the CO_2 concentration was higher with an activated than an idled system.

Another factor that could contribute to the inconsistent performance outcomes was a different duration of the testing period. Due to time constraints or because some pupils completed the task faster than allowed by the allocated time, the duration of the tasks varied sometimes even by a factor two. Although the performance metric used in the analyses was adjusted for the duration of the task (e.g. number of units completed or sentences read divided by the time used to complete the task), these differences could create systematic bias causing tasks of shorter duration to be performed faster. This particular aspect was not investigated, but it would be advisable in future experiments to aim for entirely equal duration of a given task across classes.

A comparison of the size of the effect of system operation was also made with Cohen's d. A Cohen's d of 1 shows that two populations differ by one standard deviation and that about 55% of the responses do not overlap. Cohen's d was calculated and tabulated together with the statistical analyses of the effects of retrofits on pupil performance. Cohen's d showed that the effects on performance of activating the system were generally large for the decentralized ventilation system and the system with automatically operable windows and an exhaust fan.

Although the study found only somewhat inconsistent effects of the retrofit operation on cognitive performance, the results should not be interpreted as if classroom air quality has no influence at all on the performance of tasks examining the abilities to learn. The study was not designed to investigate the effect on performance of a single environmental factor or parameter like it was in the previous ASHRAE project reported by Wargocki and Wyon (2006). Rather it was designed to examine the performance of a range of retrofit solutions during actual operation to keep the realism of the testing conditions and examine the total (complete) effect of their operation.

7.4 Subjective responses to the classroom environment

Except for isolated and possibly random effects, there were no differences in the subjective ratings of the classroom conditions or the reported intensity of acute health symptoms reported by the pupils. This is consistent with previous studies and suggest that subjective evaluations of 10-12 year old pupils may not provide robust information on the actual environmental conditions. One explanation could be that the pupils were not able to detect the environmental differences and subtle changes in their symptoms and well-being. Another reason could be that the scales used to monitor changes in pupil responses did not accommodate the mindset of the pupils. It was expected that the use of smileys instead of a continuous line to collect the responses would facilitate a response that was sensitive to environmental differences. However, this seemed not to be the case. Whether the lack of visible effects could be caused by the poor scale resolution or simply by the pupils being unable to properly rate and express their perceptions and symptoms or both, should be investigated in future experiments.

7.5 Measured energy use

The recorded heating energy use with the decentralized mechanical ventilation system was clearly higher than with the systems with automatic window opening and an exhaust fan or heat recovery units (148.7 kWh m^{-2} yr^{-1} vs. 123.4 kWh m^{-2} yr^{-1} and 53.9 kWh m^{-2} yr^{-1}). The maximum airflow rates of the decentralized system and the exhaust fan were sufficient to maintain median CO_2 concentrations in these classrooms that were well below 1000 ppm. Also, the distributions of the CO_2 concentrations were comparable in these classrooms indicating that the airflow rates may not have deviated too much from each other (assuming also comparable occupant loads). Since the decentralized mechanical ventilation unit was equipped with counter-current heat exchangers, it could be expected that the heating energy use was smaller with the decentralized system than the system with the exhaust fan, which removed the warm classroom air without recovering the available heating energy. Another possible explanation could be that the fan, during cold weather when windows were not opened by the control system, pulled warm air from the common area instead of from outdoors. Although the CO_2 concentration was not equally well controlled in the classroom with automatic window opening and heat recovery units, it seemed that the heating energy use in this room reflected better that the heat in the exhaust air was recovered by transferring it to the supply air.

As indicated by the electricity use, all systems were activated during the summer period even though the school was closed from the end of June until early August. The electricity use of the decentralized system even peaked during June and August. The other systems peaked during the heating season, when the manually openable windows and doors in the classrooms probably remained closed and there was a need to ventilate by the mechanically supported systems. For all systems, the heating energy use seemed to vary as expected with the outdoor climate.

7.6 Simulated classroom environment and energy use

Despite repeated attempts to refine the simulation models, there were large differences between the simulations and the corresponding measurements, both as regards the energy use and the indoor environment in the classrooms. Therefore, the simulation results should only be used for relative comparisons of the effect on the energy use and indoor environment of the school location or different window and door opening behavior. Several compromises had to be made in the formulation of the models and therefore the simulation outcome should be interpreted with some care. For example, the simulations showed that the temperature would drop considerably during the heating season as a consequence of opening a window, whereas this effect was not seen with the measurements, probably because the radiator/convector thermostats counteracted the temperature drop or because the simulation program predicted too high airflow rates when windows were opened during the heating season. It is assumed that the inconclusive simulation results were caused mostly by restrictions in the way the systems could be controlled. Another reason for the observed differences is most likely that the behavior of children is the least predictable, i.e. the conditions depend entirely on their will and ability to open the windows.

7.7 Concluding remarks

In the heating season intervention, all the retrofit solutions were able to improve the air quality in the classrooms, although to a different degree. At the same time, the different retrofit solutions seemed to affect the temperature and the classroom noise level only insignificantly. Prior to the intervention, the measured classroom CO_2 concentrations reached very high and clearly unacceptable levels. In one classroom in another school wing, the applied measurement instrument even reached its maximum at 5000 ppm on several occasions during the heating season. Unfortunately, the lack of ventilation is a challenge not only at the studied school, but also in many other schools in Denmark, where ventilation relies on manual window opening. These schools were built before the requirements to ventilation and the indoor environment were included in the Danish building code. Thus, the need for retrofitting ventilation is urgent in many schools located in temperate climates and particularly during the heating season, when pupils and teachers do not open windows to sustain ventilation. In this study, the solutions with automatically controlled and fan supported ventilation performed the best in terms of the indoor environment and the effect on pupil performance. These solutions were also the most costly. Low-cost solutions as the visual display unit may be used as a temporary solution, which may yield some improvement until a more permanent solution becomes available in the budget. However, this solution has been shown to have some effect shortly after installation, whereas the long-term performance still needs to be documented.

Due to the multitude of dimensions used to quantify the performance of the studied retrofit solutions, it has not been possible to identify one, distinct solution with the best overall performance and thereby to recommend one outstanding retrofit solution. Instead, the study results may be used to evaluate system performance in classrooms in which retrofitted ventilation solutions may be installed and operated as they would be in any given school subject to a similar retrofit. The measurements and observations therefore represent the variation in indoor environment, pupil perceptions and responses, behavior, and energy use that can be expected in schools with similar retrofits, when they are located in temperate climates.

These results invite for further technological development of retrofit solutions outperforming the ones examined in the present study. Such development will provide measurable effects in form of a better and healthier learning and teaching environment in school classrooms.

8 Acknowledgements

We sincerely appreciate the willingness of the pupils, teachers, and management at Ravnsholtskolen to participate in this study. Their interest in the study and their helpfulness has been extraordinary.

The municipality of Allerød and the companies that delivered and installed the tested retrofit solutions are acknowledged for their initiative to retrofit the classrooms at Ravnsholtskolen. We learned about the retrofit by coincidence, but the timing was perfect and allowed us to carry out the study.

Acknowledgements also go to all the students who participated in the project. Without them, it could not have been realized. Professor David P. Wyon is acknowledged for careful proof-reading of the manuscript enclosed as Appendix A and for his many suggestions that considerably improved the manuscript.

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10 List of appendices

A. Manuscript submitted to Science and Technology of the Built Environment "Impact of window and door opening behaviour on the carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits – ASHRAE RP1624"

B. Pupil questionnaire used in the heating season intervention study in 2014

C. Pupil questionnaire used in the intervention studies in 2015 and 2016

D. Schedules for tests and questionnaires

E. Questionnaire to teachers

F. Simulation details

G. Cost details
    - G.1 Decentralized mechanical ventilation systems
    - G.2 System with automatic window opening and heat recovery units
    - G.3 Visual display unit

H. Detailed CO_2 and temperature measurements for each intervention week

I. Noise measurements made during the non-heating season

J. Ranking of the retrofit systems based on pupil's task performance

Impact of window and door opening behaviour on the carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits – ASHRAE RP1624

Abstract

The aim of the present study was to extend the knowledge on the suitability and performance of different ventilation retrofit solutions for school buildings located in a temperate climate. A unique approach was used, where four similar and adjacent classrooms in the same school unit located north of Copenhagen, Denmark, were retrofitted either with a decentralized, balanced supply and exhaust mechanical ventilation unit with heat recovery; automatically operable windows with an exhaust fan; automatically operable windows with alternating counter-flow heat recovery through slots in the outside wall; or were equipped with a visual feedback display of the current classroom CO_2 concentration advising when the windows should be opened. For reference, one classroom retained the original approach for achieving ventilation by manual opening of windows. One year after retrofitting, the classrooms' carbon dioxide concentrations, temperatures, energy use, and window and door opening behaviour were recorded during a four week period in the heating season in January. The percentage of occupied time in which the CO_2 concentration was below 1000 ppm was: 82% with mechanical ventilation, 70% with automatic window opening and an exhaust fan, 54% with automatic window opening and heat recovery, and 36% with visual CO_2 feedback, and 48% in the classroom where windows were opened manually. The automatically controlled windows were open for up to 71% of all school days (including breaks between lessons) with an exhaust fan and for 49% with heat recovery. The façade windows were open between 3% and 14% of the occupied time in the classrooms with manual window opening (with or without visual feedback). The present results show that in temperate climates, mechanical ventilation and automatic window opening systems were able to maintain average CO_2 concentrations below 1000 ppm during the major part of the school day, as required by many codes and guidelines, while simply providing visual feedback on the current CO_2 concentration, as a motivation for window opening was not.

Keywords

School, indoor climate, air quality, occupant interaction

Introduction

Numerous studies have shown that inadequate ventilation in classrooms in elementary schools reduces the comfort, learning performance and attendance of the pupils and increases the prevalence of negative health symptoms (e.g. Wargocki et al. 2002, Haverinen-Shaughnessy et al. 2011; Bakó-Biró et al. 2012; Daisey et al. 2013, Wargocki and Wyon 2013; Mendell et al. 2014; Gaihre et al. 2014). Recent cross-sectional studies in classrooms in schools in Denmark and abroad have documented that classroom air quality is often characterised by lesson average CO_2 concentrations considerably higher than the maximum of 1000 ppm, which is typically recommended by current guidelines and building codes (e.g. Energistyrelsen 2014, ISO 15251-2007). This has been reported to occur particularly often in classrooms where ventilation is achieved by manual window opening, especially during the heating season in temperate regions (Shendell et al. 2004; Santamouris et al. 2008; Hellwig et al. 2009; Gao et al. 2014; Clausen et al. 2014; Toftum et al. 2015; Rosbach et al. 2016; Stabile et al. 2016).

Improved ventilation in elementary school buildings can be achieved by retrofitting existing classrooms or by the construction of new school buildings, the latter being easier to implement, but both being generally considered as costly investments. An interim alternative solution to either could be to motivate students and teachers to change their behaviour, by encouraging them to manually open the windows and in this way increase the ventilation rate.

The efficacy of improving the ventilation rate by manually opening windows is greatly affected by the outdoor conditions, including the location of the school (urban and/or rural), by climatic conditions (wind speed and direction, outdoor temperatures), and by how customary it is for pupils and teachers to open windows. It also depends on the classroom layout and on whether single-sided or cross-ventilation can be established. Based on measurements of air tightness in classrooms in an Italian school, Stabile et al. (2016) found that even in poorly maintained classrooms, the permeability of the envelope was too low to guarantee acceptable air exchange rates. The study also showed that during the fall and winter seasons airing seemed ineffective. Wyon et al. (2010) demonstrated in a field intervention experiment that although pupils and teachers readily opened windows when the classroom became warm, they seldom did so when the air quality was poor, possibly because they did not perceive the poor air quality due to gradual sensory fatigue (also known as adaptation, Gunnarsen and Fanger 1992). High temperature seems to be a more important factor driving window opening than any other (Dutton and Shao 2010; Fabi et al. 2013), and during cold weather window opening may seldom occur because of thermal discomfort due to the admission of cold outside air and to draughts (Griffiths and Efthekari 2008). The performance of different methods of controlling ventilation in a naturally ventilated classroom with manually operable windows was evaluated by Griffiths and Efthekari (2007) who found that it was difficult to meet air quality requirements in a heating season scenario without compromising thermal comfort.

Gao et al. (2014) investigated indoor temperature and air quality, window opening behaviour, and pupil responses in classrooms with different types of ventilation system, located in a temperate climate. Month-long measurements in the heating and non-heating seasons were made in a classroom with balanced central mechanical ventilation and in a classroom where windows were opened automatically and an exhaust fan ensured sufficient air intake. In addition, measurements were also made in two classrooms where the windows could be opened either manually or automatically (one-sided natural ventilation). In the latter two classrooms, the fan or both the fan and the systems for automatic opening of windows were inactivated in the classrooms where windows were opened automatically and where the exhaust fan was installed. . Based on CO_2 measurements, Gao et al. (2014) found that the classroom with mechanical ventilation had the highest estimated average air-change rate and that classroom windows were frequently opened in the non-heating season but very seldom in the heating season.

Wargocki and Da Silva (2015) studied changes in window opening behaviour when they provided visual feedback on the CO_2 concentration to pupils and teachers, The studies were performed during both the heating and non-heating seasons, for a week at a time. The pupils and teachers were instructed to open windows when CO_2 concentrations were above 1000 ppm, i.e. when the feedback lamps were yellow or red. They observed that in periods when the visual feedback device was in operation, more windows were opened, resulting in reduced CO_2 concentration, but at the expense of increased energy use. During the heating season, Toftum et al. (2016) used the same visual feedback device during a week-long period, but gave different instructions to different classes in the same school. In one class, pupils were instructed to open windows when the CO_2 concentration was high. The other class was simply recommended to open the windows under these conditions. In two other classes without such visual feedback, pupils in one class were told that they must open the windows for 5 min during every lesson and in another class that they must open all the windows before leaving the classroom during the break. The effectiveness of each intervention was compared by measuring CO_2 concentrations prior to and after the interventions. In both classes with the visual feedback device, the occupied time during which the CO_2 concentration was above 1000 ppm was reduced by 40-60%, but the time when the classroom temperature was below 20^{o}C seemed also to increase. The interventions without visual feedback had only negligible effects on the CO_2 concentration. On the other hand, recent measurements performed by pupils in 785 Danish classrooms showed that leaving the classroom and airing out during breaks reduced the percentage of classrooms with a CO_2 concentration higher than 1000 ppm from 60% to 39% compared to a condition when no windows were ever open (Clausen et al. 2014).

This study was carried out within the framework of the ASHRAE RP-1624 project on “Effective Energy-efficient Classroom Ventilation for Temperate Zones”. The overall objective of the study was to evaluate the performance of different methods of classroom ventilation in terms of the thermal environment and air quality in the classrooms, the window opening behaviour of children and teachers, pupil’s perceptions of the classroom environment, their reported health symptoms, their performance of school work and energy use. The objective of the work presented in this paper was to analyze CO_2 concentration, temperature and energy use, and window and door opening behaviour during the heating season in classrooms with different ventilation retrofits.

Methods

School and classrooms

The school where the measurements were performed was located in a rural area north of Copenhagen, Denmark. There were 543 pupils in 25 classes with 2-3 classes at each grade level. Prior to installation of the ventilation retrofits, pupils and teachers had to open windows and doors manually if the classrooms were to be ventilated at all. This was not sufficient to ensure an acceptable classroom air quality. The municipality together with the school management therefore decided to retrofit selected classrooms with different ventilation systems to make it possible to compare their performance *in situ* and select the one that was the best fit for the school. Different ventilation retrofits could therefore be compared in the same school building, instead of between schools.

The classrooms in which the retrofits were installed were located in a one-storey building that had been commissioned in 1980: four different retrofits were installed in four classrooms and a fifth classroom served as a reference. The classrooms were occupied by 11-12 year-old pupils in the 4th and 5th grade. Figure 1 shows the layout of the building and the location of the classrooms.

Each classroom had an area of 56 m^2 and a volume of 160 m^3. With a nominal number of 25 occupants (24 pupils plus 1 teacher), the minimum outdoor air supply rate as required by the Danish building code is about 520 m^3/h (145 l/s) (Energistyrelsen 2014). The nominal number of pupils in each class was between 23 and 26. The actual number of pupils present in the classrooms during the study period was typically between 22 and 25 pupils.

The classrooms had brick walls, acoustic ceilings and linoleum floors. Figure 2 shows the interior, which was nearly identical in all the classrooms. The classrooms had overhead windows, windows in the façade with a view to the outdoor area, and two doors, one to a common area/hallway and one to the outdoor yard (Figure 3). Both the façade and overhead windows could be opened manually prior to installation of the retrofits. The location of the windows on two opposite facades enabled cross-ventilation in the classrooms. The windows in the façade of the classrooms where the retrofits were installed were replaced with new ones with low heat transmission coefficient prior to installation of the retrofits. These were the classroom in which a mechanical supply and exhaust ventilation unit and the two in which automatic window opening was installed. In the other two classrooms the original, manually openable windows were retained.

All five classrooms were heated by water-filled radiators mounted below the façade windows and water-filled convectors below the overhead windows. Both radiators and convectors had manually adjustable thermostats.

The school was located in a temperate climate zone with mild winters and cool summers and the prevailing wind direction was west. Table 1 provides a summary of the actual weather conditions that were recorded during the measurement period.

Retrofit solutions

The four retrofit solutions for improving classroom ventilation were:

A mechanical ventilation unit, with balanced supply and exhaust airflow that was controlled by the CO_2 concentration, was suspended from the ceiling of Classroom S3 (Figure 4)

A system for natural ventilation by automatic window opening and an exhaust fan, both controlled by the CO_2 concentration, were installed in Classroom S4 (Figure 5)

A second system for natural ventilation by automatic window opening and five alternating counter-flow heat recovery units in slots in the outside wall, all six systems being controlled by the CO_2 concentration, were installed in Classroom S5 (Figure 6)

A visual CO_2 feedback display indicating when the CO_2 concentration was high and that windows therefore should be opened, was installed on the classroom wall in Classroom S8 (Figure 7)

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A mechanical ventilation unit installed in Classroom S3 was equipped with a filter (class EU7), a heat recovery unit, an electrical pre-heater, and a water-to-air heating coil. It had a maximum airflow rate of 725 m^3/h (201 l/s). The noise level at the maximum airflow was 35 dB(A) as specified by the manufacturer. The minimum airflow rate was 200 m^3/h (56 l/s). The low airflow rate was provided when the classroom CO_2 concentration was below 600 ppm; the airflow rate reached maximum at a concentration above 800 ppm. Between 600 ppm and 800 ppm, the supply airflow rate increased linearly from the minimum to the maximum. The supply air temperature was adjusted by a thermostat to keep the room air temperature at 23°C. The windows in this classroom could still be opened manually, independently of the operation of the mechanical ventilation system.

The actuators for the automatic window opening systems installed in Classrooms S4 and S5 operated the façade windows Win1, Win3, and the overhead window WinH (Figure 3). In both classrooms, the indoor CO_2 concentration, indoor air temperature, outdoor weather conditions and time of day were used as input to activate window opening by the control system. A timer control was used to open the windows at the start of each clock hour of the school day if the CO_2 concentration was above 800 ppm. Unfavourable weather conditions with precipitation or strong winds caused the window opening degree to be reduced. The windows were controlled in so-called “pulse” and “trickle” modes; during the heating season, the “pulse” control mode typically dominated. When the CO_2 concentration increased rapidly to a level above 800 ppm, the “pulse” control mode opened the windows to the maximum opening degree for 3 minutes. In this mode and during the heating season (mid-October to mid-April), the maximum opening degree was 50% of the maximum achievable opening of the windows. During the non-heating season (mid-April to mid-September) it was 80%. The “trickle” control mode opened the windows gradually to the season-dependent maximum opening degree, when the CO_2 concentration increased from 750 ppm to 1000 ppm. The control algorithm was overruled and windows were not opened when the indoor air temperature was below 19^{o}C. The occupants had the possibility to manually override the system by pushing a wall-mounted button, which opened the windows to the maximum achievable opening. When this happened, the system reverted to the original control setting 15 minutes after the button had been pushed. One of the lower windows could still be opened manually by pupils and teachers.

The automatic window control in Classroom S4 was accompanied by an exhaust fan. The fan was mounted in the overhead window to support cross-ventilation (Figure 5). The fan’s nominal airflow rate was 749 m^3/h (208 l/s) at a noise level of 40 dB(A) 10 meters from the fan as specified by the manufacturer. Operation of the exhaust fan started at a CO_2 concentration of 700 ppm and the maximum speed was reached at 1000 ppm. No heat was recovered from the exhaust flow. Supply air entered this classroom either through open windows or from the adjacent hall in cases when the fan was running and the windows were closed. The latter could happen during periods when the outdoor temperature was low and with strong winds. However, there is no indication that this situation occurred during the measurement period.

The automatic window control in Classroom S5 was accompanied by a series of ten heat recovery units, each consisting of a heat absorbing material and a row of small fan (Figure 6). These units worked in five pairs with opposite flow directions that reversed every minute. With exhaust airflow heat was absorbed and with supply airflow the absorbed heat preheated the cold supply air. The heat recovery units were installed in special slots in the outdoor wall; each section/unit contained 5-7 small fans. Altogether, five units were installed and they could deliver outdoor air at a maximum rate of 468 m^3/h (130 l/s) at a low pressure loss, resulting in a Specific Fan Power (SFP) of 300 J/m^3. At the maximum airflow rate, the nominal noise level of one unit was approximately 35 dB(A) as specified by the manufacturer. The units contained no filter. The thermal efficiency of the heat recovery was about 85%. The units were run at minimum speed when the CO_2 concentration in the classroom was below 650 ppm and their speed of operation was progressively increased to reach maximum airflow above a concentration of 750 ppm.

In Classroom S8, the display providing visual feedback on the CO_2 concentration was mounted on the wall. It had a scale consisting of differently coloured LEDs showing the CO_2 concentration from 250 ppm to 5000 ppm. The pupils and teachers were instructed to open the windows when the lights were yellow, i.e. when the CO_2 concentration was between 1000 ppm and 1600 ppm. When the lights turned red, i.e. when the CO_2 concentration exceeded 1600 ppm, they were instructed to open all windows and doors for five minutes to achieve cross-ventilation; during this time they were asked to leave the classroom. The pupils and teachers received instructions on how to respond to the feedback in October, i.e. a few months prior to the present measurements.

The ventilation in the reference classroom was either single-sided, when either the façade or overhead windows were open, or two-sided (cross ventilation) when windows in both sides were open simultaneously (Figure 8). The overhead window could be opened by using a crank handle. Classrooms S7 and S8 had the same window configuration (Figure 3).

The retrofitted systems were in operation in January and February 2014 after being installed during the Christmas break of 2013/2014. Measurements described in this paper were made from January 7th to February 2nd 2015 during normal teaching activity after the retrofitted systems had been in operation for a full year (except during three separate weeks during which other experiments were carried out in October-November 2014). The visual feedback device had been in operation for approximately four months.

Measurements

One measurement station consisting of a CO_2 transmitter (CO_2 range: 0-5000 ppm ± 100 ppm + 2% of reading) connected to a data logger (signal range: ± 2mV ± 2.5% of reading) that also monitored temperature (range: -20-70°C, ±0.35°C in the range 0-50°C) and relative humidity (±2.5% from 10%-90% RH) was installed in each classroom. Measurements were recorded in five-minute intervals. The measurement station was located away from the windows at a height of approximately 1.5 m above the floor next to the whiteboard, as indicated in Figure 1. During another period when an intervention study was carried out, but also in the heating season, two measurement stations were installed in each room; one next to the whiteboard and one at the back of the room, opposite the whiteboard. Convective currents caused by pupil movement and the temperature differences between their surface and the surrounding air resulted in well-mixed air, as indicated by nearly identical CO_2 concentrations measured at the two locations.

Window and door opening events were recorded with data loggers with binary output. These loggers recorded the events (window/door open/closed) and the time of the event. They were located on all the operable windows and the door frames in the classrooms.

In Classrooms S3, S4 and S5, the electricity used by the systems was logged. Energy meters were installed on the radiators, convectors, and the water-to-air heating coil in the mechanical system in Classroom S3. The window orientation in these rooms was the same (SSE), but the area of the external walls differed. One element of the overall study that was not reported in this paper was to simulate the energy use of the classrooms in different climate zones. This was done based on the geometry of the school building and its material properties. From the simulation program, we adopted U·A factors for each classroom and used them to adjust the heating energy use. The reference classroom (S7) and the visual feedback device tested in Classroom S8 were included in the study by the authors after the municipality had completed installation of the retrofit solutions in the other three classrooms. Energy meters had therefore not been installed in these two classrooms.

Data Processing

The measured CO_2 concentration, air temperature and the opening state of windows and doors were merged in a common data set; all data were presented in five-minute intervals. Data were aggregated for the occupied time defined as the lessons that took place in the classrooms. The breaks for recess and lunch were not included when aggregating CO_2 concentrations and temperatures, as pupils typically spent these outside the classroom. This was considered to be the approach which best represented classroom exposure conditions during occupied periods. However, break time was included in the analysis of the opening state of doors and windows that reflected full school days, because these periods also affected the environment conditions in the classrooms during lessons.

Due to the event-based functionality of the instrumentation used to record window and door opening, the loggers in some cases indicated opening or closing of doors and windows in 1-second intervals and in other cases in e.g. 1-hour intervals. The periods with high frequency recordings were caused by windows or doors that were slightly ajar and could be moved by variations in the air pressure. The loggers in such cases recorded many opening/closing events as the unit registered that the signal changed state. These periods were assumed to represent closed windows/doors. Figure 9 shows the results before and after adjustment of the events registered by the loggers. The analysis of window and door opening included not only the time the classrooms were occupied, but the whole period from start to end of the measurements.

Data analysis

The effect of retrofits on classroom CO_2 concentration and temperature was compared by analysis of variance (ANOVA). In separate analyses, the ANOVA models examined the effect on the CO_2 concentration or temperature of the type of ventilation in the classroom adjusted for the measurement week, weekday and the lesson within a day. Also, the models included all two-factor interactions between the main variables to adjust for the variability caused e.g. by the interaction between weekday and lesson. The analysis of the CO_2 concentration was made with log-transformed CO_2 concentrations due to the skewness of their distributions. Duncan's Multiple Range Test was used to allow for multiple comparisons. The residuals of both models were Normally distributed.

The binary opening state of a window or door was compared between classrooms by logistic regression analysis. For each window and door in a classroom, the processed recordings of its opening state were aligned with concurrent recordings of CO_2 and temperature made every 5 minutes of the occupied time. The binary opening state was then used as the response variable in the analysis. Classroom, CO_2 concentration and temperature were used as explanatory variables. The logistic regression analysis compared only classroom S3 with the other classrooms and therefore Wald's test was used for pairwise comparison of all other combinations of classrooms. Student's t-test for independent samples was used to compare CO_2 concentrations measured in Classroom S3 between two periods when winH was left open and when it was closed (second vs. first half of the measurement period).

All differences were considered significant at $p < 5\%$. The statistical analyses were carried out in R (University of Auckland, New Zealand) and Stata IC version 12.0 (Statacorp, TX, USA).

Results

Classroom CO_2 concentration and temperature

Figure 10 shows box-plots of the CO_2 concentrations and air temperatures measured in each classroom during the occupied school hours, excluding the breaks when pupils were outside the classroom. In the classroom with the mechanical ventilation system (S3) and the classroom with automatic window control and an exhaust fan (S4), the CO_2 concentration was found to be significantly lower than in the other three classrooms ($p < 0.01$, ANOVA); the median CO_2 concentration in these classrooms was below 1000 ppm and the CO_2 concentration varied less, as indicated by a smaller inter-quartile range, than in the other three classrooms. No statistically significant differences were observed between the CO_2 concentrations measured in the other three classrooms S5, S7 and S8. All two-factor interactions included in the ANOVA model were significant at $p < 0.01$, indicating that the CO_2 concentration varied both between lessons within a day and between days within a week. The mean CO_2 concentration measured between 7:30 and 7:40 in all classrooms prior to arrival of pupils and teachers was 410 ppm (ranging from ca. 375 ppm to 600 ppm).

The temperature was significantly higher in the classroom with visual feedback (S8) than in all the other classrooms ($p < 0.01$, ANOVA) (Figure 10), presumably because the radiator thermostats were set higher. In this classroom, the median temperature was also higher than the recommended maximum heating season temperature of 24^{o}C (ASHRAE 55-2013; ISO 15251-2007). The temperature in the classroom with the mechanical ventilation system (S3) was significantly higher than in the classrooms with automatic window control (S4 and S5) and the reference classroom (S7) ($p < 0.01$, ANOVA). The temperature did not differ significantly between Classrooms S4, S5, and S7 and it was generally within the recommended thermal comfort range of 20^{o}C to 24^{o}C (ASHRAE 55-2013; ISO 15251-2007), although events with lower temperature were sometimes recorded in Classroom S4.

Figure 11 shows profiles of the CO_2 concentration and temperature in each classroom together with the outdoor temperature; all as an average over each of the five school days in the third measurement week. The variability during the school day of the CO_2 concentration was smaller in S3, S4, and S5 than in the other classrooms without dedicated ventilation systems. Also, the peak concentration was lower in these classrooms, although in S4 and S5 the ventilation rate could not completely keep a CO_2 concentration below 1000 ppm. Temperatures varied between rooms, but the variation within classroom was rather modest during the school day.

Occupant interaction with windows and doors in the classrooms

For each day and time of day during the measurement period, Figure 12 shows the number of windows opened simultaneously; Figure 13 provides similar information on the opening state of the two doors in each classroom. Many frequent opening events of short duration were observed in classrooms S4 and S5 where the windows were opened automatically, compared with the other classrooms. In S4 and S5 with automatically operable windows, the teachers and pupils opened windows manually for only 5% of the time. In the reference classroom (S7) and the classroom in which visual feedback on CO_2 was provided (S8), the windows were surprisingly rarely opened. In classroom S3 with mechanical ventilation, one window (winH) was left open during the entire second half of the measurement period. This seems not to have affected the temperature, which was generally higher in this classroom than in the other rooms. However, the CO_2 concentration was significantly higher during the first period with a closed winH than during the second period with an open winH (median 899 ppm vs. 564 ppm) ($p < 0.05$, t-test).

The external door in the classrooms with dedicated ventilation systems (S3, S4 and S5) was generally opened less frequently than in S7 and S8 ($p < 0.05$, logistic regression). Events with two open doors were more prevalent in the reference classroom (S7) and in the classroom with the visual feedback display (S8), as could be expected (Figure 13). The door to the hall was left open or ajar in S4 for an extended period and for a few days in S3 and S5.

For each classroom, Figure 14 shows the percentage of the occupied time when each of the doors and windows was open, aggregated for the whole measurement period. The door to the yard was open for only 1-2% of the occupied period in the classrooms with dedicated ventilation systems. In contrast, this door was open for 31% and 33% of the occupied period in the reference classroom (S7) and the classroom with visual feedback (S8), respectively. The entrance door in the classroom with automatic window opening and an exhaust fan (S4) was open for 47% of the occupied period (Figure 13), mostly during the second half of the measurement period (Figure 12). This could be due to a particular teacher, who did not mind that there was a door open during lessons.

Figure 14 shows that the façade windows were open for less than 15% of the occupied period including breaks in the classrooms without automatic control of window opening (S3, S7 and S8). In comparison, the windows that were automatically controlled (Win3 and WinH) in classrooms S4 and S5 were open for 44-71% of the occupied time. Particularly low temperatures were measured in S4, and this corresponded well with the lower CO_2 concentrations measured in this room, indicating an increased supply of cold outdoor air due to the frequent opening of the windows in combination with the exhaust fan.

WinH and Win2 in the classroom with visual feedback (S8) were open more frequently than in the reference classroom (S7) ($p < 0.05$, logistic regression), suggesting that the visual CO_2 feedback had some impact on the pupils' and teachers' window opening behaviour (Figure 14). However, the CO_2 concentration measured in S8 did not differ significantly from what was measured in the reference classroom, so in this study, the feedback display was insufficient to significantly reduce the CO_2 concentration.

Energy use

Table 2 shows the energy used by the systems in each of the retrofitted classrooms from January 7 to February 2 when outdoor air temperature was in the range from -2,9°C to 10.3°C (Table 1). The heating energy use was compensated for the difference in U·A between the classrooms according to the correction factors shown in Table 2. In the two classrooms with automatic window control and an exhaust fan or the heat recovery units, the use of heating energy included the radiator under the façade windows and the convector below the overhead windows. In the classroom with the mechanical ventilation system the energy used by the water-based heating coil was also included. The electricity use included the energy used by the fans in the mechanical ventilation system, the exhaust fan and the fans in the heat recovery units as well as by the actuators that opened the windows. Auxiliary electricity use (computer for central management of all systems, wiring closet, etc.) is not included in the values presented in Table 2.

Discussion

This study was undertaken to evaluate system performance and occupant interaction with windows and doors in classrooms in which retrofitted ventilation solutions had been installed and were being operated as they would be in any given school subject to a similar retrofit. The measurements and observations therefore reflect the variation in indoor environment, occupant behaviour, and energy use that can be expected in schools with similar retrofits, when they are located in temperate climates, during the heating season. The present study is built partly on the methodology used previously by Gao et al. (2016) and Wargocki and Da Silva (2015). However, one important distinction between these and the present study was that in the present experiments the examined solutions had been in use for one year, except the visual feedback device, which had been used through four months. The different retrofits were thus not installed temporarily for the purpose of the experiments. Consequently, the pupils and teachers were used to them before the measurement campaign was started. Another addition was that the use of visual feedback was monitored for a month and not for a week. Finally, the measurements included also monitoring of the energy used for heating and ventilation.

The lowest median CO_2 concentration and the smallest variation in the CO_2 concentration were observed in classrooms with dedicated ventilation systems. Among these rooms, however, the CO_2 concentration was significantly lower only in the classroom with the mechanical ventilation system (S3) and with the automatic window opening and an exhaust fan (S4). The maximum supply airflow achieved in the classroom with automatic window opening and the heat recovery units (S5) was only 60-65% of the maximum airflow rate in the classroom with the mechanical ventilation system (S3) and with automatic window opening with the exhaust fan (S4). The supplementary ventilation provided by the heat recovery units was sufficient to reach a median CO_2 concentration below 1000 ppm, but not sufficient to significantly improve the air quality in this classroom in comparison with the rooms without system controlled ventilation.

During the heating season, the motivation of pupils and teachers to manually open windows in classrooms in temperate climates is generally quite low. This was shown by Gao et al. (2014) and Wargocki and Da Silva (2015), and observed also in this study in the reference classroom (S7), where the windows were rarely opened. There could be several reasons why pupils open the windows less frequently when it is cold outside, but the most obvious is that a low outdoor temperature causes cold draughts when windows are open. During the present measurements the average outdoor temperature was around 3^oC and the maximum temperature for the whole period around 10^oC. In the study by Gao et al. (2014) performed also in Denmark in November-December and by Wargocki and Da Silva (2015) in March-April, the average outdoor temperatures were ca. 2^oC and 8^oC, respectively; classroom occupation was the same as in the present study. Temperatures in this range may be sufficiently low to discourage the teachers and pupils from opening the windows.

In the classroom with a visual feedback display (S8) windows were opened for longer than in the reference classroom (S7), but this did not result in consistently better air quality as the median CO_2 concentration was slightly higher than in the reference classroom. The inter-quartile range of the measured CO_2 concentrations was wider and events with CO_2 concentrations higher than 2500 ppm were more frequent in the classroom with a visual feedback display, although the daily occupancy was comparable in both classes. This finding differs from what was found in other studies in which a similar visual feedback display did significantly reduce the measured CO_2 concentration in classrooms (Wargocki and Da Silva 2015; Toftum et al. 2016). A possible explanation for this difference could be that the pupils simply forgot to pay any attention to the feedback display because it had been present in the classroom for several months already. This may indicate that users of such devices should be regularly reminded to act upon the feedback provided. As an alternative to the visual feedback used in this study, a unit with a larger or animated display that attracts more attention or even one that is supplemented by an auditory signal may be more efficient in encouraging pupils to open the windows manually when needed.

Periods with simultaneously open windows or doors were very limited in both classrooms, i.e. cross-ventilation rarely occurred. Figures 12 and 13 show that opening events were typically clustered within the same time slots. The visual feedback display did not result in more time with an open door to the outdoors than in the reference classroom, but in both these rooms this door was actually open for longer time than in the other three classrooms with dedicated ventilation systems. This could also have been for other reasons than poor classroom air quality, e.g. easier access to the outdoor playground. The air temperatures in the classroom with a visual feedback display were significantly higher than in the reference classroom ,most likely due to a different thermostat setting.

The façade windows were open 71% of the occupied period in the classroom with automatic window opening and an exhaust fan (S4). In the classroom with automatic window opening and heat recovery units (S5), the façade windows were open for only 44% of the time. In S4, the CO_2 concentration was lower, which suggests that the duration of time with open windows was an important factor contributing to the reduction of the CO_2 concentration. However, as the classrooms used two different systems for forced ventilation (exhaust fan and heat-recovery units with small fans) it is difficult to attribute the lower CO_2 concentration solely to the time during which windows were open. Although the temperature did not differ significantly between these two classrooms, the median temperature was approximately 1°C lower in the one with an exhaust fan (S4) than in the one with the heat recovery units (S5), as they delivered air at a median temperature of about 19°C (estimated with a thermal efficiency of 0.85, a median indoor temperature of 22°C and median outdoor temperature of 2.5°C). Due to the heat recovery and the reduced time with windows open, the heating energy used in this classroom was lower than in S4.

Neglecting the presumably forgotten open or slightly ajar overhead windows (WinH) in the classroom with the mechanical ventilation system (S3), windows and doors to the outside in this classroom were open between 2% and 15% of the occupied time. In this room, a CO_2 concentration below 1000 ppm was maintained for 82% of the occupied time. However, the average indoor air temperature was rather high, possibly due to a malfunctioning valve in the ventilation system, which therefore supplied air at a temperature that was too high. The valve defect was not discovered until after completion of the measurement period so the heating energy use in this classroom may not reflect what can be expected with a correctly functioning system. Unfortunately, the defective valve in the mechanical ventilation system also invalidated meaningful comparison of energy use between classrooms with dedicated ventilation systems, where the energy meters were installed.

In summary, the present measurements during the heating season show that manual opening of windows rarely takes place in schools located in a temperate climate unless pupils are triggered (informed) to do so. Therefore, manual opening of windows can be considered as less reliable to improve the classroom air quality compared with retrofits that allow automatic control of ventilation. The installed nominal capacity of such systems should match minimum code requirements for airflow, even if ventilation can be achieved by manual opening of windows.

Conclusions

With a visual CO_2 feedback display in the classroom, windows were open for a greater proportion of the occupied time including breaks than in the reference classroom, in which windows were also opened manually, but this did not result in a significantly lower CO_2 concentration.

In a classroom with automatic window opening and an exhaust fan, windows were open for 71% of the occupied period including breaks. This resulted in a significantly lower CO_2 concentration than in the classrooms with only manual opening of windows and doors.

In a classroom with automatic window opening and heat recovery units, windows were open for 49% of the occupied period. This did not result in a significantly lower CO_2 concentration than in the two classrooms with only manual window opening.

The longest proportion of the occupied period with pupils in the classroom (excluding breaks) during which a CO_2 concentration below 1000 ppm was recorded was in the classroom with a mechanical ventilation system. In this classroom the CO_2 concentration did not differ significantly from the classroom with automatic window opening and an exhaust fan.

The ventilation retrofits seemed to have only minor effect on the classroom temperature, which depended mostly on the setpoint of the radiator thermostats in each classroom.

Acknowledgement

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Figure captions

Figure 1. Floor plan of school building with location of the classrooms evaluated (left) and picture of classroom from the outside (right); dots indicate the approximate location of the measurement stations.

Figure 2. Interior of a typical classroom.

Figure 3. Cross section, floor plan, elevations of classroom and location of openable windows (windows which could not be opened are not named).

Figure 4. Mechanical ventilation system in Classroom S3. In this classroom, windows could be opened manually as before the retrofit.

Figure 5. Ventilation in Classroom S4 with automatically controlled windows and an exhaust fan installed in one of the overhead windows.

Figure 6. Ventilation in Classroom S5 with automatically controlled windows and heat recovery units installed in the façade and in one overhead window.

Figure 7. Ventilation in Classroom S8 with a visual feedback display of the CO_2 concentration.

Figure 8. Ventilation principle in the reference classroom (S7).

Figure 9. Example of processing of event-based data for opening/closing of a door (1=closed, 0=open).

Figure 10. Box-plots of the classroom CO_2 concentration (left) and indoor air temperature (right) in each classroom during the periods with pupils present in the classrooms (excluding breaks). (S3-classroom with mechanical ventilation; S4-classoom with automatic window opening and exhaust fan; S5-classroom with automatic window opening and heat recovery units; S7-classroom with only manual opening of windows; S8-classroom with visual feedback on CO_2 levels and manually operable windows)

Figure 11. CO_2 concentration (left) and temperature (right) in each classroom during a school day (average over each of the five school days in the third measurement week). The figures show also the average outdoor temperature. (S3-classroom with mechanical ventilation; S4-classoom with automatic window opening and exhaust fan; S5-classroom with automatic window opening and heat recovery units; S7-classroom with only manual opening of windows; S8-classroom with visual feedback on CO2 levels and manually operable windows)

Figure 12. Number of open windows as a function of day and time of day during the measurement period. (S3-classroom with mechanical ventilation; S4-classoom with automatic window opening and exhaust fan; S5-classroom with automatic window opening and heat recovery units; S7-

classroom with only manual opening of windows; S8-classroom with visual feedback on CO2 levels and manually operable windows)

Figure 13. Number of open doors as a function of day and time of day during the measurement period. (S3-classroom with mechanical ventilation; S4-classoom with automatic window opening and exhaust fan; S5-classroom with automatic window opening and heat recovery units; S7-classroom with only manual opening of windows; S8-classroom with visual feedback on CO2 levels and manually operable windows)

Figure 14. Percentage of the occupied time including breaks with open or closed doors and windows in each classroom. In Classroom S7 and S8 with no dedicated ventilation system windows termed Win 1 and Win 3 could not be opened. (S3-classroom with mechanical ventilation; S4-classoom with automatic window opening and exhaust fan; S5-classroom with automatic window opening and heat recovery units; S7-classroom with only manual opening of windows; S8-classroom with visual feedback on CO2 levels and manually operable windows)

Table captions

Table 1. Weather conditions aggregated for the entire measurement period from the 7^{th} January to 2^{nd} February 2015 (including unoccupied periods).

Table 2. Use of heating and electrical energy in the sub-metered classrooms (S3, S4, S5).

Table 1

	Min	Max	Median	Mean	Sd
Air temperature, °C	-2.4	10.3	2.5	2.9	2.2
Relative humidity, %	80.0	100.0	100.0	97.0	4.4
Wind speed, m/s	0.0	33.8	6.4	7.6	6.5

Table 2

	Classroom with mechanical ventilation system (S3)	Classroom with automatic window opening and exhaust fan (S4)	Classroom with automatic window opening and heat recovery units (S5)
Electricity use, kWh	10.7	10.2	8.9
Measured heating use, kWh	646	365	259
Correction factor	1[*)]	1.02	1.11
Corrected heating use, kWh	646[**)]	372	287

*) Measured heating energy use was multiplied with the correction factor to compensate for differences in external wall area.

*) A malfunctioning valve may have affected the heating provided by the mechanical ventilation system.

Figure 1

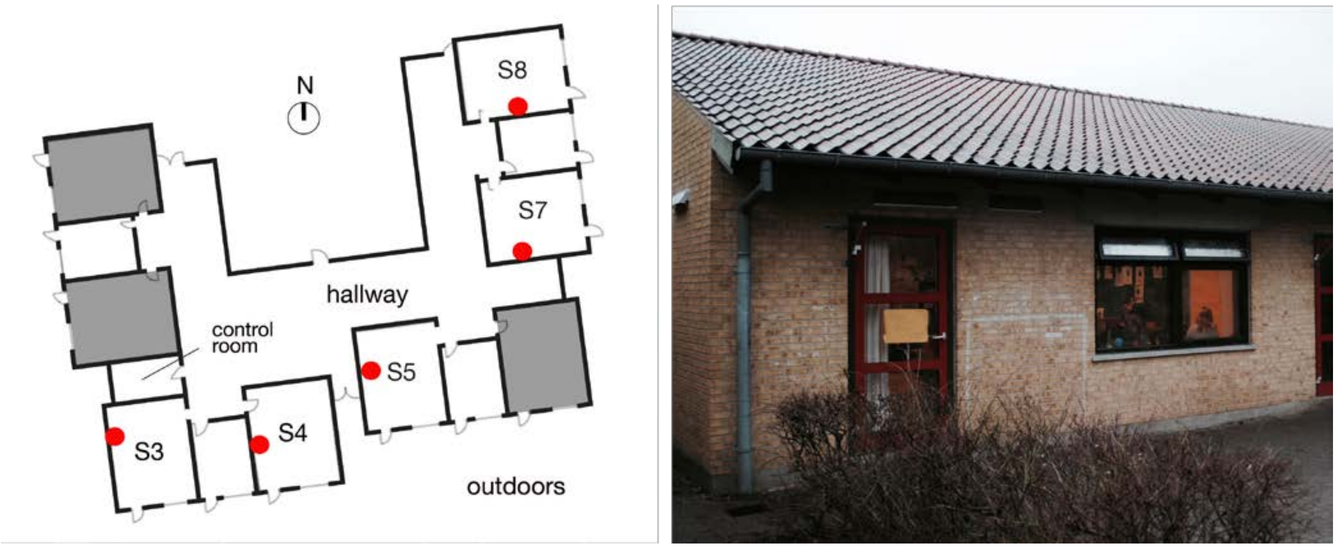
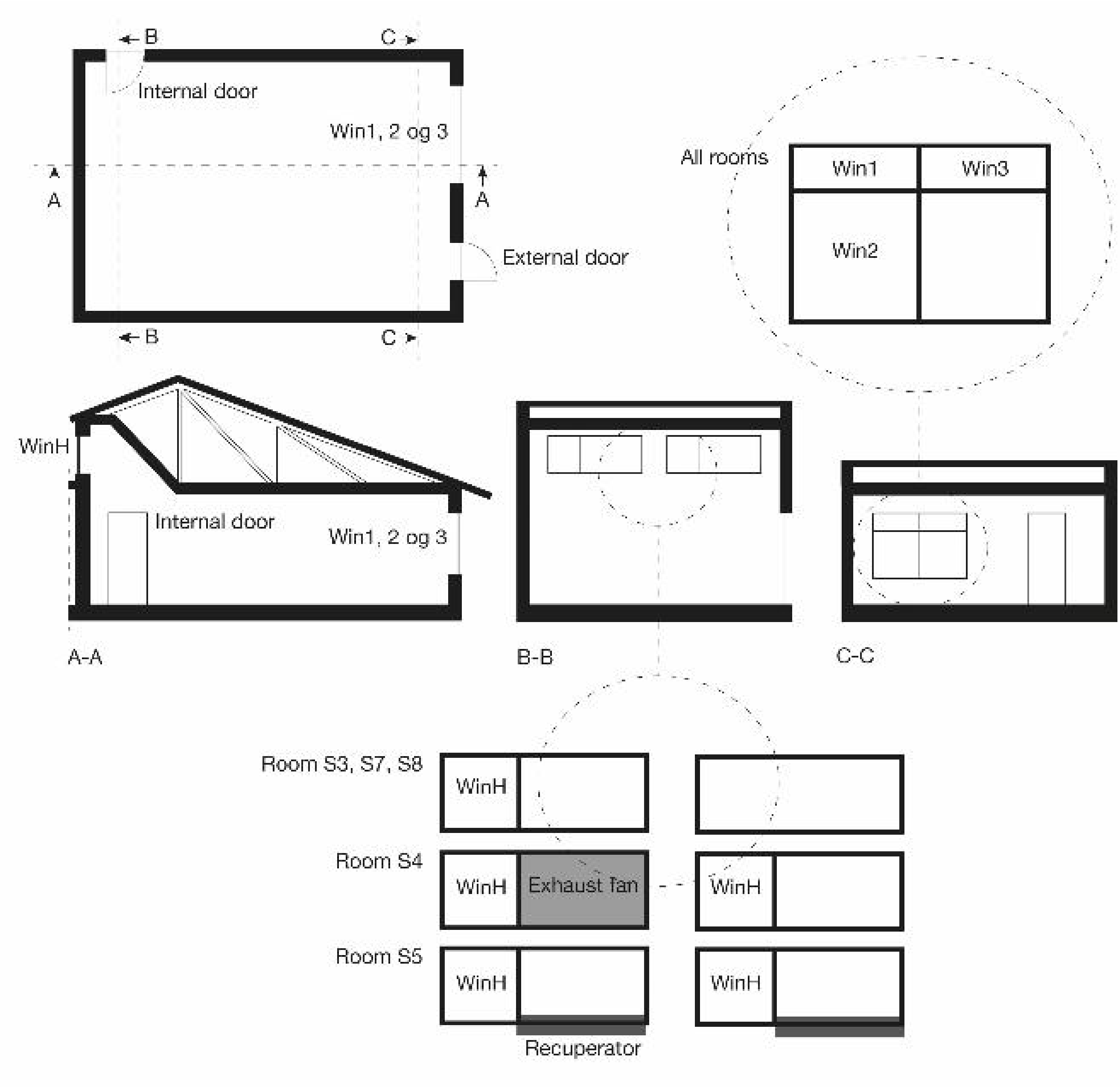


Figure 2

Figure 3



B
C
Internal door
Win1, 2 og 3
A
A
External door
B
C
All rooms
Win1
Win3
Win2
WinH
Internal door
Win1, 2 og 3
A-A
B-B
C-C
Room S3, S7, S8
WinH
Room S4
WinH
Exhaust fan
WinH
Room S5
WinH
WinH
Recuperator

Figure 4

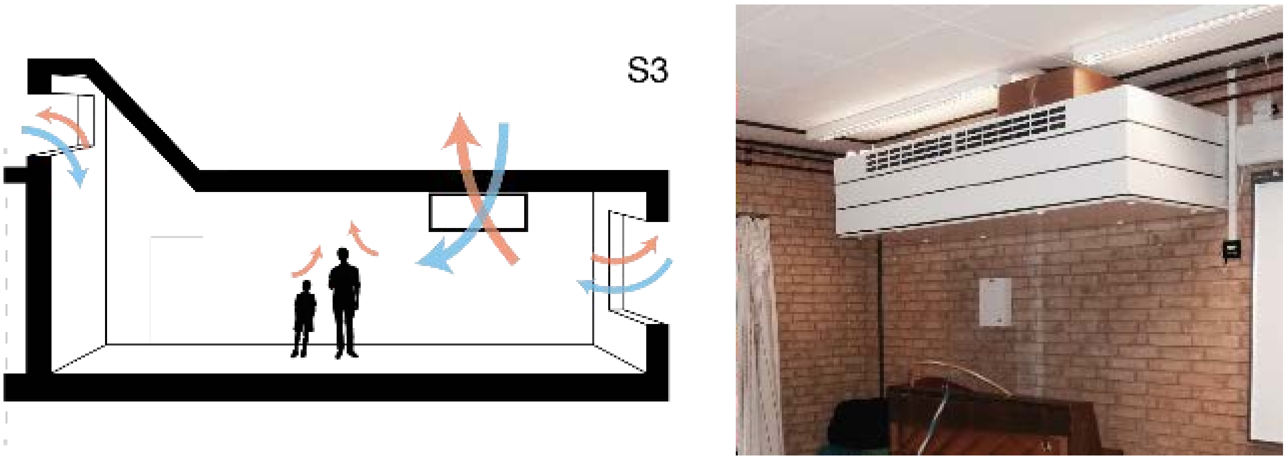
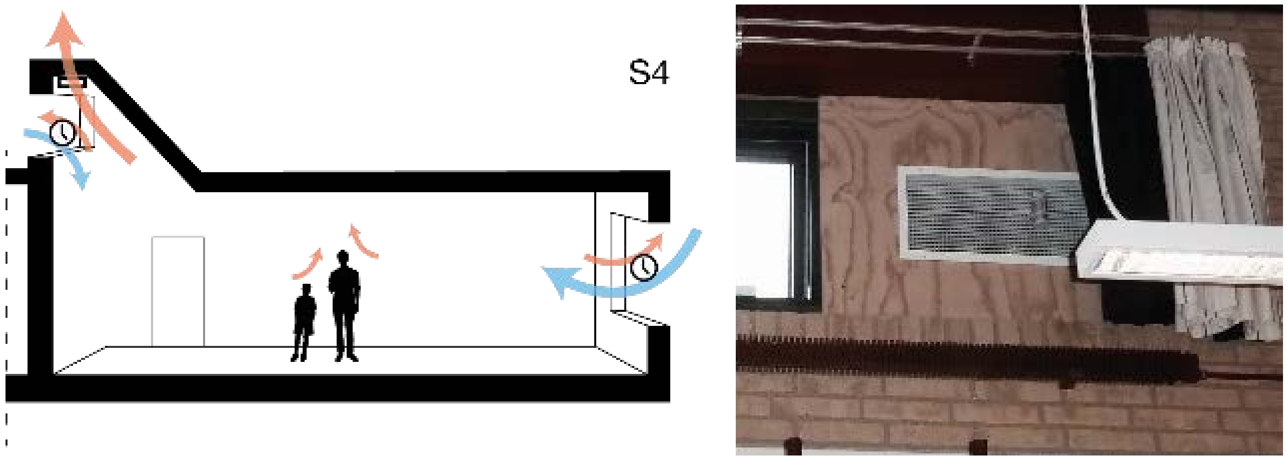


Figure 5



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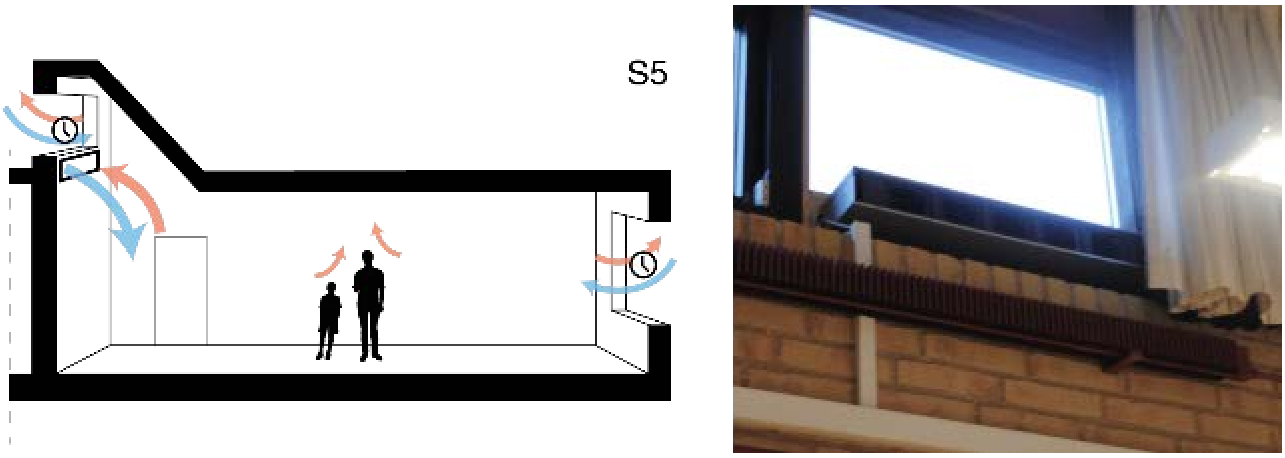


Figure 7

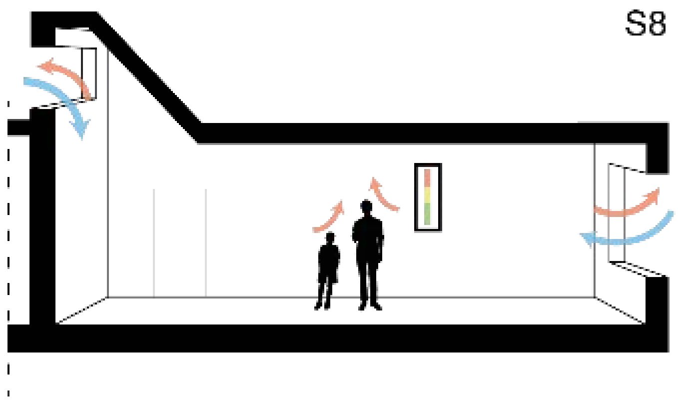


Figure 8

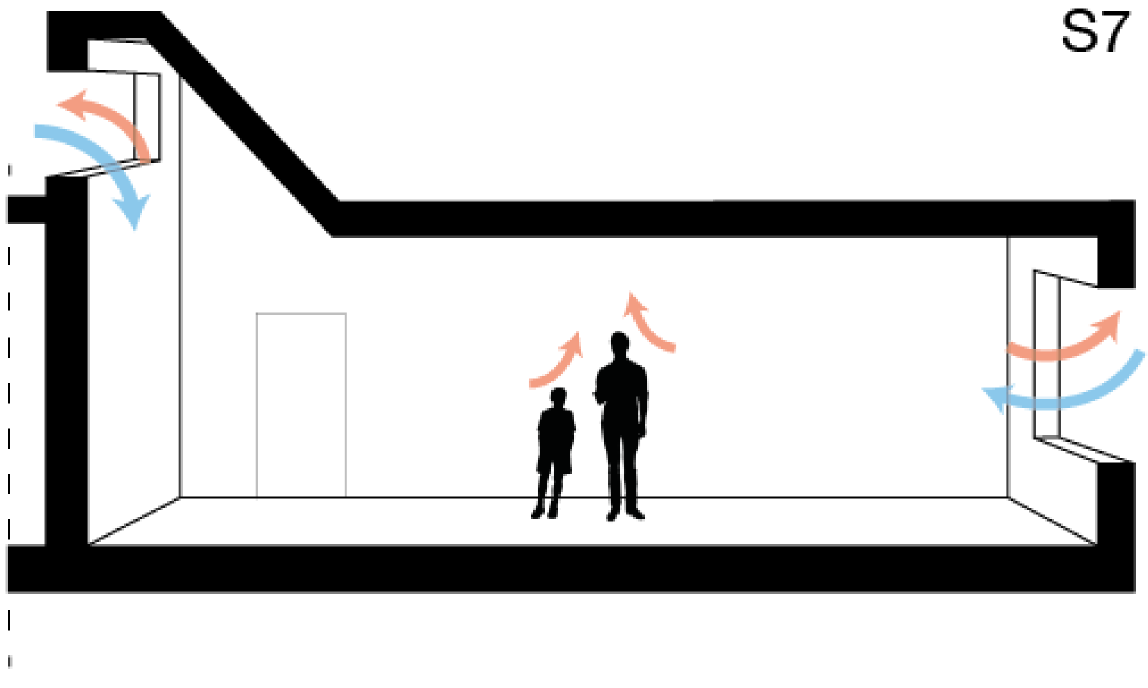


Figure 9

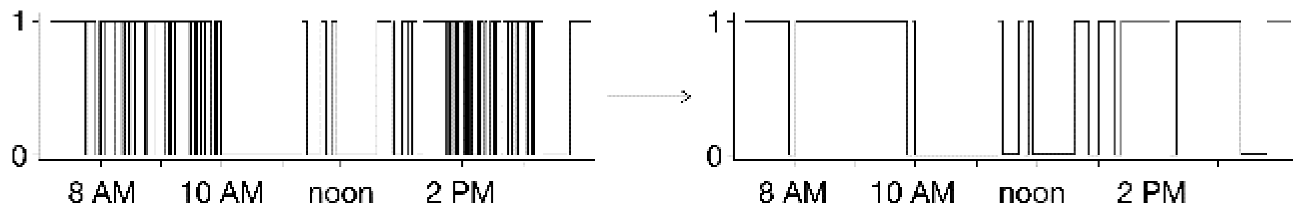


Figure 10

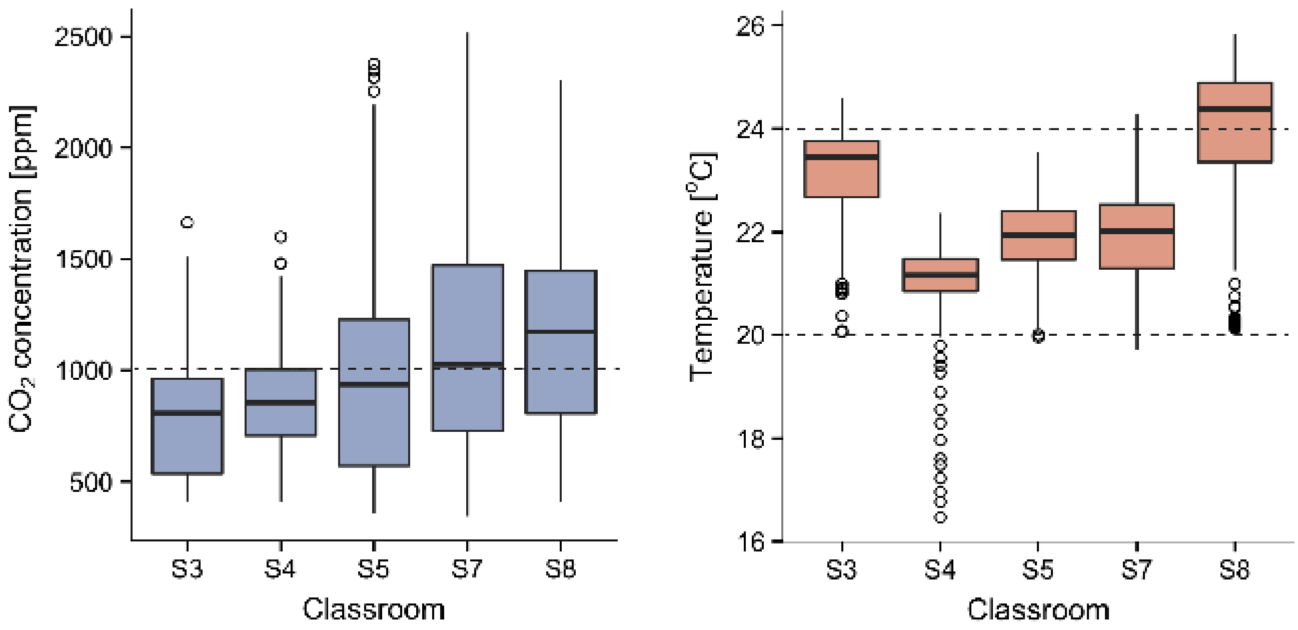
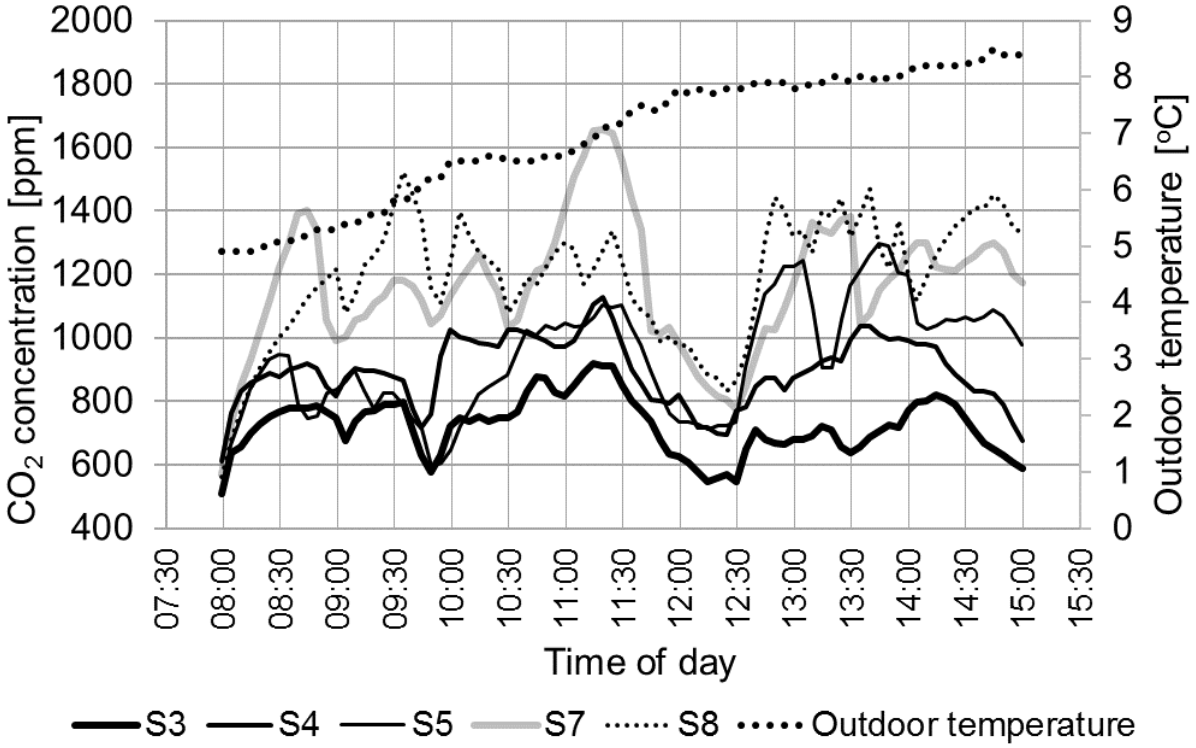
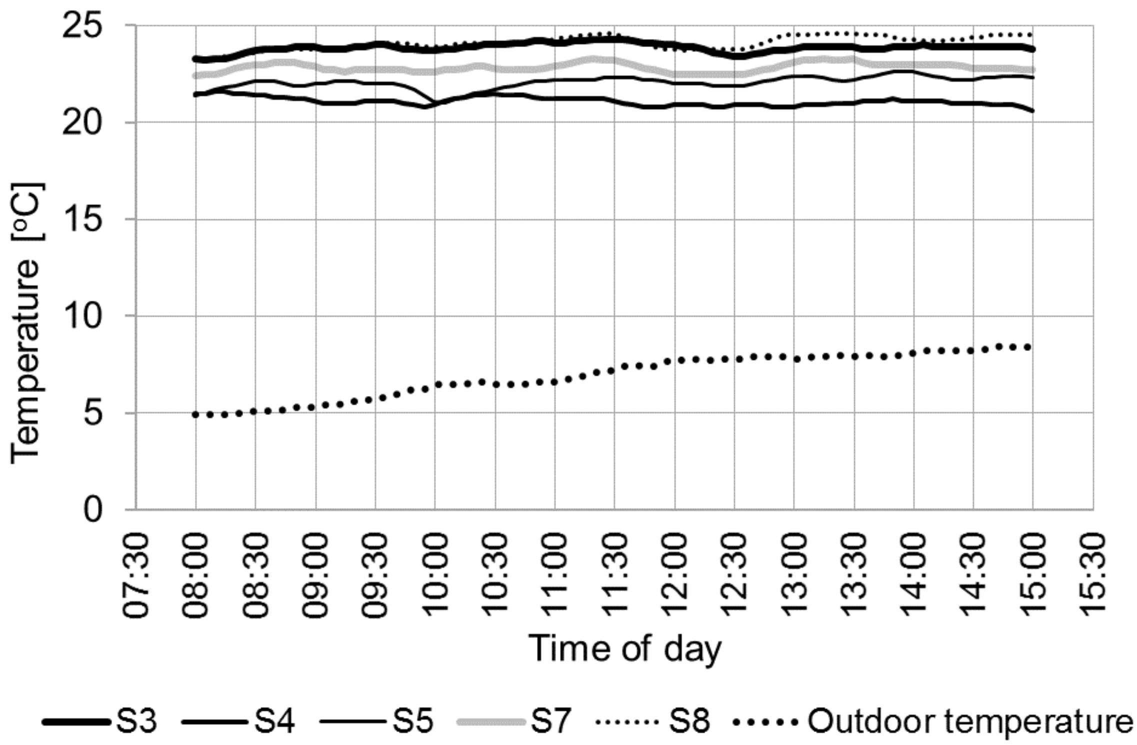


Figure 11


2000
1800
1600
1400
1200
1000
800
600
400
CO_2 concentration [ppm]
9
8
7
6
5
4
3
2
1
0
Outdoor temperature [ºC]
07:30
08:00
08:30
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
Time of day
S3
S4
S5
S7
S8
Outdoor temperature


25
20
15
10
5
0
Temperature [ºC]
07:30
08:00
08:30
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
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14:30
15:00
15:30
Time of day
S3
S4
S5
S7
S8
Outdoor temperature

Figure 12

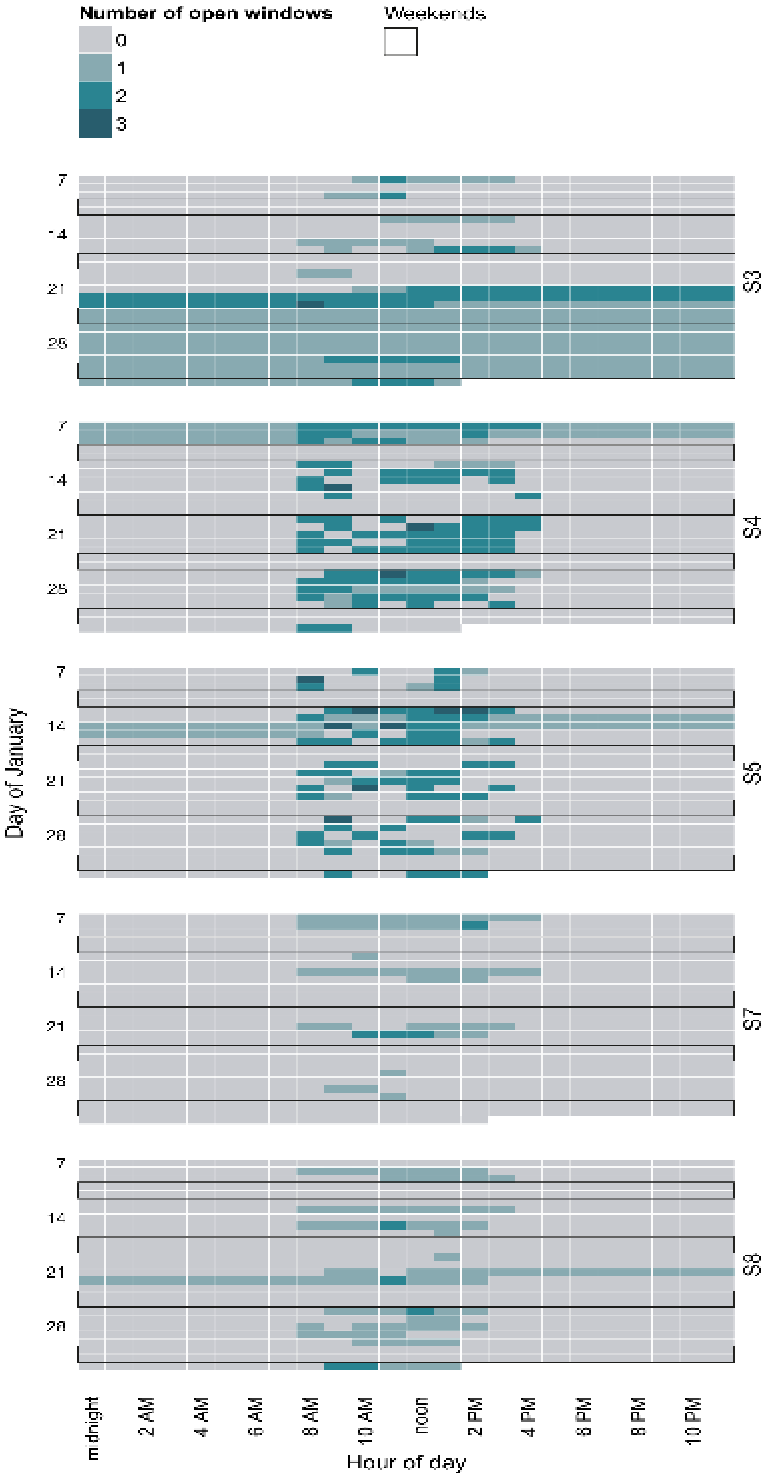

Number of open windows
0
1
2
3
Weekends
S3
S4
S5
S7
S8
Day of January
7
14
21
28
midnight
2 AM
4 AM
6 AM
8 AM
10 AM
noon
2 PM
4 PM
6 PM
8 PM
10 PM
Hour of day

Figure 13

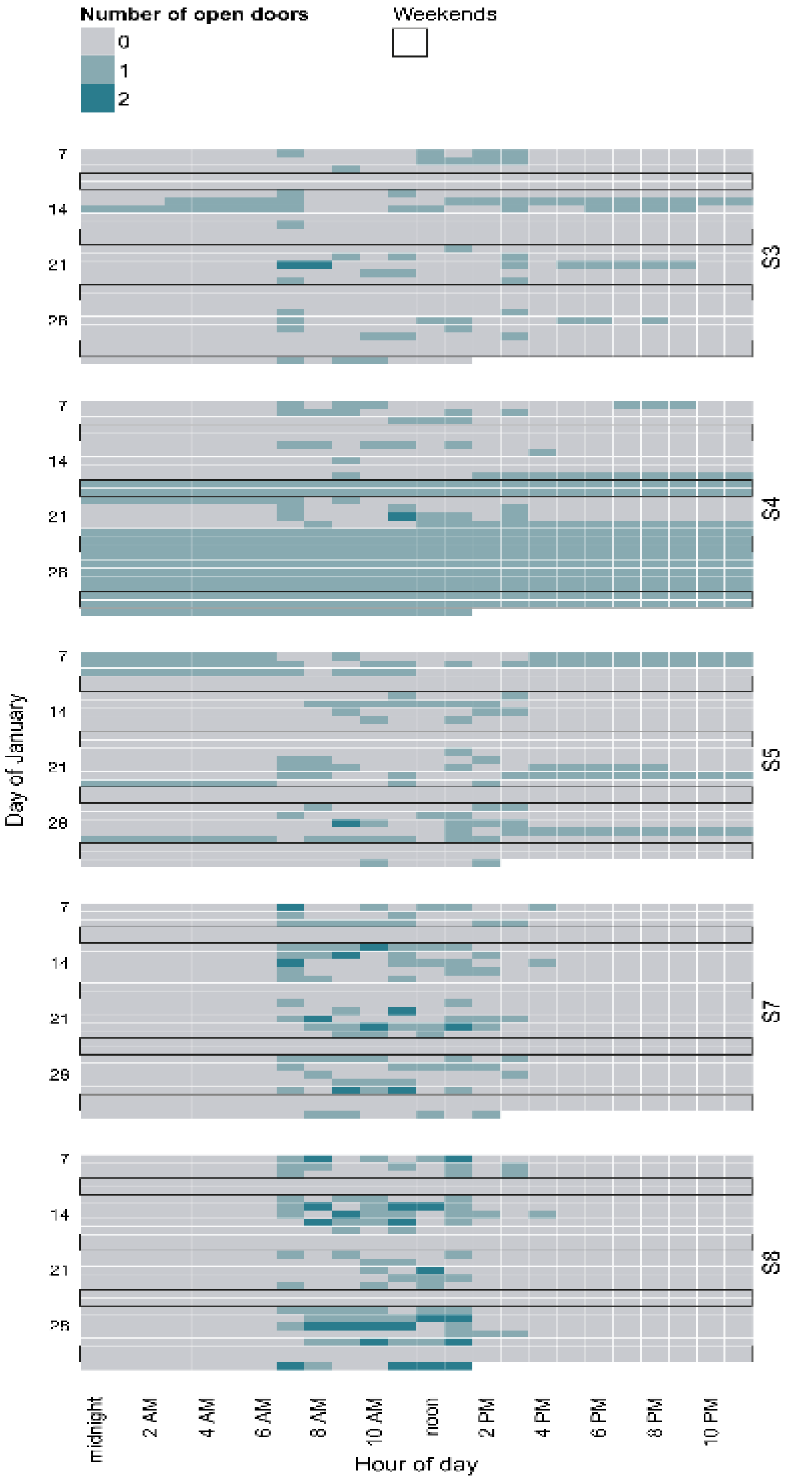
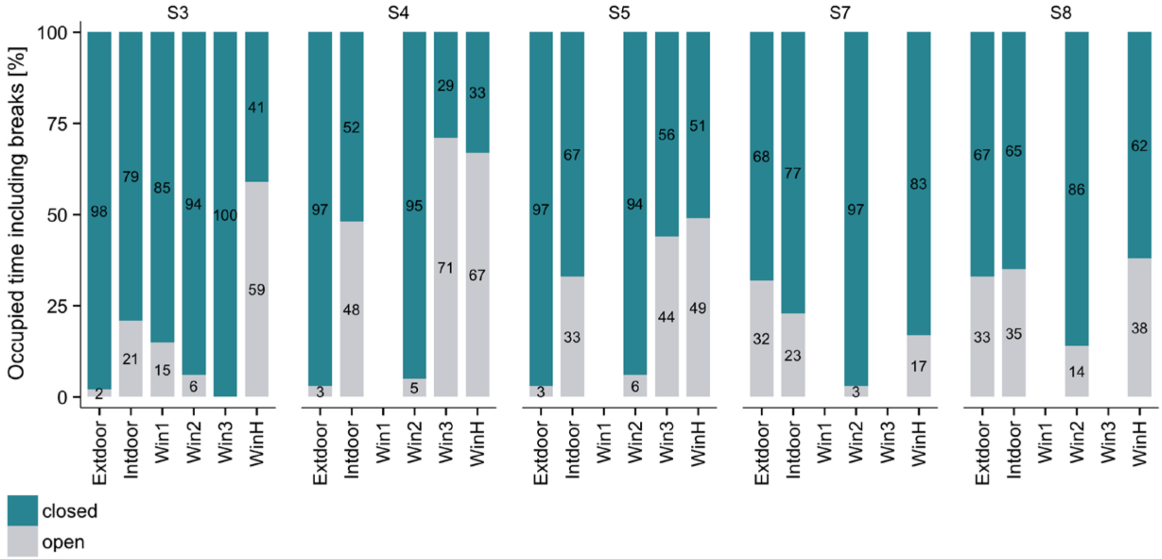

Number of open doors
0
1
2
Weekends
7
14
21
28
S3
S4
S5
S7
S8
Day of January
midnight
2 AM
4 AM
6 AM
8 AM
10 AM
noon
2 PM
4 PM
6 PM
8 PM
10 PM
Hour of day

Figure 14

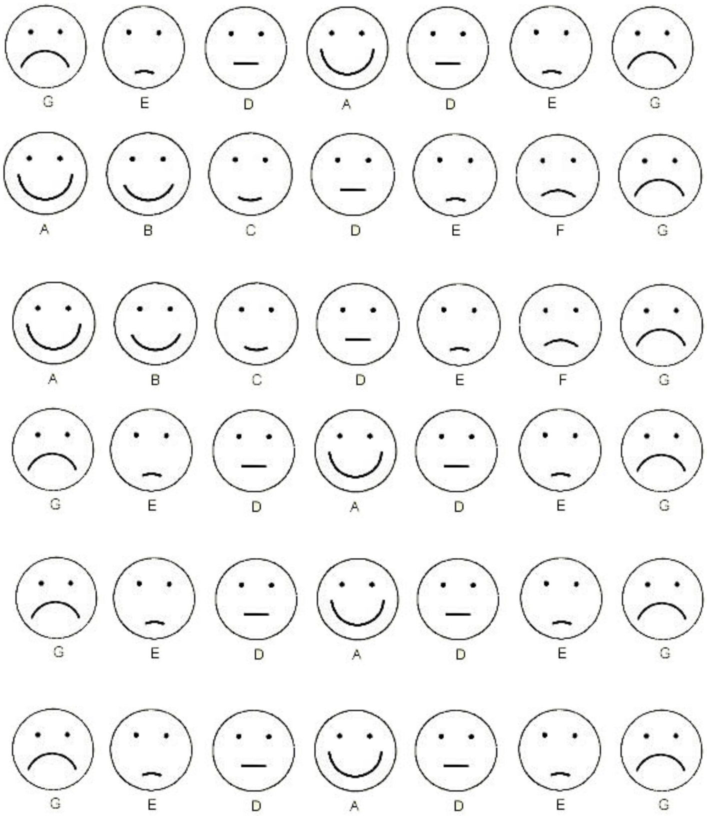

S3
S4
S5
S7
S8
Occupied time including breaks [%]
100
75
50
25
0
98
2
79
21
85
15
94
6
100
41
59
97
3
52
48
95
5
29
71
33
67
97
3
67
33
94
6
56
44
51
49
68
32
77
23
97
3
83
17
67
33
65
35
86
14
62
38
Extdoor
Intdoor
Win1
Win2
Win3
WinH
closed
open

Class_______________Initials______________________

Are you a boy or a girl: BOY GIRL

Please answer by marking a smiley:

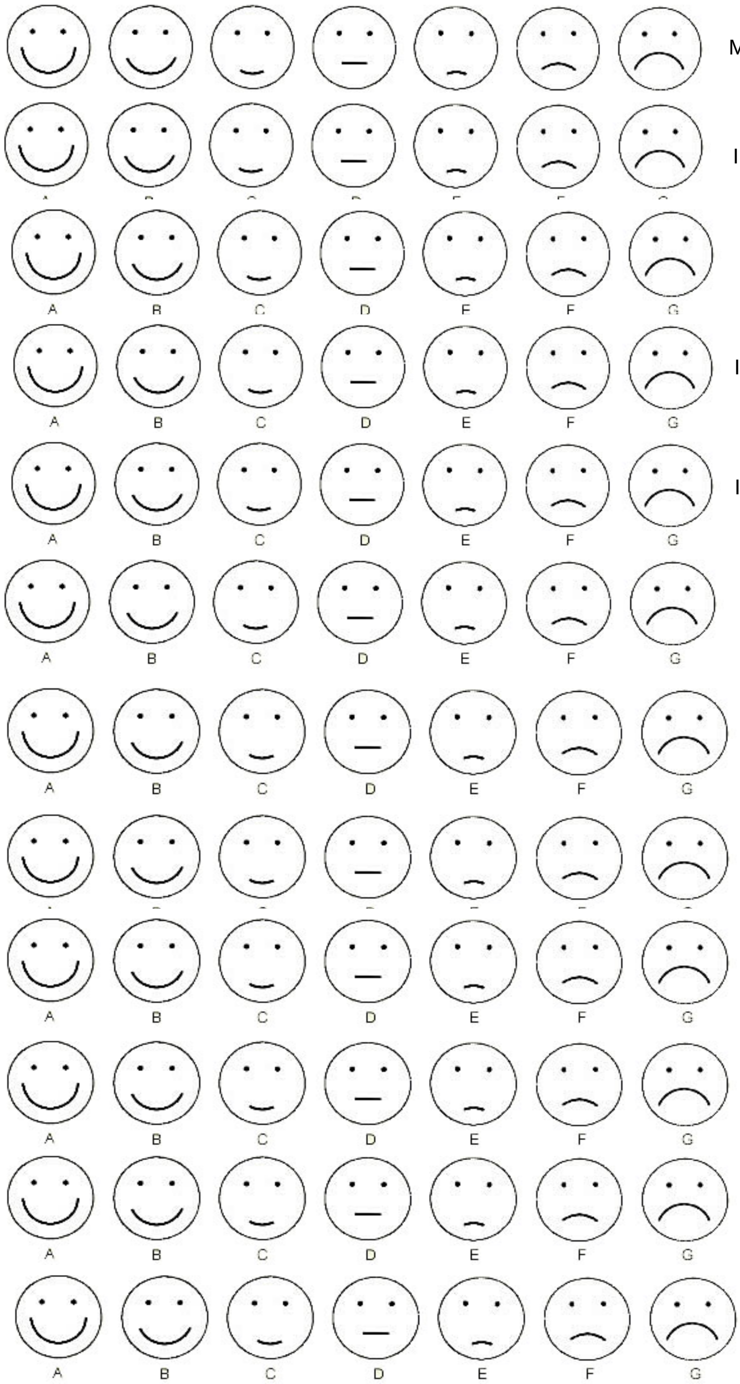
How was the classroom this week?



Much too cold	G	E	D	A	D	E	G	Much too warm
The air was fresh	A	B	C	D	E	F	G	The air was poor
There was no draught	A	B	C	D	E	F	G	It was draughty
The noise level was too low	G	E	D	A	D	E	G	The noise level was too loud
It was too humid	G	E	D	A	D	E	G	It was too dry
Too little light	G	E	D	A	D	E	G	Too much light

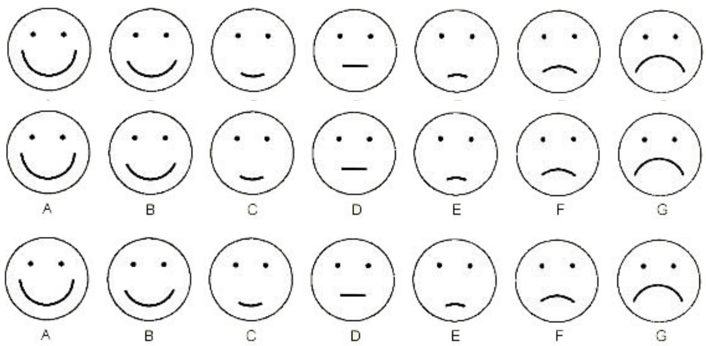
Turn

How did you feel this week while in school?



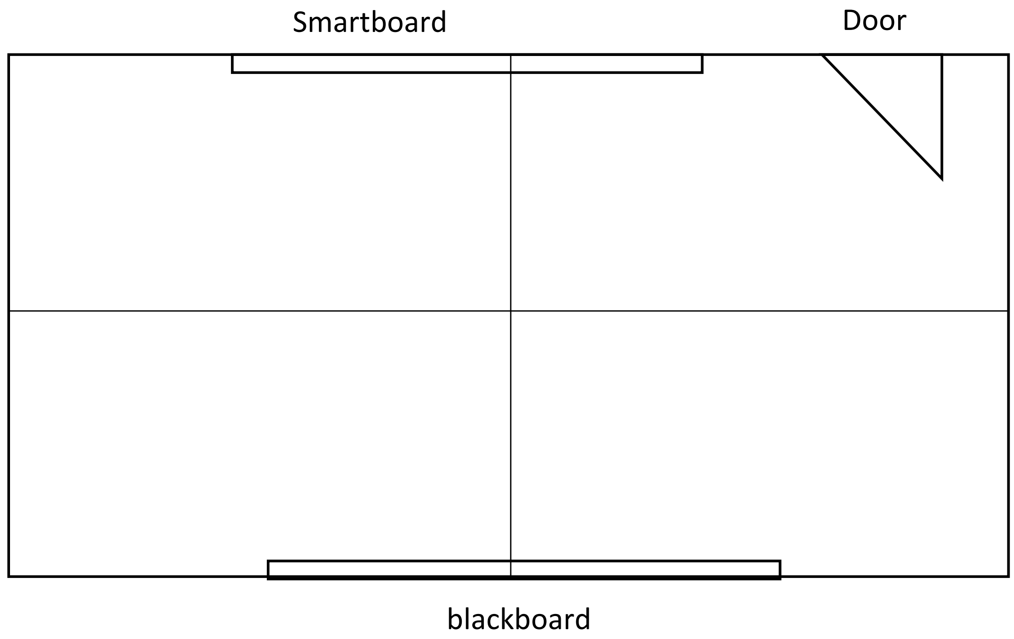
I could breathe freely	My nose was blocked
I was tired	I was not tired at all
I did not have headaches	I had headaches
I wanted to work	I did not want to work
I did not have dry lips	I had dry lips
I did not have dry skin	I had dry skin
I did not have a dry throat	I had a dry throat
I felt well	I did not feel well
I did not have stinging eyes	I had stinging eyes
It was easy to concentrate	It was difficult to concentrate
I was awake	I was sleepy
There was no noise	There was too much noise

How was learning this week?



I was not disturbed by the other pupils	I was disturbed by the other pupils
The other pupils were quiet	The other pupils were noisy
I could hear the teacher loud and clear	I could not hear the teacher

Mark on the drawing with an [X] where in class you were sitting:
mark with an [O], where the teacher was mostly sitting or standing:



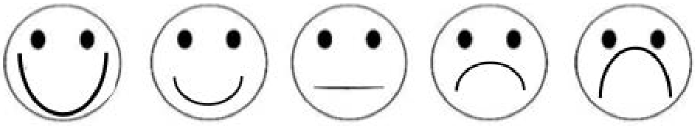
Class_______________**Name**______________________

Are you a boy or a girl: BOY GIRL

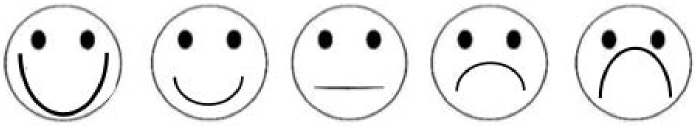
10.1.1

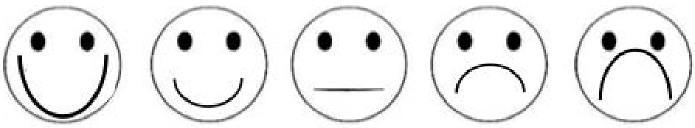
Please answer by marking a smiley:

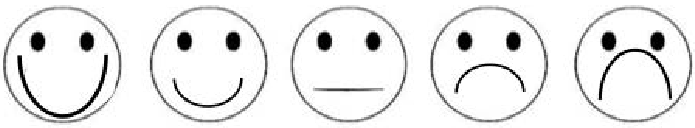
How was your week in school?

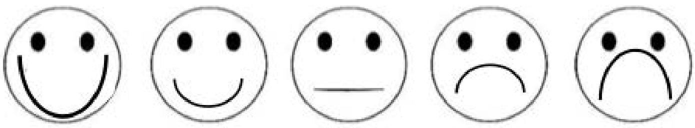
Fantastic  Miserable

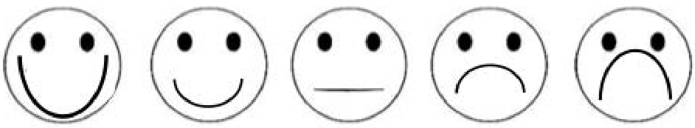
How was the classroom this week?

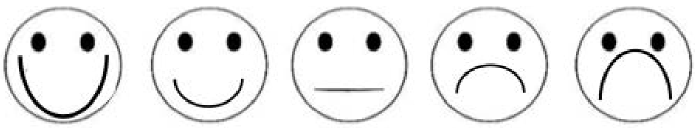
Fantastic  Miserable

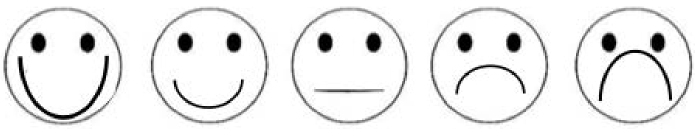
Not too warm  Too warm

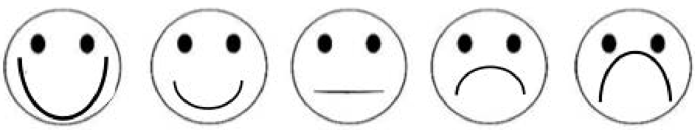
Not too cold  Too cold

Not draughty  Draughty

The air was fresh  The air was poor

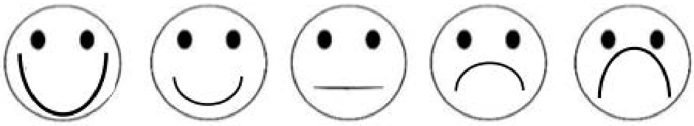
Not too much noise  Too much noise

Not too much light  Too much light

Not too dark  Too dark

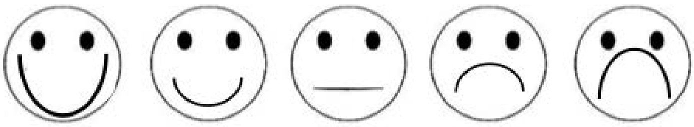
How did you feel this week while in school?

The temperature was fine



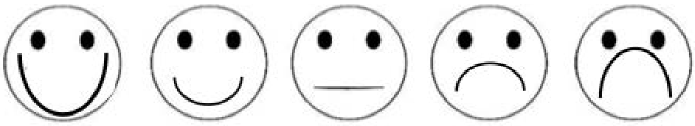
The temperature was not fine

I could breathe freely



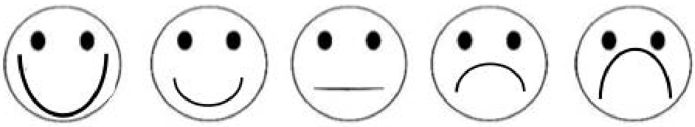
My nose was blocked

My skin was not dry



My skin was very dry

My throat was not dry



My throat was very dry

Table D.1. Schedule of presentation of performance tasks and questionnaires for collecting subjective evaluations in the heating season 2014; the day, time and duration (in brackets) of a task are shown.

Heating season 2014							
		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
S3 Decentralized mechanical ventilation	Subtraction test	Wed-09:00 (8:00)	Wed-09:00 (6:30)	n/a	n/a	Wed-08:50 (5:44)	Wed-08:45 (4:58)
	Multiplication test	n/a	n/a	Wed-08:45 (10:00)	Wed-08:45 (10:00)	n/a	n/a
	Grammatical reasoning	Wed-11:20 (5:32)	Wed-11:20 (4:21)	n/a	n/a	Wed-n/a	Fri-11:45 (4:30)
	Reading and comprehension	Not used in the analyses					
	d2-test	Thu-11:35	Fri-10:35	n/a	Wed-11:20	Thu-10:35	Fri-10:55
	Questionnaire	Fri-13:00	Fri-13:00	Fri-10:35	Thu-13:15	Wed-11:20	Thu-10:35
S4 Automatic window opening, exhaust fan	Subtraction test	Wed-13:05 (9:30)	Wed-13:15 (7:02)	n/a	n/a	n/a	Wed-13:15 (7:45)
	Multiplication test	n/a	n/a	Wed-13:15 (10:00)	Wed-13:15 (10:00)	n/a	n/a
	Grammatical reasoning	Wed-11:20 (10:00)	Wed-11:45 (10:00)	n/a	n/a	Wed-11:20 (10:00)	Wed-11:45 (10:00
	Reading and comprehension	Not used in the analyses					
	d2-test	Thu-11:35	Thu-10:35	Tue-12:30	Thu-10:35	Thu-10:35	Thu-10:35
	Questionnaire	Thu-13:15	n/a	Thu-13:15	Thu-10:35	Thu-10:35	Thu-10:35
S5 Automatic window opening	Subtraction test	n/a-13:15 (9:23)	Tue-13:15 (6:15)	n/a	n/a	Tue-13:15 (7:22)	Tue-13:15 (5:07)
	Multiplication test	n/a	n/a	Tue-13:15 (4:21)	Tue-14:00 (4:31)	n/a	n/a
	Grammatical reasoning	Wed-11:00 (6:30)	Wed-11:00 (4:30)	n/a	n/a	Wed-10:35 (4:12)	Wed-10:35 (4:43)
	Reading and comprehension	Not used in the analyses					
	d2-test	Thu-12:30	Thu-13:15	Thu-13:15	Thu-13:15	Fri-08:15	Thu-13:15

	Questionnaire	Thu-13:00	Thu-13:15	Thu-13:15	Thu-13:15	Fri-08:15	Thu-13:15
S8 Visual display unit	Subtraction test	Wed-n/a (9:40)	Wed-09:50 (6:41)	n/a	n/a	Wed-09:35 (5:52)	Wed-10:35 (6:22)
	Multiplication test	n/a	n/a	Wed-10:35 (5:58)	Wed-10:35 (5:49)	n/a	n/a
	Grammatical reasoning	Wed-12:40 (7:30)	Wed-13:20 (7:00)	n/a	n/a	Wed-13:15 (6:00)	Wed-12:55 (7:00)
	Reading and comprehension	Not used in the analysis					
	d2-test	Thu-13:15	Thu-12:35	Fri-13:15	Thu-13:30	Thu-13:50	Thu-13:15
	Questionnaire	Thu-13:15	Thu-13:15	Thu-13:15	Thu-13:15	Thu-13:15	Thu-13:15
S7 Reference classroom (no retrofit)	Subtraction test	Wed-09:50 (8:40)	n/a-09:50 (10:00)	n/a	n/a	Thu-09:50 (7:41)	Thu-09:50 (8:40)
	Multiplication test	n/a	n/a	Thu-11:20 (7:30)	Thu-09:50 (5:51)	n/a	n/a
	Grammatical reasoning	Wed-14:30 (10:00)	Wed-13:30 (5:25)	n/a	n/a	Wed-13:15 (10:00)	Wed-13:15 (3:15)
	Reading and comprehension	Not used in the analysis					
	d2-test	Fri-14:00	Fri-14:00	Fri-13:15	Fri-13:15	Fri-13.15	Fri-13:15
	Questionnaire	Fri-13:30	Fri-13:15	Fri-13:15	Fri-13:15	Fri-13:15	Fri-13:30

Table D.2. Schedule of presentation of performance tasks and tests and questionnaires for collecting subjective evaluations in the non-heating season 2015; the day, time and duration (in brackets) of task are shown

Non-heating season 2015							
		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
S3 Decentralized mechanical ventilation	Modified math test	n/a	Wed-11:47 (8:00)	Wed-11:40 (8:00)	Wed-11:20 (8:00)	Wed-11:45 (8:00)	Wed-11:45 (n/a)
	Graphical-logical test	n/a	Wed-08:15 (5:00)	Fri-11:05 (5:00)	Wed-11:40 (4:05)	Fri-11:15 (5:00)	Fri-11:15 (n/a)
	d2-test	n/a	Wed-08:30	Wed-08:20	Wed-11:50	Wed-09:15	Wed-09:00
	Questionnaire	n/a	Wed-08:30	Wed-08:30	Wed-11:45	Wed-09:15	Wed-09:00
S4 Automatic window opening, exhaust fan	Modified math test	Fri-08:25 (8:00)	Wed-13:25 (08:00)	Wed-13:45 (8:00)	Wed-13:45 (n/a)	Wed-13:45 (n/a)	Wed-12:45 (a/a)
	Graphical-logical test	Fri-13:30 (5:00)	Wed-10:30 (5:00)	Fri-13:30 (5:00)	Wed-10:30 (5:00)	Fri-13:15 (5:00)	Fri-13:50 (5:00)
	d2-test	Wed-11:00	n/a	Wed-11:20	n/a	Wed-10:00	Wed-11:00
	Questionnaire	unknown	Wed-10:30	Wed-11.20	Wed-11:20	Wed-.10:00	Wed-11:00
S5 Automatic window opening	Modified math test	n/a	Unknown (8:00)	Thu-11:06 (8:00)	Thu-10:35 (8:00)	Thu-11:11 (8:00)	Thu (11:10 (8:00)
	Graphical-logical test	n/a	Tue-12:42 (5:00)	Wed-09:50 (5:10)	Wed-09:50 (9:00)	Tue-12:30 (8:40)	Tue-12:30 (6:25)
	d2-test	Fri-08:15	Thu-08:45	Thu-08:20	Thu-08:15	Thu-08:15	Thu-09:00
	Questionnaire	unknown	Thu-09:00	Thu-08:50	Thu-08:30	Thu-08:30	Thu-09:15
S8 Visual display unit	Modified math test	n/a	n/a	Wed-10:00 (8:00)	Wed-10:15 (8:00)	Wed-11:10 (8:00)	n/a
	Graphical-logical test	Tue-14:45 (8:00)	Tue-13:45 (5:00)	Tue-13:45 (5:00)	Tue-13:45 (5:00)	Tue-13:45 (5:00)	Tue-13:40 (5:00)
	d2-test	Thu-11:10	n/a	Thu-11:15	Thu-11:15	Thu-12:37	Thu-11:05
	Questionnaire	Thu-11:15	n/a	Thu-11:15	Thu-11:20	Thu-12:45	Thu-11:10

S7 Reference classroom (no retrofit)	Modified math test	Thu-11:10 (8:00)	Thu-11:00 (8:009	Thu-11:10 (8:00)	Thu-11:10 (8:00)	Wed-11:15 (8:00)	Thu-11:05 (8:00)
	Graphical-logical test	Thu-9:00 (5:00)	Wed-09:25 (5:00)	n/a	Wed-09:20 (5:00)	Tue-11:10 (5:00)	Wed-08:45 (n/a)
	d2-test	Fri-13:15	Thu-09:30	Thu-09:15	Thu-09:20	n/a	Thu-08:45
	Questionnaire	Fri-13:30	Thu-09:50	Thu-09:15	Thu-09:20	n/a	n/a

Table D.3. Schedule of presentation of performance tasks and tests and questionnaires for collecting subjective evaluations in the heating season 2016; the day, time and duration (in brackets) of task are shown

Heating season 2016							
		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
S5 Automatic window opening, heat recovery units	Modified math test	Mon-14:11 (8:00)	Mon-14:10 (10:00)	Mon-13:15 (8:00)	Mon-14:20 (8:00)	Mon-n/a (8:00)	Mon-14:07 (8:00)
	Graphical-logical test	Wed-14:40 (5:00)	Wed-14:14 (5:00)	Wed-14:06 (5:00)	Wed-14:15 (n/a)	n/a	Wed-14:15 (5:00)
	d2-test	Thu-13:30	Fri-13:54	Thu-13:30	n/a	n/a	unknown
	Questionnaire	Wed-14:00	Wed-14:00	Wed-14:00	Wed-14:00	n/a	Wed-14:00
S7 Reference classroom (no retrofit)	Modified math test	Tue-14:20 (8:00)	Tue-14:15 (8:00)	Tue-n/a (8:00)	Tue-11:21 (8:00)	Tue-14:10 (8:00)	Tue-12:35 (8:00)
	Graphical-logical test	Wed-13:50 (n/a)	Wed-10:45 (7:25)	Wed-14:00 (4:00)	Thu-11:15 (4:30)	Wed-n/a (3:20)	Wed-14:00 (3:00)
	d2-test	Mon-14:40	Mon-14:50	Mon-14:55	Mon-15:00	Mon-15:00	Mon-15:00
	Questionnaire	Wed-13:15	Wed-13:15	Wed-13:15	Wed-13:15	Wed-13:15	Wed-13:15

Date:	
Name: Room:	

Please mark on the scale how you perceived the classroom this week?

Air too humid	├──────┤	Luften for tør
Stuffy air	├──────┤	Frisk luft
Too little light	├──────┤	For meget lys
Too quiet	├──────┤	For støjende

During this week, how did you feel while in the classroom?

Dry nose	├──────┤	Runny nose
Dry throat	├──────┤	Not dry throat
Dry skin	├──────┤	Not dry skin
Dry eyes	├──────┤	Not dry eyes
Stinging eyes	├──────┤	Not stinging eyes
Strong headache	├──────┤	No headache
Difficult to think	├──────┤	Easy to think
Not well	├──────┤	Well
Tired	├──────┤	Rested
Difficult to concentrate	├──────┤	Easy to concentrate
Alert	├──────┤	Sleepy

How do you think teaching went this week, while being in this classroom?

Teaching was:

Very easy |———————————| Very demanding

The pupils were:

Calm |———————————| Disturbing

I used:

0% |———————————| 100% of my maximum capacity

Table F.1 shows the area, volume, occupant density, and window area in each type of room in the south wing. The total area of the south wing is 938 m^2.

F.2 shows the properties of the materials used in the walls, doors, ceilings and roof.

Table F.1. Geometrical details of the rooms in the simulation model of the south wing.

Name	Room Height [m]	Floor area [m^2]	Volume [m^3]	Occupant density [Pers./m^2]	Window area [m^2]
Classroom	2.7 - 2.97	55.57	164.79	0.43	6.27
Group room	2.70	28.13	74.51	0.36	3.37
Smaller group room	2.70	19.08	51.52	0.52	3.37
Toilet1	2.70	13.19	35.61	0.3	0
Toilet2	2.70	10.13	27.84	0.39	0
Depot 1	2.70	14.33	38.68	0.0	3.37
Depot 2	2.70	27.51	74.29	0.0	3.37
Common area	2.83	301.20	851.64	0.08	34.74

Table F.2. Material properties of the building components.

Ext. Heavy wall	Brick [m]	Insulation [m]	Brick [m]			Total thickness [m]	U-Value [W/(m2·K)]
	0.11	0.13	0.11			0.35	0.2404
Ext. Light wall	L/W Concrete [m]	Insulation [m]	[Gypsum]				
	0.02	0.11	0.026			0.156	0.2876
Int. Heavy wall	Brick [m]	Insulation [m]	Brick [m]				
	0.11	0.13	0.11			0.35	0.2404
Int. Light wall	Gypsum [m]	Insulation [m]	Gypsum [m]				
	0.026	0.1	0.026			0.152	0.3141
Ceilling	Gypsum [m]	Chipboard [m]	Insulation [m]				
	0.026	0.025	0.2			0.251	0.1657
Sloping roof	Brick [m]	Chipboard [m]	Gypsum [m]				
	0.12	0.022	0.013			0.155	1.652
Flat roof	Chipboard [m]	Insulation [m]	Wood [m]				
	0.025	0.1	0.055			0.18	0.656
Floor	Sand [m]	Concrete [m]	Sand [m]	Insulation [m]	Chipboard [m]		
	0.15	0.12	0.03	0.05	0.022	0.372	0.5217
2 pane glazing						-	2.9

Systems

Table F.3 shows the different systems, their control, and control type. The lights and equipment were controlled by occupant presence and were activated on an on/off basis, as the school did not have light sensors to regulate the internal lights according to the available daylight. With no occupants present, the lights were turned off.

Table F.3. Systems and system control types that were used in the model.

	Control	Control Type
Light	Occupant presence	On/off
Equipment	Occupant presence	On/off
Boiler	Season	On/off
Windows	Temperature	Proportional
Windows #2	CO_2	Proportional
Doors	Shedule	On/off
Radiators	Temperature	Proportional
Toilet ventilation	Occupant presence	On/off
AHU	Occupant presence	Proportional
Solar shading	Light and occupant presence	On/off

The heating system comprised one water based radiator (lxh 2m x 0.5 m) located below the façade windows and two water based convectors (lxh 1.2m x 0.5m) below the overhead windows. The maximum heat output of the radiators was estimated at 3 kW in the classrooms and 17 kW in the common areas, based on historical guidelines and reference values, as no information on the radiators and convectors was available. The radiators had proportional control to mimic the thermostat on a radiator. The radiators were thermostat controlled with a set-point of 20°C during the occupied time during the heating season. At night, the thermostat was set back at 18^{o}C. The heating season was from 1st September to 30th April.

In each classroom, the internal heat gains were estimated at 385 W from lighting and 75 W from equipment. Both lighting and equipment were switched off during holidays.

Interior doors were opened 15 % during recess. Exterior doors were kept closed. Infiltration of outdoor air was estimated at 1.5 h^{-1} at 50 Pa pressure difference between inside and outside, corresponding to ~0.9 l/s pr. m^2 floor area. The outdoor CO_2 concentration was 400 ppm and the wind profile selected to suburban.

The toilets had exhaust fans controlled by occupant presence at recess. There was no information on the fan type so a SFP of 1 kJ/m^3 was assumed. The fans exhausted 15 l/s when occupants were present as defined in the Danish Building code (BR 2015).

The internal solar shading was defined as medium dark, thickly woven drapes, similar to the ones used at the school.

Occupancy

The simulations were run with 25 occupants in each classroom.

The school was considered unoccupied during weekends, holidays, and vacation periods as shown in Table F.4.

Table F.4. Periods when the school was considered unoccupied due to weekends, holidays, and vacations.

	Start	End
Weekends	-	-
Winter vacation	8th of February	14th of February
Easter	12th of April	21st of April
Summer vacation	28th of June	10th of August
Autumn vacation	11th of October	19th of October
Christmas vacation	20th of December	2nd of January

Estimated installation and maintenance costs:

AIRMASTER AS

Montage- og serviceomkostninger

Grundlæggende informationer

Beskrivelse	Ravnsholdt skolen
Udfyldt af	Lars Rasmussen
Dato	03.06.2015

Angiv det aktuelle antal anlæg

AM 100 H		AM 800 H	1
AM 100 V		AM 800 V	
AM 300 H		AM 900 H	
AM 300 V		AM 900 V	
AM 500 H		AM 1200 H	
AM 500 V		AM 1200 V	
Samlet antal anlæg			1

Angiv konstruktionstype og serviceniveau

Vægkonstruktion	Mursten
Ønsket serviceniveau	Sølv
Servicekontraktens længde	1 år

Beregningsresultater

Samlede montageomkostninger	7,400.00 DKK
Samlede serviceomkostninger	813.80 DKK

De grønne felter KAN ændres ved ændrede forudsætninger

BEREGNING		Pris pr. time	Pris pr. hul	Antal timer	Antal anlæg	Montage i alt	Serviceomkostninger i alt
Serviceomkostninger							
Opstartsomkostning		-	-	-	1		175.00
AM 100, AM 300		-	-	-	0		0.00
AM 500, AM 800, AM 900		-	-	-	1		638.80
AM 1200		-	-	-	0		0.00
Vægmodel							
	Montage						
AM 100, AM 300	Hulboring	-	640	-	0	0.00	
	Transport af anlæg til lokale	500	-	0.5	0	0.00	
	Isætning af murgennemføring og udvendig rist	500	-	1.5	0	0.00	
	Opskruning af vægbeslag og ophæng af anlæg på vægbeslag	500	-	1.5	0	0.00	
AM 500, AM 800, AM 900	Hulboring	-	1200	-	1	2,400.00	
	Transport af anlæg til lokale	500	-	0.5	1	250.00	
	Isætning af murgennemføring og udvendig rist	500	-	1.5	1	750.00	
	Opskruning af vægbeslag og ophæng af anlæg på vægbeslag	500	-	2	1	1,000.00	
AM 1200	Hulboring	-	2000	-	0	0.00	
	Transport af anlæg til lokale	500	-	1	0	0.00	
	Isætning af murgennemføring og udvendig rist	500	-	2	0	0.00	
	Opstilling af anlæg på gulv og justering	500	-	3	0	0.00	
	(timer fra Andersen og Thybo tømrerfirma)						
Tagmodel							
	Montage						
AM 100, AM 300	Transport af anlæg til lokale	500	-	0.25	0	0.00	
	Opskruning af vægbeslag og ophæng af anlæg på vægbeslag	500	-	1.5	0	0.00	
	Hulskæring i lofter og tag samt montage af kanaler og taginddækning	500	-	4	0	0.00	
	Påbrænding af tagpap/montage af inddækning	500	-	2	0	0.00	
AM 500, AM 800, AM 900	Transport af anlæg til lokale	500	-	0.5	0	0.00	
	Opskruning af vægbeslag og ophæng af anlæg på vægbeslag	500	-	2	0	0.00	
	Hulskæring i lofter og tag samt montage af kanaler og taginddækning	500	-	5	0	0.00	
	Påbrænding af tagpap/montage af inddækning	500	-	2	0	0.00	
AM 1200	Transport af anlæg til lokale	500	-	1	0	0.00	
	Opstilling af anlæg på gulv og justering	500	-	3	0	0.00	
	Hulskæring i lofter og tag samt montage af kanaler og taginddækning	500	-	5	0	0.00	
	Påbrænding af tagpap/montage af inddækning	500	-	2	0	0.00	
	(timer fra Andersen og Thybo tømrerfirma)						
Fællesomkostninger							
EL							
3000	Pris for første anlæg incl.	-	-	-	1	3,000.00	
1350	Priser for efterfølgende anlæg	-	-	-	0	0.00	
	(Priser fra Frederiks elforretning incl. kombi relæ)						
Øvrig	Beskriv						
I ALT						7,400.00	813.80

Tender for Ravnsholtskolen:

AIRMASTER
Ventilation in balance

Allerød Kommune
Mogens Jensen, Pedel
c/o Allerød Service
Bjarkesvej 2
3450 Allerød
Denmark

Salg - tilbud

Tilbud nr. SQ-16146-5

Sælger	John Rene Nielsen	Side 1
Bearbejdet af	Tina Damm	Tilbudsversion 5
Kundens telefonnr.	48100385	25. oktober 2013

Deres reference KLASSELOKALE WINDOWMASTER

Nummer	Beskrivelse	Antal	Pris	Brutto beløb	Rabat %	Netto beløb
9010800101	AML 800 H (afkast/indtag, horisontalt)	1	37.583,00	37.583,00		37.583,00
25091	AM800 indblæsning i top, T	1				
24301	AM800P panelsæt, top/midt med rist	1	441,00	441,00		441,00
24302	AM800P panelsæt, midt	1	390,00	390,00		390,00
24303	AM800P panelsæt, bund	1	433,00	433,00		433,00
11225	AM800H tilluftsfilter, M5	1	147,00	147,00		147,00
11226	AM800 fraluftsfilter, M5	1	107,00	107,00		107,00
13580	Betjeningspanel, Orbit - Airmaster	1	1.625,00	1.625,00		1.625,00
25009	AM/CC800 vægramme	1	1.087,00	1.087,00		1.087,00
25013	AM800 bypass	1	1.880,00	1.880,00		1.880,00
25014	AML800 vandeftervarmeflade	1	4.328,00	4.328,00		4.328,00
10954	Modulerende CO2 sensor T8031, indbygget	1	1.395,00	1.395,00		1.395,00
10982	Energimåler EM10	1	695,00	695,00		695,00
11008	Facaderist Ø315	2	457,00	914,00		914,00
	Fragt	1	765,38	765,38		765,38
	I alt DKK ekskl. moms			**51.790,38**		**51.790,38**
	25% moms					12.947,60
	I alt DKK inkl. moms					**64.737,98**

Priserne er ekskl. moms og ab fabrik

Leveringsbetingelser	NL 92
Betalingsbetingelser	Efter forudgående aftale
Leveringstid	ca. 3 uger fra ordre
Gyldighed	3 måneder fra tilbudsdato

Airmaster A/S
Industrivej 59
9600 Aars
Telefon: +45 98624822

Email: airmaster@airmaster.dk
Website: www.airmaster.dk
SE/CVR: DK29527393

Bank Danske Bank
Kontonr. DKK 4368-8713537
IBAN DKK DK1430000008713537
IBAN EUR
BIC / SWIFT DABADKKK

Appendix G.2 Costs for purchase, installation, and maintenance of the system with automatic window opening and heat recovery units

Email from Martin Kongskov, WindowMaster:

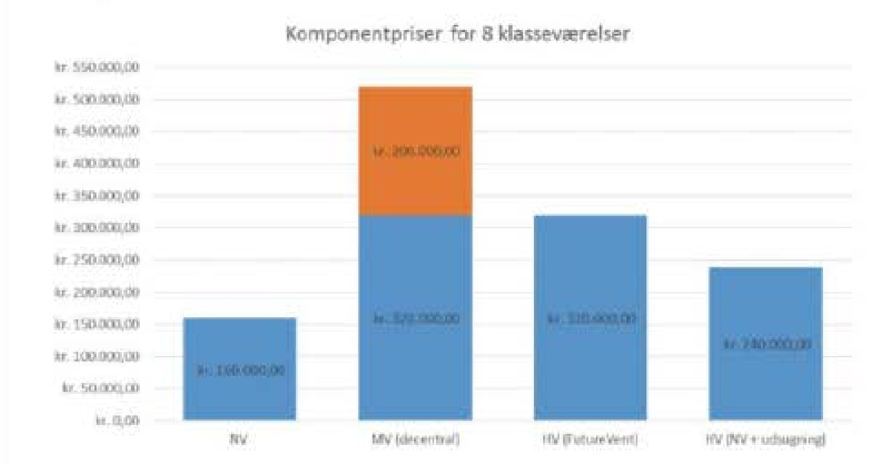
Martin Kongskov <mko.dk@windowmaster.com>
Til: Anna Heebøll <heeboell.anna@gmail.com>
Cc: "Jannick K. Roth" <jkr.dk@windowmaster.com>

3. juni 2015 kl. 03.16

Hej Anna

Nej den har ikke gemt sig, vi har bare meget travlt, bla. pga. stor efterspørgsel på FutureVent.

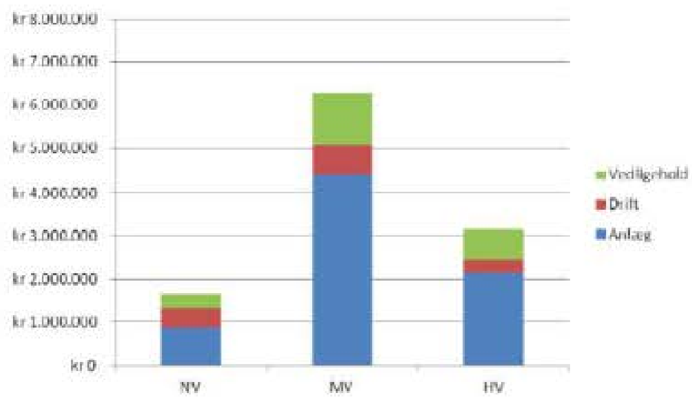
Nedenstående graf viser komponentpriser for 8 rum på alle de løsninger du efterspørger nedenfor. Dertil skal ligges montage og installation.



For MV og HV(FutureVent) udgør montage og installation ca. 15.000,00 – 17.000,00 pr. lokale.

For NV ca. 8.000,00 pr. lokale.

For HV(Udsugning) ca. 12.000,00 pr. lokale.



Med venlig hilsen / Kind Regards

Martin Kongskov

WindowMaster A/S

Email from Claus Hagen Ødum Jørgensen, Exhausto:

Claus Hagen Ødum Jørgensen <chj@exhausto.dk> 29. maj 2015 kl. 06.56
Til: Anna Heebøll <heeboell.anna@gmail.com>

Hej Anna

Såfremt vi beslutter at gøre det salgsbart vil prisen ligge omkring 1000-1500 DKK

Ha en gid weekend

Med venlig hilsen/Best Regards
EXHAUSTO A/S

Claus Ødum Jørgensen

Appendix H. Distribution of CO_2 concentration and temperature measured during each intervention week

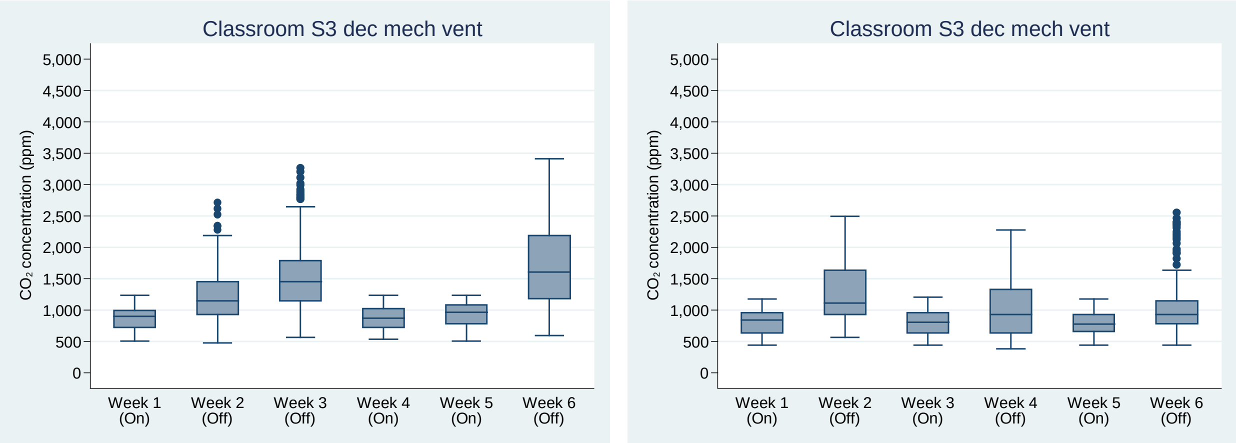


Figure H.1. Boxplot showing the CO_2 concentration during the occupied lessons in each week in the intervention period during the heating (left) and non-heating season (right) in classroom S3 with mechanical ventilation.

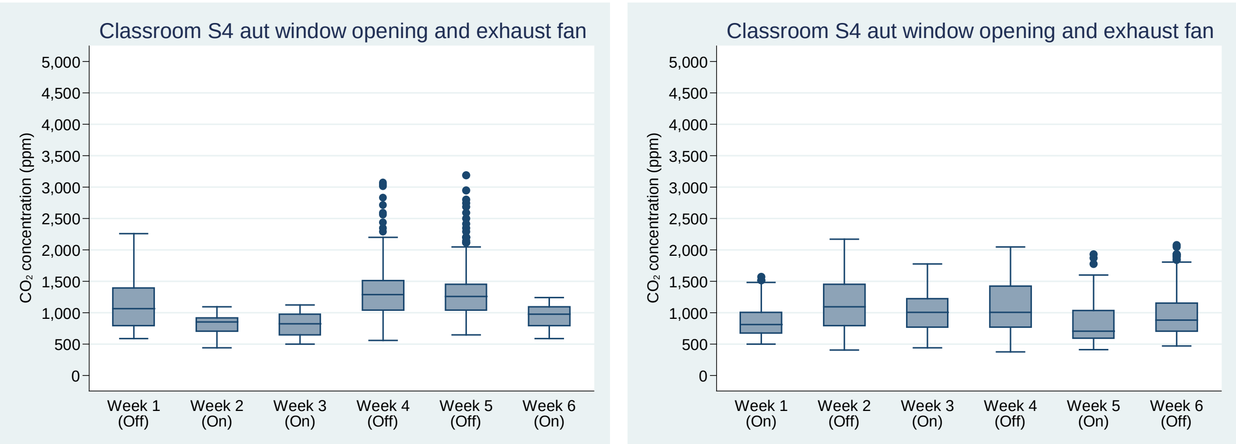


Figure H.2. Boxplot showing the CO_2 concentration during the occupied lessons in each week in the intervention period and during the heating (left) and non-heating season (right) in classroom S4 with automatic window opening and an exhaust fan.

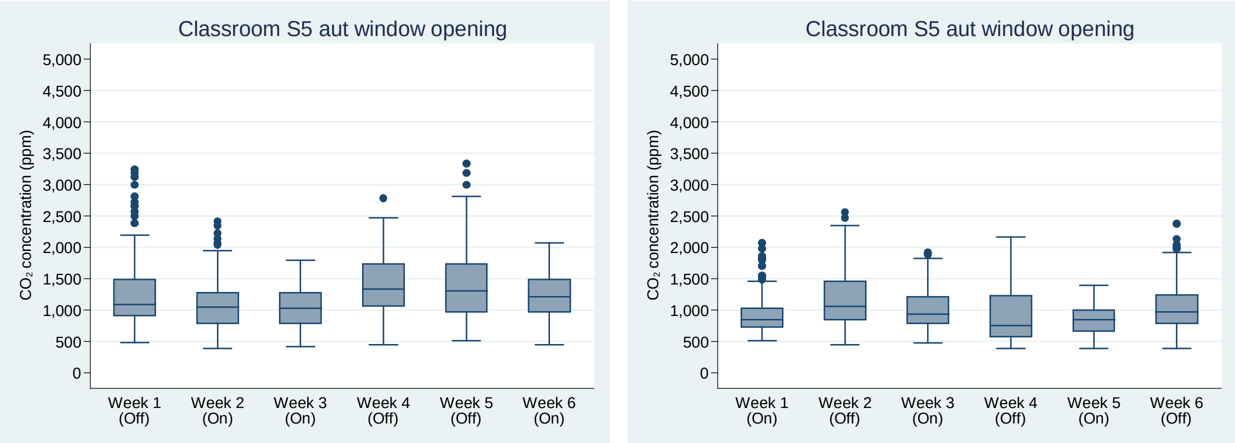


Figure H.3. Boxplot showing the CO_2 concentration during the occupied lessons in each week in the intervention period and during the heating (left) and non-heating season (right) in classroom S5 with automatic window opening.

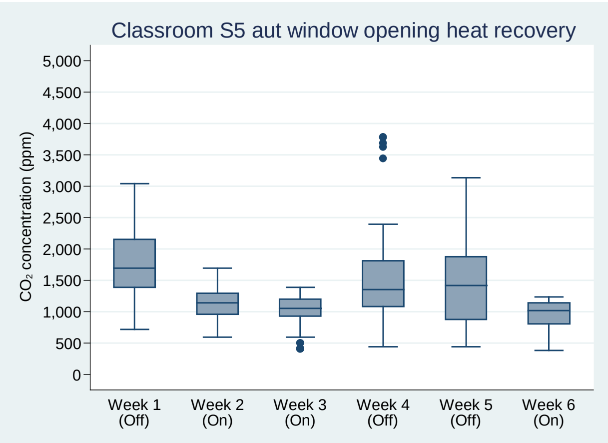


Figure H.4. Boxplot showing the CO_2 concentration during the occupied lessons in each week in the intervention period and during the heating season in classroom S5 with automatic window opening and heat recovery units.

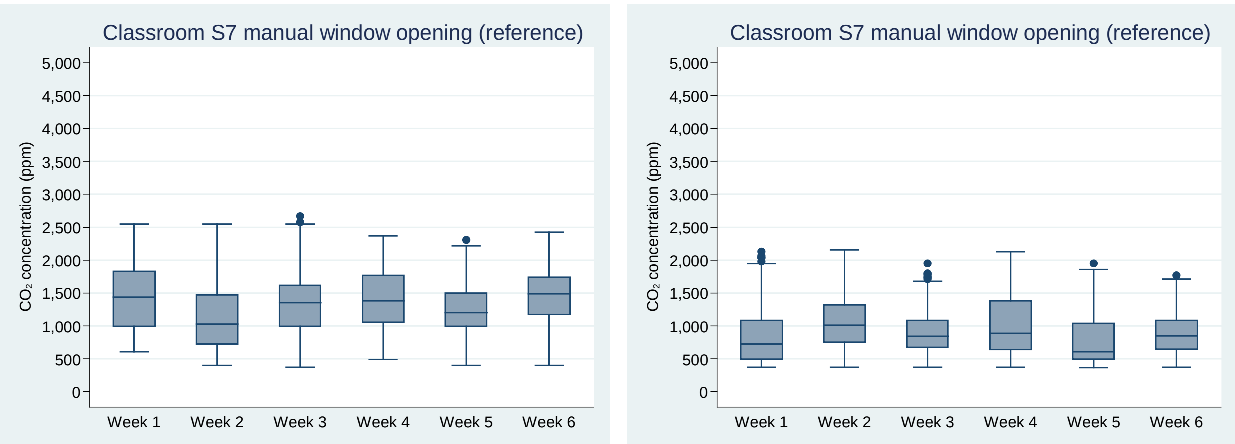


Figure H.5. Boxplot showing the CO_2 concentration during the occupied lessons in each week in the intervention period and during the heating (left) and non-heating season (right) in classroom S7 with manual window opening (reference).

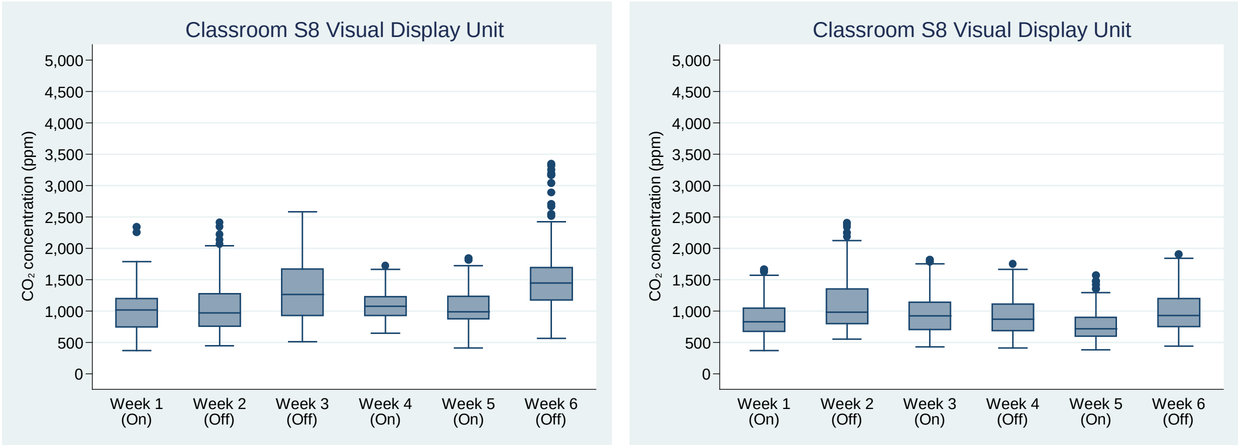


Figure H.6. Boxplot showing the CO_2 concentration during the occupied lessons in each week in the intervention period and during the heating (left) and non-heating season (right) in classroom S8 with a visual display unit.

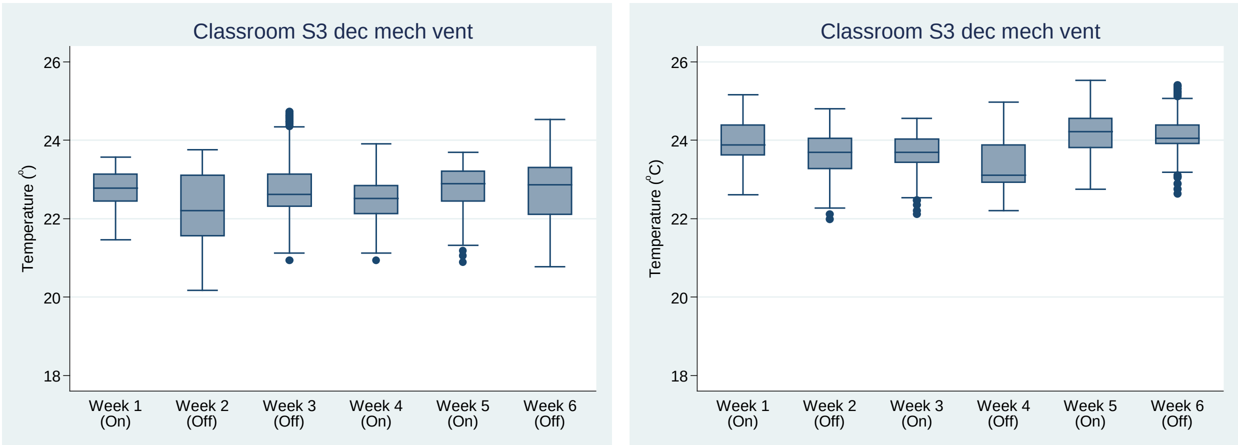


Figure H.7. Boxplot showing the temperature during the occupied lessons in each week in the intervention period and during the heating (left) and non-heating season (right) in classroom S3 with mechanical ventilation.

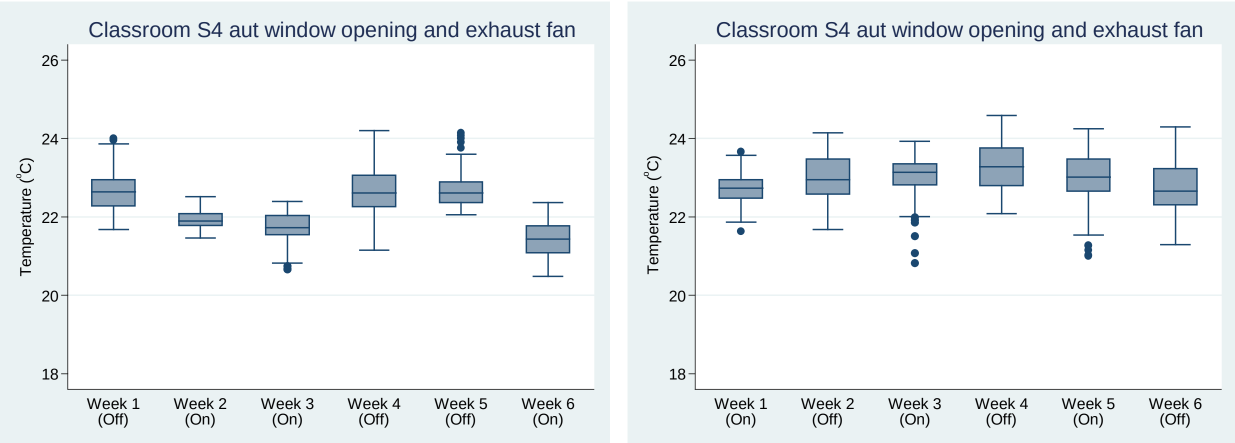


Figure H.8. Boxplot showing the temperature during the occupied lessons in each week in the intervention period and during the heating (left) and non-heating season (right) in classroom S4 automatic window opening and exhaust fan.

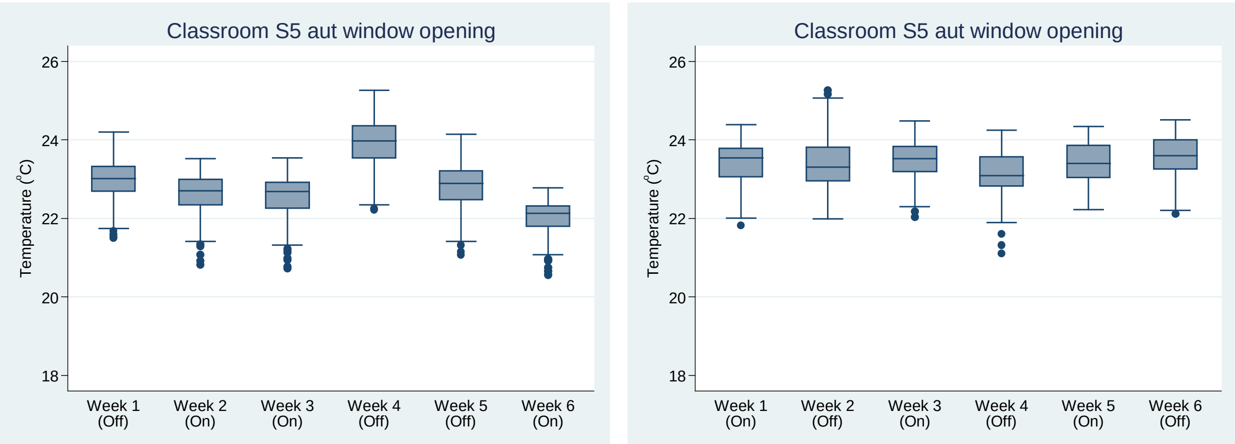


Figure H.9. Boxplot showing the temperature during the occupied lessons in each week in the intervention period and during the heating (left) and non-heating season (right) in classroom S5 with automatic window opening.

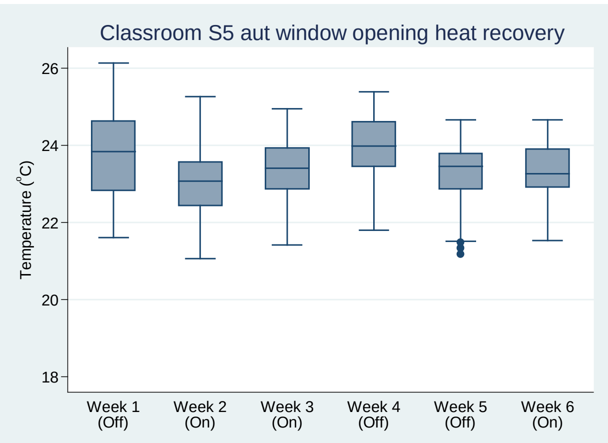


Figure H.10. Boxplot showing the temperature during the occupied lessons in each week in the intervention period and during the heating season in classroom S5 with automatic window opening and heat recovery units.

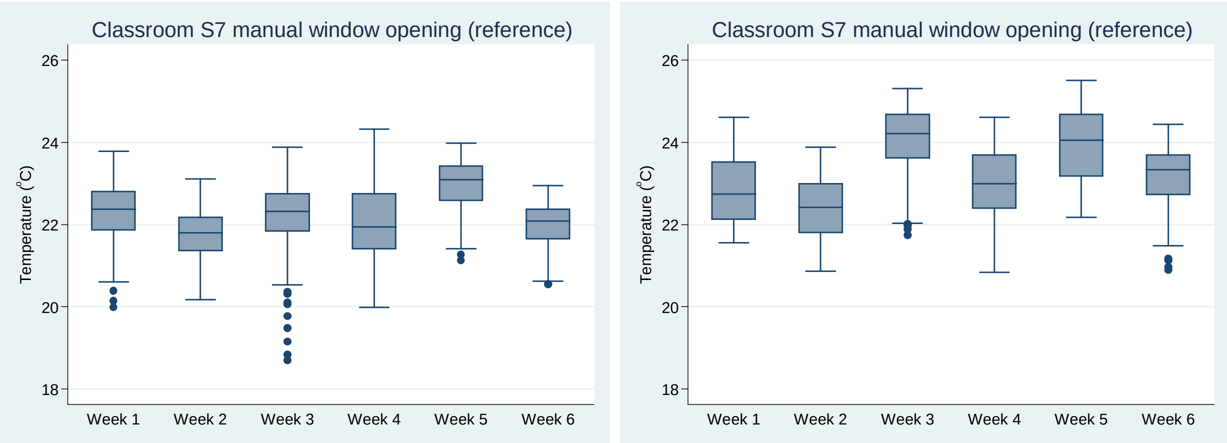


Figure H.11. Boxplot showing the temperature during the occupied lessons in each week in the intervention period and during the heating (left) and non-heating season (right) in classroom S7 with manual window opening (reference).

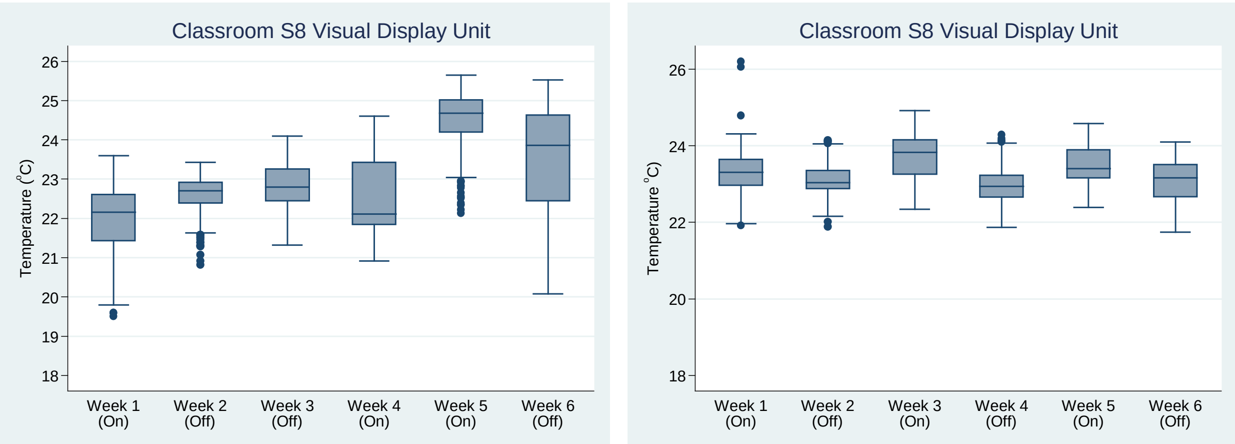
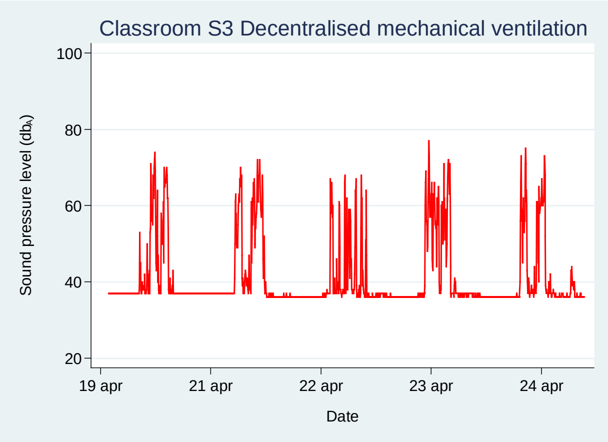
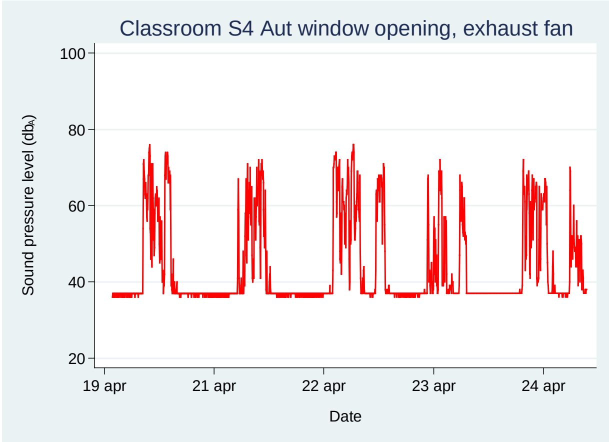
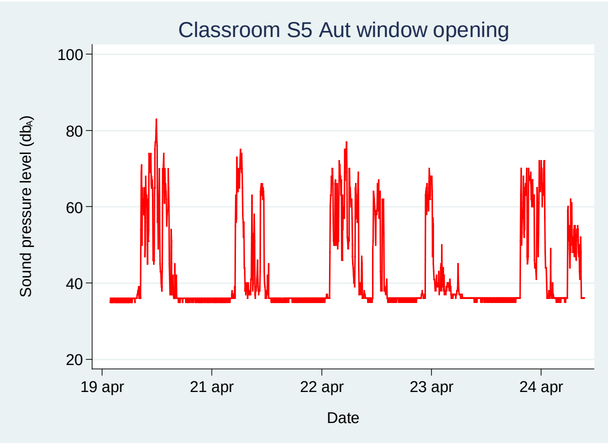
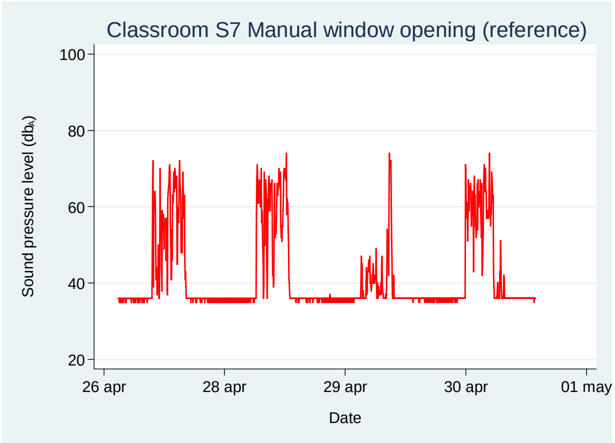


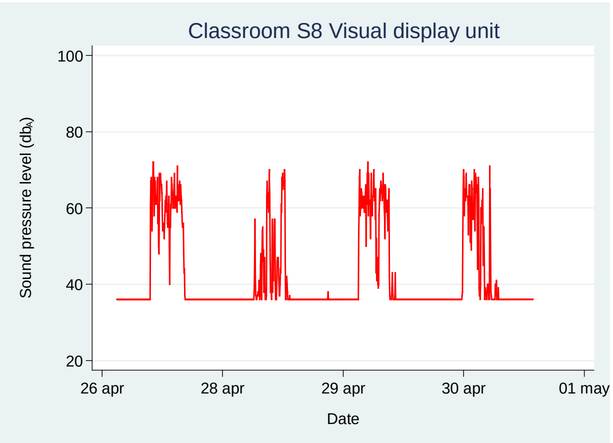
Figure H.12. Boxplot showing the CO_2 concentration during the occupied lessons in each week in the intervention period and during the heating (left) and non-heating season (right) in classroom S8 with a visual display unit.











In classrooms S7 and S8, the figure shows measurements from intervention week 2 as only few measurements were made during week 1.

A ranking of the effects on pupil performance of alternating system control between idling and activated modes was carried out based on the summarized performance results presented in Table 6.10.12 and in Figures 6.10.2 and 6.10.3. The rank of each task and for the tasks combined[4)] was then added to get the cumulative score in Table J.1.

Table J.1. Ranking of the retrofit solutions according to their effect on pupil performance.

System	Math[1)]	Logical reasoning[2)]	d2[3)]	All tests combined based on CO_2[4)]	∑performance	Rank
Decentralized mechanical ventilation	1	1.5	1.5	1	5	1
Automatic window opening and exhaust fan	4	1.5	3.5	2	11	2
Automatic window opening and heat recovery units	4	4.5	1.5	3	13	3
Automatic window opening	4	4.5	5	4	17.5	5
Visual display unit	2	3	3.5	5	13.5	4

[1)] Math: Primarily, the effects on the math performance of alternating between idling and activated control were most consistent in the classroom with the decentralized system, then in the classroom with the visual display. In the classrooms with the three other retrofits either no effect or an unexpected effect was seen.

[2)] Logical reasoning: Primarily, the effects on the logical reasoning performance of alternating between idling and activated control were most consistent in the classrooms with the decentralized system and automatic window opening with an exhaust fan. Some effects were seen in the classroom with the visual display unit. In the other classrooms system control mode did not affect pupil performance.

[3)] d2: Primarily, the effects on the d2 performance of alternating between idling and activated control were most consistent in the classroom with the decentralized system, then in the classroom with automatic window opening and heat recovery units. Although not consistent, some effects were seen in the classroom with the visual display unit and in the classroom with automatic window opening and an exhaust fan. In the classroom with automatic window opening there was no effect on the d2 performance of the system control mode.

[4)] Figures 6.10.2 and 6.10.3 indicated that the performance in all classrooms generally improved with decreasing CO_2 concentration. An additional ranking in terms of projected CO_2 effects on performance that matched the rating of the CO_2 concentration in Table 7.1.1 resulted in this ranking. Using the more robust CO_2 ranking also in the ranking of the task performance reduces the uncertainty caused by the somewhat ambiguous performance results.