A COMPARATIVE STUDY OF THE INDOOR ENVIRONMENTAL QUALITY IN RENOVATED AND NON-RENOVATED CLASSROOMS

Christian A. Hviid[1,2,*], Henrik N. Knudsen[3], Jakob Markvart[3]

[1]Saint-Gobain Nordic, Copenhagen, Denmark
[2]Technical University of Denmark, Dept. of Civil Engineering, Kgs. Lyngby, Denmark
[3]Aalborg University, Danish Building Research Institute, Copenhagen, Denmark
[*]*Corresponding email: cah@byg.dtu.dk*

SUMMARY

This paper reports on a comparative study of the indoor environment in two adjacent classrooms, one renovated, and the other non-renovated. The aim of the study was to investigate the positive consequences of renovating classrooms, but also to disclose unanticipated side-effects.

The non-renovated classroom was without mechanical ventilation, fitted with woodwool ceiling plates for acoustics and lighting fixtures with horizontal illuminances of 200-300 lux on the tables.

The renovated classroom was retrofitted with a new acoustic ceiling made from perforated gypsum tiles and suspended lighting fixtures and mechanical ventilation via decentral room unit mounted below the ceiling. The ventilation air was supplied in the void above the acoustic ceiling, which distributes air through perforations and joints in the ceiling to the occupied zone – a concept often referred to as diffuse ventilation. In this setup, the acoustic ceiling also acted as silencer for the ventilation inlet.

Different indoor environmental parameters were comparatively measured in each classroom, including longterm CO_2-concentration, temperature and noise levels as well as reverberation time and technical noise from the ventilation equipment. In all respects, the objective measurements improved in the renovated classroom.

Interviews with pupils and questionnaire surveys were conducted, and – while showing less evidence of the improvements than expected – did indicate increased user satisfaction with the retrofit.

Keywords: ventilation, schools, indoor environmental quality, air distribution

1 INTRODUCTION

Education of younger generations is a major societal task and the quality of the teaching and learning in schools receives greater attention than ever from politicians, governmental bodies, authorities, teachers, and parents alike.

The indoor environmental quality plays a key role in the abilities of pupils to absorb, process and use knowledge. Several studies indicate a positive relationship between the quality of the indoor environment in classrooms and the score of school children when doing tests in reading, math, comprehension and cognitive abilities (Wargocki & Wyon, 2017). At the same time young pupils spend more time in school than in any other environment besides their home. The increased attention on the importance of the indoor environment in schools, has intensified the pace of classroom renovation in Denmark, which has earlier been limited. Multiple studies have investigated and compared retrofit solutions with regard to IAQ and energy (Heebøll et al., 2018), but fewer has taken on a holistic approach (Dhalluin & Limam, 2014). This study reports on a concurrent all-round indoor environmental quality comparison of two classrooms, located side-by-side, one renovated, and the other non-renovated.

2 METHODS

2.1 Description of classrooms

Two adjacent classrooms, room 15 (renovated) & 16 (non-renovated), were identified in a school in a suburb to Copenhagen in Denmark. The classrooms are of equal size with the dimensions 6.1x8.0 m. The room height was initially 3.1 m but later reduced to 2.9 m in the renovated classroom. Three windows in each classroom of size 2.3x2.0 m (h x w) are oriented towards East, see Figure 1. There is an overhang of 1.2 m and also manually controlled external grey-woven screens for solar protection. The insulation level in the parapet is estimated to be approx. 75 mm. The windows have double layer glazings but without low-energy coatings. The U-value is estimated to be 3.0 W/m^2K. There are three operable windows in each classroom, but only two radiators, i.e. no radiator below the window in the middle. The façade was not renovated nor changed.

Initially the two classrooms did not have sufficient ventilation, but in Jan/Feb 2017, room 15 was renovated with mechanical ventilation, new acoustics ceiling made from white-painted gypsum tiles, and new lighting system. Room 16, the non-renovated one, kept the old lighting systems and the wood-wool acoustic ceiling.

In room 15, the air change is handled by a decentral mechanical ventilation unit suspended below the ceiling, see Figure 2b. The unit has a counterflow heat exchanger with an efficiency of 82% at nominal flow rate 950 m3/h and the specific fan power is 800 W/(m3/s). Thus, we consider the ventilation unit to be quite energy efficient. The unit is fitted with internal CO_2 and temperature sensors and demand-control.

The new acoustic ceiling was suspended 20 cm, in effect embedding the air handling unit partly and creating a void above the acoustic ceiling where the two inlet jets from the air handling unit exit. Thus the acoustic ceiling forms a pressure chamber permitting to distribute air evenly to the occupied zone below.

This combined solution was selected because in rooms with high-density occupancy such as classrooms it can be challenging to renew the air without a high risk of draught sensations and/or noise from the technical installations. 2x20 mm of soft non-fibrous sound absorbing material is placed on top of the gypsum tiles to reduce noise.

The lighting system was changed to six lighting fixtures suspended 40 cm below the acoustic ceiling. The fixtures distribute artificial light both downwards and upwards, where the reflections with the white gypsum tiles together with the micro-prismatic optics in the fixtures create a uniform lighting level in the room. The color temperature is 3000 K and CRI>90. Five downlights along the walls creates a wall-wash effect.

Based on the class schedules, occupancy is from 8-15 and counts a maximum of 18 pupils in each of the rooms. The pupils are grade 6, approx. 12 years old.

2.2 Measurements

The following investigations and comparisons are reported in this paper:

- CO_2-concentration
- Temperature
- Noise levels and reverberation time in the classrooms
- Sound pressure level from decentral ventilation unit
- Lighting level
- Air velocities
- Perceived IEQ based on questionnaires & interviews

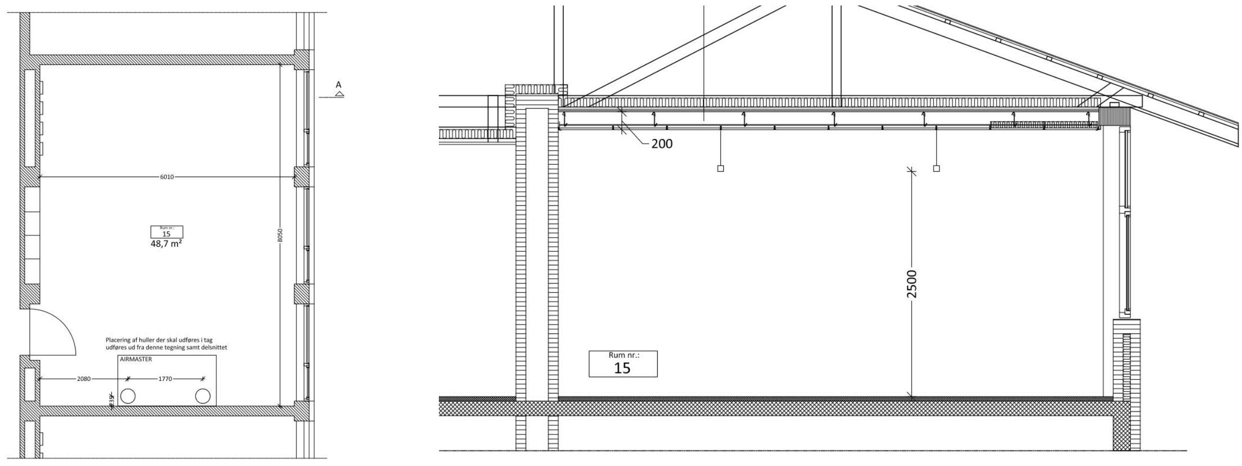


Figure 1. Plan view and cross-section of renovated classroom

(a) Classroom 16, non-renovated (b) Classroom 15, renovated

Figure 2. Picture of non-renovated room 16 (a) and renovated classroom 15 (b). Acoustic ceilings, partly embedded decentral ventilation unit and lighting systems are visible.

2.3 Equipment

The following equipment was used to measure the different parameters.

IC-Meter is an IoT-enabled measuring device that uploads 5 min logged IEQ data to the cloud. The accuracy of the CO_2-sensor is ±30 ppm or ±3%, whichever is highest, of the reading. The IC-Meter temperature sensor has an accuracy of ±0.3°C and max <0.4°C in normal comfortable operating conditions. The relative humidity sensor has an accuracy ±2% and max ±3% in normal comfortable operating settings. The microphone has a range of 32-104 dB. The accuracy is unknown but for these measurements, the location of the sensor on the wall will in it-self produce biased values in absolute terms. However, IC-Meters are placed alike on the walls in each of the classrooms and therefore data is comparable relatively.

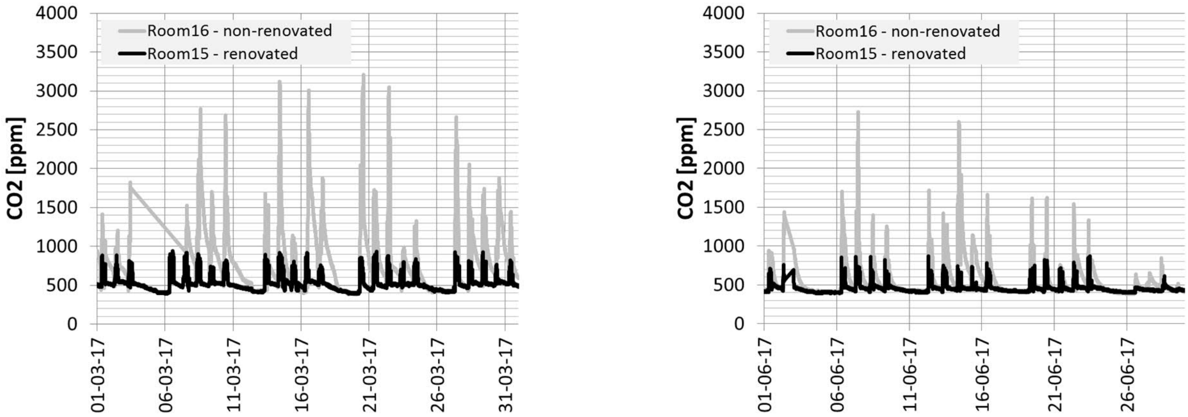
Air velocity are measured by four omnidirectional thermal anemometers SenseAnemo5100SF from Senseelectronic. The accuracy of the anemometers is ±0.02 m/s in the interval 0.05-5 m/s.

Reverberation time and noise from technical installations are measured with a handheld sound level meter from Brüel & Kjær model 2270 in the frequency interval 50-10 kHz. The same instrument was used to measure the reverberation time.

Light intensity was measured using Testo 540 handheld light-meter.

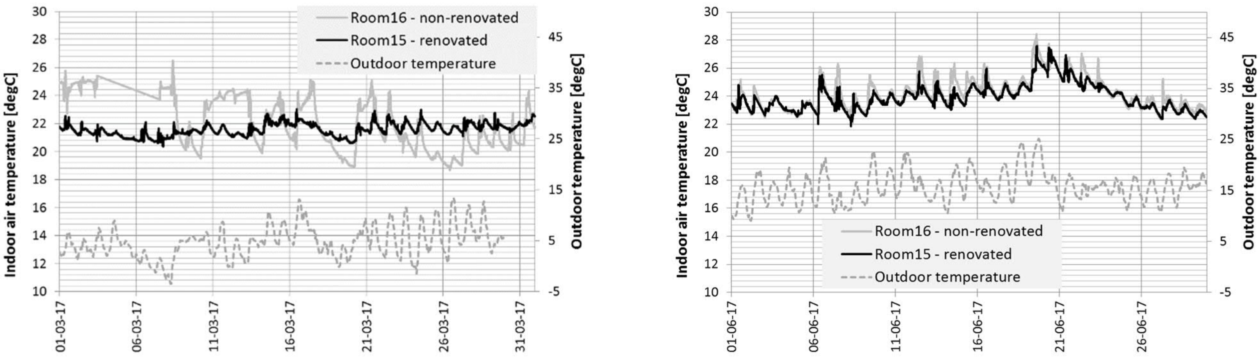
3 RESULTS

By comparing the CO_2 concentration, Figure 3 shows that the mechanical ventilation system has significantly improved the indoor air quality and that the demand-control functions correctly.



March (a) June (b)

Figure 3. CO_2-concentration in March (a) and June (b) in classrooms 15 (renovated) and 16 (non-renovated).



March (a) June (b)

Figure 4. Indoor air temperature in March (a) and June (b) in the classrooms (solid lines, left y-axis) along with the outdoor temperatures (dashed line, right y-axis).

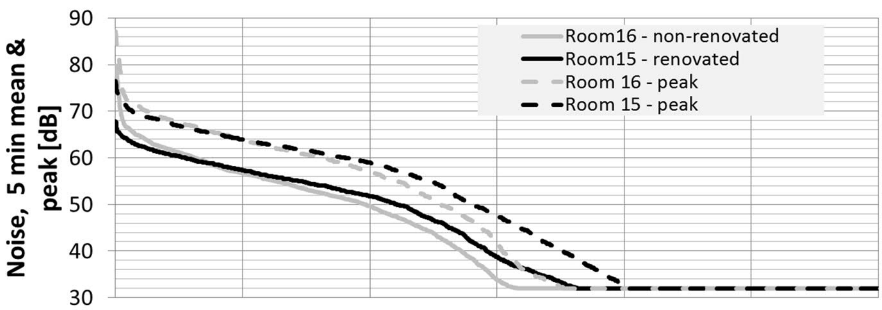
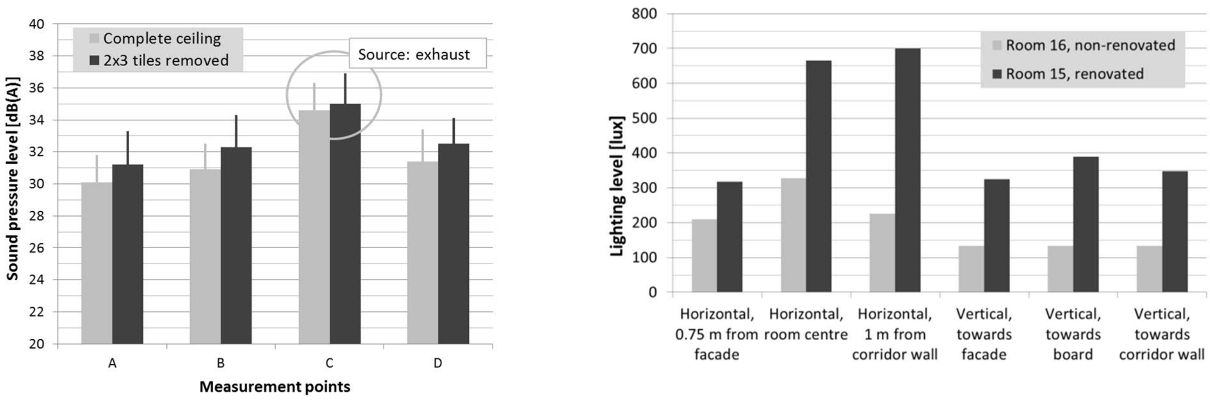


Figure 5. Sorted mean and peak noise levels in renovated and non-renovated classrooms in March.

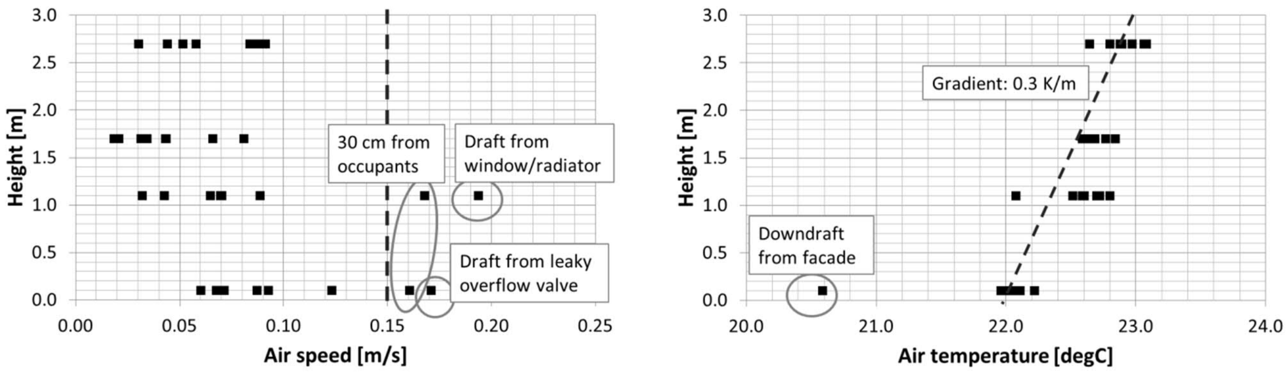
Figure 4 shows the indoor air temperature in a winter (March) and summer scenario (June). The outdoor temperature is also shown. The March values show that the temperature of the renovated classroom is much more within the comfort range of 21-23°C. The fluctuating temperature of the non-renovated room is probably due to manual airing, by opening windows. In the summer time, the mechanical ventilation is able to reduce the peak temperatures. It is unknown how much this is attributable to the day ventilation, and how much to the automatic night ventilation control. Relative humidity even in ventilated plenum was never above 60% (data not shown). Figure 5 shows lower maximum peak levels for the renovated room but remains rather inconclusive. More sophisticated sound measurements are necessary to quantify the acoustic performance accurately.

Figure 6a shows the sound pressure level from the technical installations (air handling unit). Some of the ceiling (2 m^2 below the ventilation inlets) was removed to evaluate the effect of embedding the AHU in the acoustic ceiling. The technical noise was approx. 30-34 dB in the occupied zone of which approx. 1 dB was attributable to the extra silencing effect of the acoustic/ventilation ceiling. The reverberation time was approx. the same in both renovated and non-renovated classroom (0.53 vs 0.56). The lighting level (Figure 6b) was overall increased from 200-300 to 600-700 lux.



Mean sound pressure level (a) Lighting level (b)

Figure 6. The 3 min mean sound pressure level (a) from the mechanical ventilation in room 15 in four points at height 1.35 m. Lighting level (b) has doubled in the renovated classroom.



(a) (b)

Figure 7. Air velocities (a) and air temperature (b) at different heights in renovated classroom 15.

The air velocities and temperature gradient are reported in Figure 7. In general the air speeds are as expected below 0.10 m/s, and the ones above are due to local explainable phenomena. The airflow rate is indirectly calculated from the CO_2-peak, number of pupils and space volume to be approx. 700 m^3/h. The gradient on Figure 7b shows very little stratification.

Lastly, Figure 8 shows the questionnaire responses, where pupils were asked before and after the renovation in both rooms (average of approx. 17 pupils' answers). 'All pupils' denotes the mean response of all pupils asked in 9 classrooms, incl. room 15 & 16.

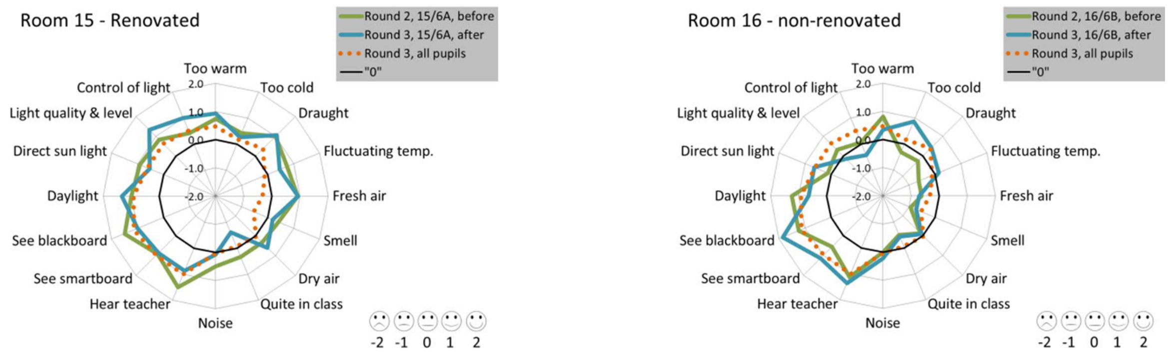


Figure 8. The questionnaire responses in the classrooms during winter.

Selected student quotes: “We are less tired”, “Air is normal”. Teacher quotes: “I think the ventilation does what it is supposed to do, I just don’t notice”, “It is more the lighting and acoustics you notice”, “Actually, there are fewer complaints on headache”, “The light makes it easier to see”.

4 DISCUSSION

The objective measurements show that the indoor environmental conditions have improved for all parameters in the renovated classroom. The questionnaire survey and interview show that the pupils are paying little attention to the indoor environment, both before and after, which is positive, because it means that bringing mechanical ventilation into renovated classrooms can be achieved with success. From the interview quotes we may learn that there is in fact increased user satisfaction with the new conditions among some pupils.

5 CONCLUSIONS

Retrofitting classrooms is inherently associated with the risk that the new solutions perform inadequately or even poorly compared to the former conditions. Despite introducing a mechanical air handling unit in the renovated classroom with an ACH of 5 h^{-1}, changing the acoustic ceiling from dark woodwool to a light-colored perforated gypsum tile and changing the lighting system, the measurements and the pupils responses prove the efforts to be successful in terms of IEQ and energy.

ACKNOWLEDGEMENTS

The authors wish to extend their gratitude to the public (EUDP programme, Danish Energy Agency, grant 64014-0153) and private project partners that made this study possible.

REFERENCES

Dhalluin, A. and Limam, K. (2014). Comparison of natural and hybrid ventilation strategies used in classrooms in terms of indoor environmental quality, comfort and energy savings, Indoor and Built Environment, 23, 4, pp 527-542, DOI: 10.1177/1420326X12464077

Heebøll, A., Wargocki, P. and Toftum, J. (2018). Window and door opening behavior, carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits - ASHRAE RP1624, DOI: 10.1080/23744731.2018.1432938

Wargocki, P., and Wyon, D. P. (2017). Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. Building and Environment, 112, 359-366. DOI: 10.1016/j.buildenv.2016.11.020