Comparison of two ventilation control strategies in the first Norwegian school with passive house standard

Axel Cablé*[1], Hugo Lewi Hammer[2], and Mads Mysen[1,2]

1 SINTEF
Forskningsveien 3B
N-0314, Oslo, Norway
*Corresponding author: axel.cable@sintef.no

2 Oslo and Akershus University College of Applied Sciences
Pilestredet 35
N-0166, Oslo, Norway

ABSTRACT

The perceived indoor climate resulting from two ventilation control strategies was evaluated in a classroom of the first school built according to the Norwegian passive house standard.

Both strategies consisted in varying the ventilation rate according to room demand, *ie.* Demand-Controlled Ventilation (DCV). The existing strategy consisted in varying the ventilation rate in order to maintain a constant carbon dioxide concentration of 800 ppm in the classroom (constant-CO_2 DCV). A new strategy was implemented which consisted in a combined CO_2 and temperature DCV, *ie.* to control towards a proportionally lower CO_2 concentration when the indoor temperature increases. The aim with this strategy was to address both overheating and the fact that perceived indoor air quality decreases when temperature rises.

Indoor climate measurements, as well as questionnaires on the perceived indoor air quality and thermal comfort filled up by the pupils were used to compare both strategies. The data from the questionnaires were then analyzed using a random effect linear regression model. The regression analysis revealed that the initial ventilation strategy was responsible for discomfort resulting from too high variations in the indoor temperature. The new combined CO_2 and temperature DCV strategy provided a perceived indoor climate which was significantly better than the existing strategy.

KEYWORDS

Demand-Controlled Ventilation, passive house, indoor climate, school, questionnaires

1 INTRODUCTION

The Marienlyst School is the first school in Norway built according to the passive house (PH) standard (Dokka 2010); see Fig.1. It has been operational since 2010, with around 500 pupils from age 13 to 15. The school is 6500 m^2, and is located in Drammen, a city in southern Norway situated in a humid continental climate zone.

Figure 1: a) Marienlyst school, Oslo. b) View of a classroom.

The PH concept, initially developed in Germany (Feist 1999), has been adapted to the local climate and constraints of Norway (Müller 2013). A country-specific PH standard for residential buildings was released in 2010 (NS 3700 Standard Norway), according to which the Marienlyst school was built. Subsequently to the construction of the school, a PH standard for non-residential buildings was released in 2012 (NS 3701, Standard Norway). Hence, the building benefits from several passive energy saving measures, among which a super-insulated and airtight envelope (U-values ranging from 0.05 to 0.12 W/m²K for the envelope, and air leakage inferior to 0.6 vol/h under 50 Pa).

While this reduces the heating demand largely, it also enhances the risk for poor indoor air quality (IAQ) and overheating compared to conventional buildings. It is therefore even more important to ensure an efficient ventilation of the classrooms. Indeed, lack of ventilation and poor IAQ have been associated with adverse effects on health, well-being and productivity (Wargocki et al. 2000, Sundell et al. 2011). In particular, the relationship between IAQ in classrooms and the academic performance of pupils has been revealed in various studies (Haverinen-Shaughnessy et al. 2011, Wargocki et al. 2013, Stafford 2014).

In educational buildings, large variations of occupancy occur between periods with empty and occupied classrooms. This results in large variations of the heat and pollutant loads in the rooms, which is especially challenging in terms of control of the ventilation system. CAV (Constant Air Volume) ventilation has been traditionally used in schools, and consists in supplying fresh air into the classrooms at a constant rate. However, this implies that the classrooms are ventilated even when unoccupied, which can have a significant impact on the energy use of the building (Santos, 2012).

Demand-Controlled Ventilation systems (DCV) consist in varying the ventilation rate according to a demand measured at room level. It is therefore particularly fitted to educational buildings. In fact, previous studies have shown that DCV systems can reduce the energy use due to ventilation in the average classroom up to 51% compared to a system operating with full airflow from 7:00 am to 5:00 pm (Mysen, 2005). It is however necessary to evaluate how DCV strategies perform in practice, particularly in the new context of educational buildings with low energy demand, and whether they enable to maintain an appropriate perceived indoor climate.

The relevance of DCV in educational buildings has been evaluated in several studies (Aalraees 2011, Persilli 2003, Fisk, 2014, Norbäck, 2013, Ng, 2011) which underlined the positive influence on both indoor climate and reduced energy use of such systems. To develop Aalraees 2011: impact on energy consumption of schools: significant energy savings, depending on location and occupancy profile.

In this prospect, a new combined CO_2 and temperature DCV strategy was implemented in a classroom of the building. The objective of this study was to assess whether the new strategy provided a better perceived indoor climate than the existing ventilation control strategy, using both indoor climate measurements and questionnaires filled in by the pupils.

Outline the uniqueness of the paper

More studies needed to evaluate the impact of DCV.
Test a new ventilation strategy. Evaluate its impact on the perceived indoor climate.
The indoor climate in PH dwellings has been evaluated in various studies in Scandinavia (Thomsen and Berge (2012), Larsen 2012, Rohdin et al. 2014).
There are studies of the indoor climate in schools (Turunen 2014:extensive study of IAQ)
To the knowledge of the authors, there are however few articles addressing the topic of perceived indoor climate in schools with passive house standard (Heudorf 2007, Peper 2008), especially under cold climate.

Explain the structure of the paper

First of all, the ventilation control strategies are described.
As well as the method employed for the questionnaires and regression analysis.
The results are then presented, which consist in both measured indoor climate in the classrooms during the interventions and score to the questionnaires.

To add somehwere.. Automatic sun shading are installed in the rooms facing south and west in order to address overheating. Balanced mechanical ventilation with heat recovery (84% efficiency)
The building has a water-based floor heating system, a district heating system, with heat pump as energy source. Night ventilative cooling is used in very warm periods, and the floor heating system can also be used as floor cooling in summer.

2 METHODOLOGIES

2.1 Ventilation control strategies

The existing control strategy in the building consisted in varying the ventilation rate in order to maintain a constant carbon dioxide concentration of 800 ppm in the classrooms (constant CO_2 control). This strategy is based on the fact that the CO_2 concentration in a room is considered as a good proxy of the concentration of bio-effluents (Chatzidiakou, 2015). Staying under a given CO_2 concentration therefore guarantees a certain perceived IAQ level in a classroom that is in use. When the classroom is unoccupied, a minimum ventilation rate is applied, ensuring that the pollutants which are not human related (e.g. from construction materials) are disposed of. In Norway, the minimum ventilation rate when the classroom is empty is set to 2,5 m^3/hm^2, and to 0,7 m^3/hm^2 outside of operation time (Mysen et al. 2014). When the room is in use, the minimum ventilation rate is set to 2,5 m^3/hm^2 + 26 m3/h/person.

In addition to the CO_2 control, an "overheating mode" was included in the existing strategy. It consisted in forcing the opening rate of the Variable Air Volume ventilation dampers to 100% when the indoor temperature reached 23.8°C and until the temperature went down to 23°C, independently of the CO_2 concentration in the room. This results in a larger amount of outdoor air being supplied through the ventilation system, which aims to prevent overheating in the classroom.

A new strategy was implemented which consisted in a combined CO_2 and temperature control. It consisted in controlling the ventilation rate towards a proportionally lower CO_2 concentration when the indoor temperature increased over 22.5°C; see Figure 2. The aim with this strategy is to address both overheating and the fact that perceived indoor air quality decreases when indoor temperature rises. In fact, previous studies have revealed that a lower concentration of bio-effluents is perceived as acceptable, the more indoor temperature rises (Mysen, 2005). As a consequence, the ventilation rate should be increased for higher indoor temperatures in order to maintain an acceptable perceived indoor air quality in the classrooms. Accordingly, a higher concentration of bio-effluents is considered as acceptable the more the indoor temperature decreases, which should allow to reduce to control the ventilation towards a higher level of CO_2, while still maintaining the same perceived IAQ.

The study was carried out in one classroom located on the second floor of the building. The indoor room temperature, indoor CO_2 concentration, as well as the opening rate of the VAV damper were recorded on the building management system during the study.

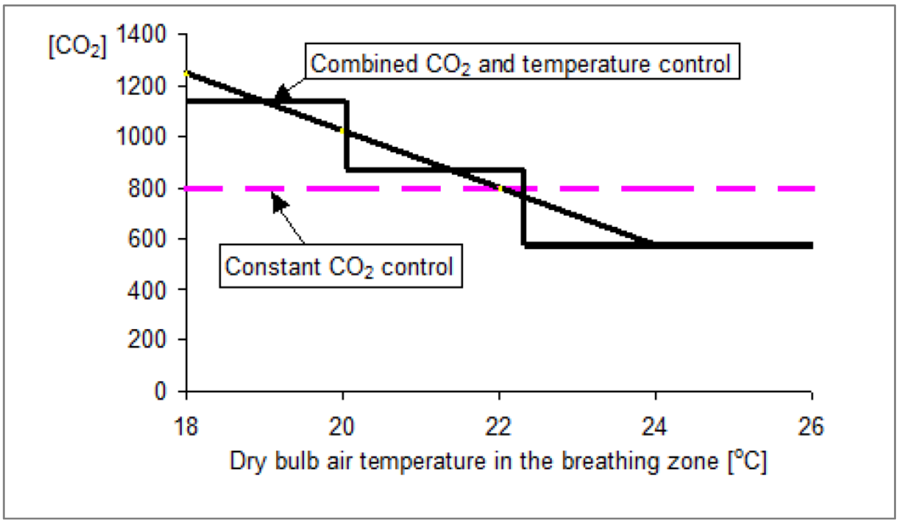

Figure 2: Combined CO_2 and temperature control (Mysen, 2005).

2.2 Questionnaires and regression analysis

In order to compare the performance of the two ventilation strategies described above, a case cross over study was carried out in one classroom of the building during February, March, and May 2012, see Table 1.

Table 1: Date and ventilation control for the interventions

Date	20 February 2012	14 March 2012	30 May 2012
Ventilation control	Constant CO_2 with "overheating mode"	Combined CO_2 and temperature	Combined CO_2 and temperature

The method used in this study is based on the work from Jerkø and Mysen (2006) who developed a simplified questionnaire to evaluate the perceived indoor climate in schools. It is based on the Örebro questionnaire on indoor climate developed in Sweden (Örebro University Hospital Sweden 2014), but adapted for pupils. The main difference is that the pupils are asked to assess the current conditions, and not about conditions three months earlier. This change was made because younger pupils do not necessarily have the ability to reflect far back in time. After discussions with school officials, we considered this method to be the most suitable for our study.

At the end of each class session, the pupils were given a questionnaire with 19 questions relating to Sick Building Syndrome-symptoms and perceived indoor climate. On each question, the pupil gave a value between 0 and 1, ranging from very comfortable to very uncomfortable. The questionnaire also included health questions, such as whether a pupil suffered from asthma or cold. The questions are listed in Table 2.

Questions
Are you tired?
Does your head feel heavy?
Do you have a headache?
Do you feel faint or dizzy?
Do you have problems concentrating?
Do you feel itching or burning in your eyes?
Do you feel hoarse or dry throat?
Do you feel itching or burning in your face or on your hands?
Do you feel nauseous or otherwise unwell?
Is it too warm?
Is there bothersome warmth because of sunshine?
Is it too cold?
Do you feel a draught around your feet or your neck?
Does the temperature in the room vary?
Does the air feel heavy?
Does the air feel dry?
Is there any unpleasant smell?
Do you have a stuffy or runny nose?
Do you cough?

Table 2: List of questions composing the questionnaire

Data from the questionnaires were analysed using a random effect linear regression model with the score for each question as the dependent variable. The two ventilation control strategies: "Constant CO_2 control" and "Combined CO_2 and temperature control" represented the main independent variable. We also included gender and whether the pupils suffered from cold as independent variables, in order to be able to compare the ventilation control strategies independently of these factors. Statistical analyses were performed using the program R (R development team, 2013) and the R package lme4 (Bates, 2013).

3 RESULTS

3.1 Actual conditions during the interventions

The average outside temperature during the interventions, and obtained from the meteorological station of Drammen (ref:eklima.met.no) are presented in Table 3.

Date	20 February 2012	14 March 2012	30 May 2012
Average outside temperature (°C)	-0,8	4,5	12,7

Table 3: Average outside temperature

The CO_2 concentration inside of the classroom, as well as indoor temperature were measured every 2 minutes during the intervention.

The measurements during the intervention on February 20 with constant CO_2 control are plotted on Figure 3. The setpoint for the indoor CO_2 concentration deriving from the ventilation control strategy is also indicated on Figure 3 (dotted line), as well as the periods during which the "overheating mode" was used (override of the constant CO_2 control and full opening of the ventilation dampers – bold line).

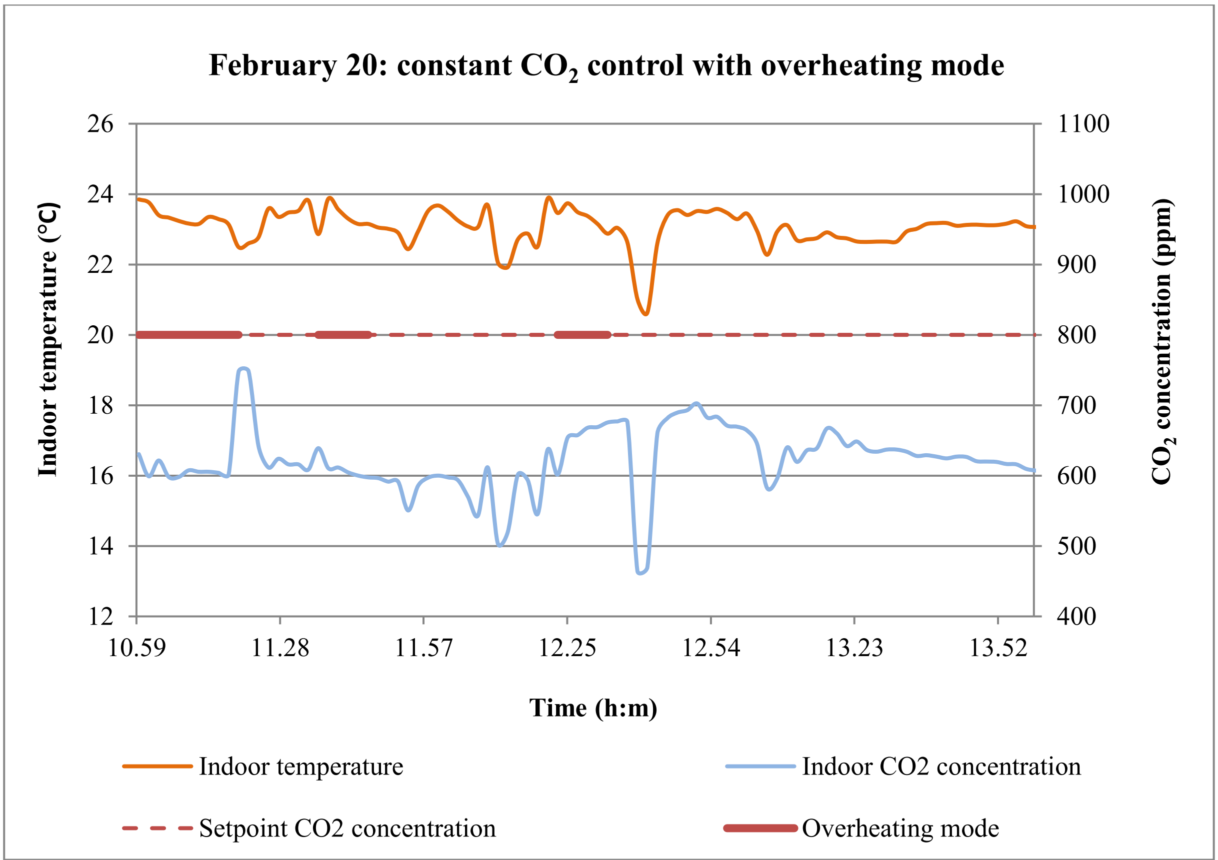

Figure 3: Measured indoor climate parameters on February 20 (constant CO_2 control with "overheating mode")

The measurements during the interventions on March 14 and May 30 with combined CO_2 and temperature control are plotted on Figure 4 and Figure 5, respectively. Similarly, the setpoint for the indoor CO_2 concentration derived from the curve presented on Figure 2 is also indicated.

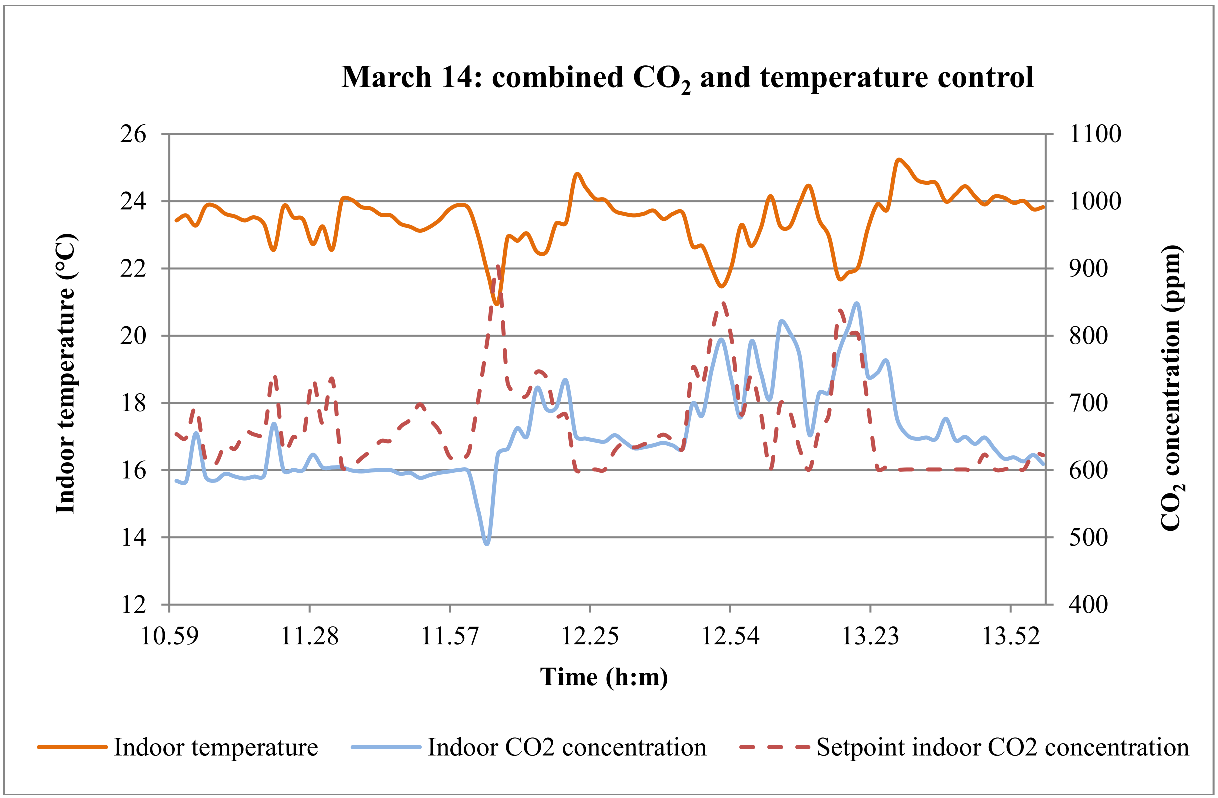

Figure 4: Measured indoor climate parameters on March 14 (combined CO_2 and temperature control)

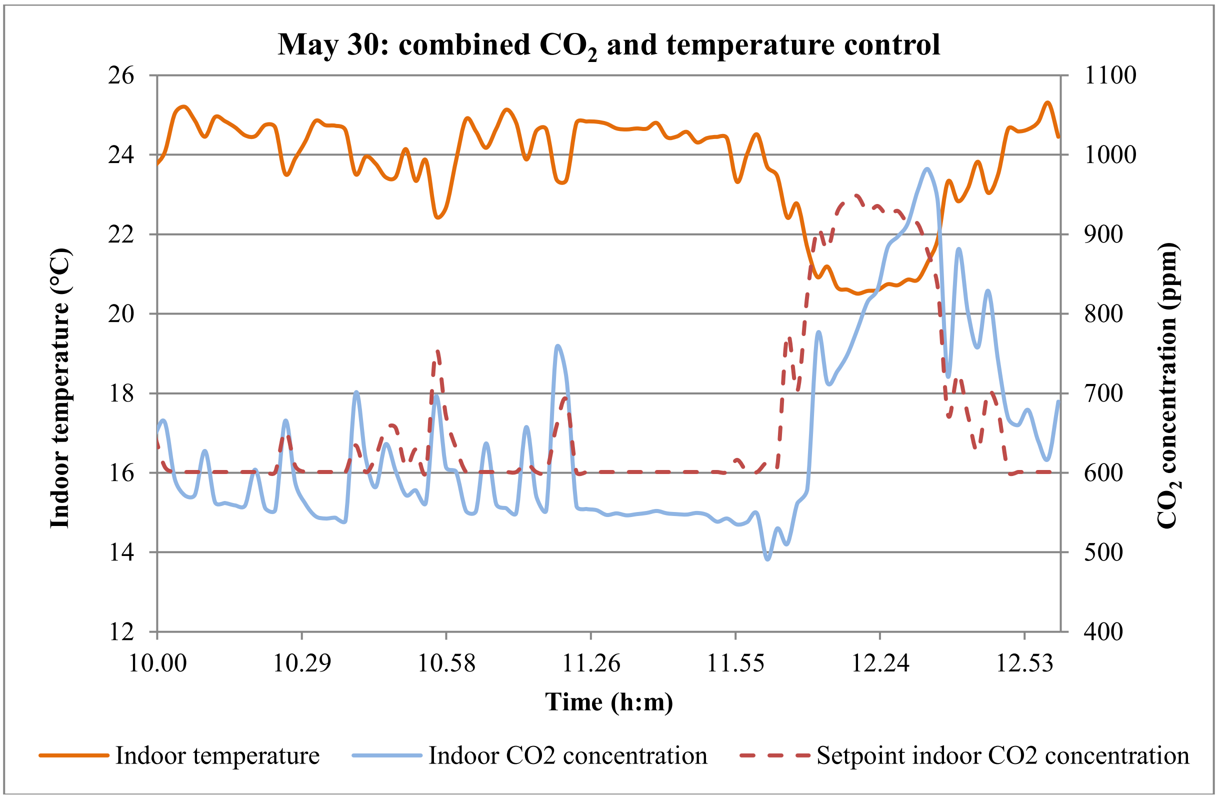

Figure 5: Measured indoor climate parameters on May 30 (combined CO_2 and temperature control)

The following observations were made:

- On February 20, the indoor temperature reached 23.8°C on three occasions, causing the "overheating mode" to override the constant CO_2 control of the ventilation rate, and supplying an increased amount of fresh air into the room. As a consequence, the indoor CO_2 concentration was lower than 800 ppm. A clear drop of the indoor temperature and indoor CO_2 concentration can be noticed subsequently to each of period of "overheating mode".
- On March 14 and May 30, the indoor temperature exceeded 22.5°C. As a consequence, the combined CO_2 and temperature control strategy controlled towards a lower concentration of CO_2 (see the red dotted line on Figure 4), down to 600 ppm. The actual CO_2 concentration in the room agreed fairly well with the CO_2 concentration setpoint on both days.
- On May 30, the classroom was empty from 12:00 to 12:15. As a consequence, the indoor temperature dropped down to 20.5°C. This caused the combined CO_2 and temperature control strategy to control towards a higher concentration of CO_2, reducing the ventilation rate. This illustrates the ability of this ventilation control strategy to help saving energy by reducing the ventilation rate when the room is empty.
- The temperature in the classroom was relatively high for all cases, ranging from 23.1°C to 23.7°C on average. Moreover, the temperature was relatively similar during all three interventions; see Table 4 for average values during the interventions.
- Likewise, the indoor CO_2 concentration was similar for all cases and relatively low, ranging from 622 ppm to 652 ppm, see Table 4.

Table 4: Average indoor temperature and CO_2 concentrations during the interventions

	Average indoor temperature (°C)	**Average indoor CO_2 concentration (ppm)**
20 February (constant CO_2 control with overheating mode)	23,1	622
14 March (combined CO_2 and temperature control)	23,5	652
30 May (combined CO_2 and temperature control)	23,7	635

3.2 Average scores and regression analysis

To reduce the effect of sun light in our analysis, we only included pupils that were not sitting on the window row. 39 pupils answered to the questionnaires which did not sit on the window row. Among them, 19 answered to all three questionnaires and were considered in the analysis. Figure 6 shows the average scores with 95% confidence intervals for these 19 pupils on each SBS question under both ventilation strategies. Comparing the confidence intervals, the question whether the pupils felt bothersome warmth because of sunshine shows clear difference between the two strategies. We also see some indications of significant differences for the questions if pupils felt faint or dizzy, if it was too warm and if the room temperature varied. The average of all the SBS questions do not indicate any significant difference between the two strategies.

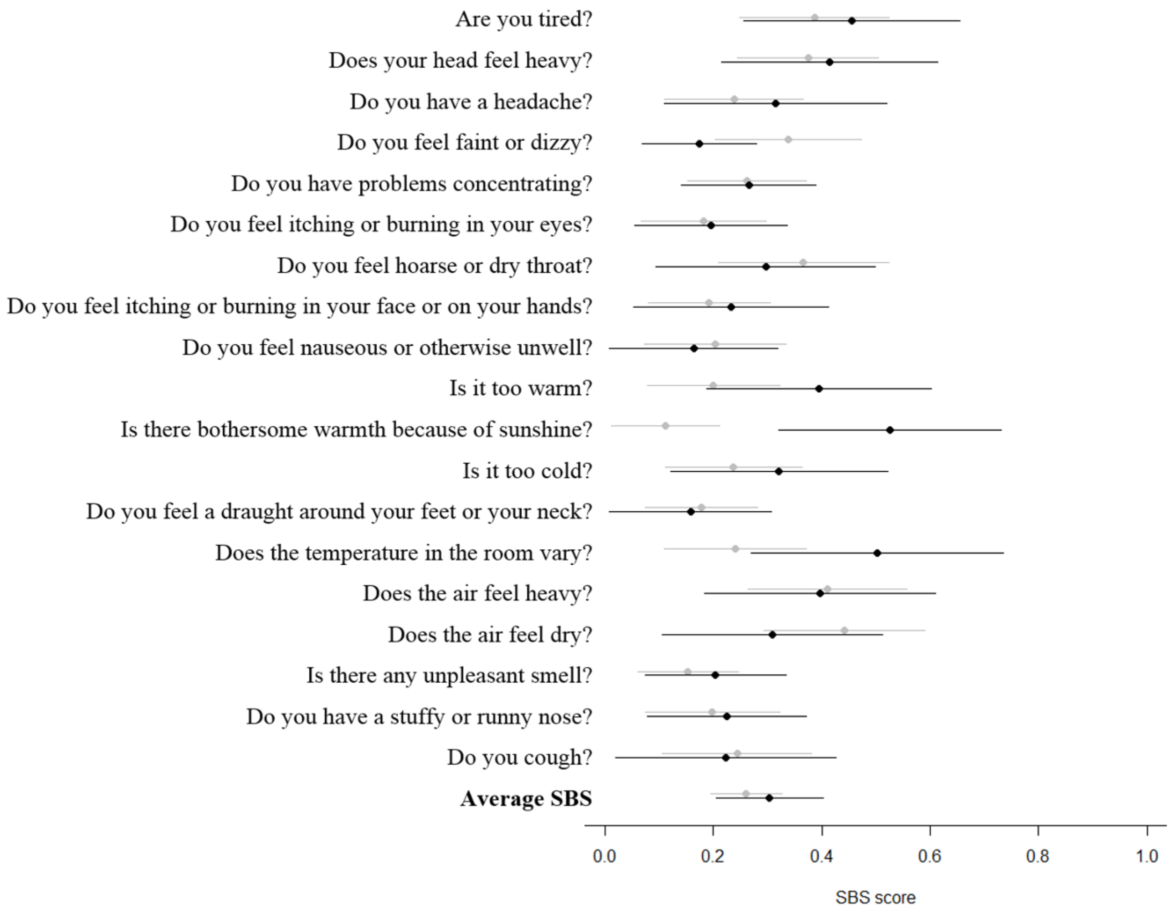

Figure 6. Average score for the pupils with 95% confidence intervall for each question in the questionnaire. The gray and the black lines refer to combined CO_2 and temperature control and constant CO_2 control, respectively. The bottom row shows the same as the other rows, but with the average score of all the questions except of just one question.

Next we analyze differences in perceived indoor climate between the two strategies closer by using regression analysis as described in the method section. We first ran a regression analysis with the average of all the SBS questions as the dependent variable. The analysis did not reveal any significant difference between the two ventilation strategies.

Secondly, we ran regression analyses for each question individually as the dependent variable. Two questions revealed significant differences and the results are shown Tables 5 and 6.

Table 5 documents a significant relationship between ventilation strategy and temperature variations in the classroom. The new combined CO_2 and temperature strategy reduced the discomfort by variations of the indoor temperature significantly compared to the existing strategy (constant CO_2 control with “overheating mode”). We do not observe any significant relation between gender and cold and varying room temperature.

Table 6 shows that the pupils are significantly less bothered with warmth from the sun under the strategy with combined CO_2 and temperature control.AXEL, FÅR DU SKREVET LITT HER OM SOLSKJERMING OL? EN TANKE JEG HAR ER AT DET TROLIG VAR MER

SOL PÅ DAGEN HVOR UNDERSØKELSENE MED CONSTANT CO2 BLE GJENNOMFØRT OG SOM GIR DETTE RESULTATET.

Table 5: Results from the linear regression for the question if the room temperature varied.

Variables	Estimate	Std. Error	Df	T-value	P-value
Combined CO_2 and temperature control (reference: constant CO_2 control)	–0.29	0.11	26.40	–2.62	0.015 *
Gender male (reference: female)	–0.25	0.13	19.98	–1.89	0.073
Has a cold (reference: Does not have a cold)	0.15	0.12	34.96	0.97	0.335

*Signif. Codes: p-value < 0.01:**, p-value < 0.05:**

Table 6: Results from the linear regression if the pupils felt bothersome warmth because of the sun.

Variables	Estimate	Std. Error	Df	T-value	P-value
Combined CO_2 and temperature control (reference: constant CO_2 control)	–0.37	0.07	22.12	–5.72	$9.31 \cdot 10^{-6}$**
Gender male (reference: female)	–0.03	0.13	22.92	–0.21	0.837
Has a cold (reference: Does not have a cold)	0.07	0.08	28.32	0.82	0.42

*Signif. codes: p-value < 0.01:**, p-value < 0.05:**

4 DISCUSSION

The average scores revealed that the perceived indoor air quality was good under both strategies. This is in agreement with the low level of measured indoor CO_2 (average indoor CO_2 concentration between 622 ppm and 652 ppm, see Table 2).

The regression analysis revealed that the initial ventilation strategy was responsible for discomfort resulting from too high variations of the indoor temperature. The hypothesis is that the rough control of the ventilation rate for this control strategy was accountable for this.

In fact, right after a period under "overheating mode" with high ventilation rate, the indoor CO_2 concentration was much lower than 800 ppm; see Figure 3. As a consequence, as soon as the constant CO_2 control mode was active again (*ie.* indoor temperature 23°C), it controlled towards the lowest ventilation rate. This resulted in fluctuations between maximum and minimum ventilation rate, which may be responsible for the obtained results.

The combined CO_2 and temperature control strategy allowed to have more gradual variations of the ventilation rate according to room temperature, which is likely the reason why it allowed to significantly reduce the perceived discomfort by temperature variations.

Moreover, the results from the measurements revealed that the indoor temperature was somewhat high in the classroom during all interventions (ranging from 23,1°C to 23,7°C), despite of the relatively low outside temperature in February (-0,8°C).
This underlines the importance of having a ventilation control strategy capable of providing a higher ventilation rate when this occurs, in order to maintain an acceptable perceived indoor air quality.

Possible causes are:

Comment about the regulation of the district heating
Solar gains (Automatic sun shading are installed in the rooms facing south and west in order to address overheating. The position of the shadings was however not monitored)
highly efficient building envelope.
control of the district heating
bypass of the heat exchanger
shadings
lack of info...

This illustrates that the ventilation could be controlled towards an even lower level of CO2 in order to reduce the indoor temperature when the classroom is in use.

State the limits of the study (number of pupils; reduced number of sensors,
Particulate matters, and chemicals were not measured.)
What would be needed to study in further studies

During the interventions, the measured indoor temperature did not go below 22,2C; temperature below which the CO_2 and temperature control strategy starts to reduce the ventilation rate. Therefore, it was not possible to assess the efficiency of the new strategy in the lowest range of the graph displayed on Figure; and observe whether it provided a perceived IAQ which was as good as the perceived IAQ obtained with the constant CO2 ventilation strategy.

The CO_2 and temperature controlled DCV strategy should ideally be compared to CAV without overheating mode to enable the comparison.

A previous study in the school reported that the control of the solar shadings was not optimal.?

5 CONCLUSIONS

A combined CO_2 and temperature ventilation control strategy was efficiently implemented in a classroom of the first school in Norway with passive house standard.

Questionnaires concerning the perceived indoor comfort and indoor air quality were handed to the pupils on February 20, March 14 and May 30 2012, which were exposed to both the existing constant CO_2 ventilation strategy and to the new combined CO_2 and temperature control strategy.

The analysis of the questionnaires revealed that the perceived IAQ was good for both strategies, with no significant difference reported with the CO_2 and temperature control strategy compared to the existing strategy.

However, the regression analysis revealed that the existing ventilation strategy was responsible for discomfort resulting from too high variations in the indoor temperature. For this question, the new combined CO_2 and temperature strategy provided a perceived indoor climate which was significantly better than the existing strategy.

Therefore, this ventilation strategy appears to be a relevant solution in order to address the problem of overheating and perceived indoor climate in educational buildings with passive house standard. Develop the conclusion. Conclude about DCV in passive house schools.

The study should however be reproduced on a larger sample in order to confirm the obtained results. Should be reproduced for a lower indoor temperature.
State the limits of the study

Gradual variations
This emphasizes the fact that a fine-tuning of the control of the ventilation system

Balanced mechanical ventilation with demand-controlled ventilation has known challenges and requires further development (Mysen et al. 2014). From the design, choice of sensors and components, commissioning, balancing, handover documentation (report DCV), operation phase.

Balanced ventilation is a major challenge in countries where ventilation is traditionally not widely used. In Norway, both the construction industry and users have had more experience with this solution, especially in recent years, because these facilities are installed in most new buildings in compliance with new building codes.

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Is CO2 a good proxy for indoor air quality in classrooms? Part 1: The interrelationships between thermal conditions, CO2 levels, ventilation rates and selected indoor pollutants

Is CO2 a good proxy for indoor air quality in classrooms? Part 2: Health outcomes and perceived indoor air quality in relation to classroom exposure and building characteristics

Lia Chatzidiakou1

Dejan Mumovic1

Alex Summerfield2

The PH concept has initially been developed by the Passivhaus Institute in Germany. It consists in applying passive measures in order to reduce the energy requirements of the building, among which a super-insulated and airtight building envelope. A simplified heating system can then be used to cover the remaining heating demand. While some countries have kept the characteristics of the German standard, others have adapted the PH standard to the local climate and constraints (Müller 2013). It is the case of Norway, where a country-specific PH standard for residential buildings was released in 2010 (NS 3700, Standard Norway), according to which this school has been built. Subsequently to the construction of the school, a PH standard for non-residential buildings was released in 2012 (NS 3701, Standard Norway).