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Study of the measured and perceived indoor air quality in Swedish school classrooms

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Abstract. The influence of a classroom's indoor environment on children's health, performance and comfort is a concern that receives increasing attention. Many schools experience problems with inadequate indoor air quality and climate. Investigations of the indoor air quality (IAQ) in schools have been often non-systematic, which can lead to costly ad-hoc remediation actions. It is therefore important to develop a holistic approach to the assessment of IAQ in schools.

This paper presents a field study on the indoor air quality and thermal environment conditions of elementary schools in Gothenburg, Sweden. The focus of the paper is on the methodology to investigate the IAQ using both objective measurements and subjective assessment of the perceived IAQ. The indoor environmental measurements include indoor air quality and thermal comfort parameters for which guideline values exist. Finally, a questionnaire was developed to evaluate the perception of the classroom's thermal environment and air quality by young children.

The paper presents the study protocol and diagnostics approach for IAQ in classrooms. Examples of results from the first 10 investigated classrooms are presented.

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1. Introduction

Good indoor environment is of major importance for human health, comfort and cognitive performance, including learning. The indoor air quality (IAQ) in schools is of particular importance because: a) children are more sensitive to environmental exposure than adults, due to their immature, growing and developing bodies [1], b) children spend a substantial part of their day at school; c) poor IAQ poses a risk for exacerbation of health issues, increased absenteeism and decreased learning performance among the pupils, as well as for adverse health effects among staff/teachers.

Many schools experience problems with inadequate indoor air quality, thermal environment and its indicators. According to a recent report from The Public Health Agency of Sweden, 15% of Swedish schools had poor or rather poor indoor air quality [2]. Investigations of poor IAQ in schools and its causes have been often non-systematic, resulting in costly ad-hoc remediation actions. It is therefore of importance to develop comprehensive methods for the evaluation of the indoor air quality and thermal environment in schools.

Indoor air quality and climate monitoring in classrooms is mainly linked to technical difficulties as it should be minimally invasive. The parameters that should be considered when evaluating the IAQ in schools include CO_2, which is an indicator of ventilation rate [3], thermal comfort [4,5], gaseous air pollutants such as NOx, ozone, total volatile organic compounds and aldehydes, including formaldehyde [6,7] and particulate matter [8].

The Project "Ways to Improving Indoor Environmental Quality in Swedish Schools" aims to develop a comprehensive assessment and ranking method for schools according to their indoor air quality and thermal environment, in order to identify appropriate solutions for remediation, renovation, retrofitting and construction of school buildings that promote better indoor environment. The overarching aim of the project is to combine results from objective and subjective evaluations to produce a comprehensive evaluation tool for school buildings. This paper presents the overall approach, the methods applied in the field investigation and preliminary results from a subset of the investigated school classrooms.

The need for sustainable development and energy conservation influence our choices in buildings' construction and ventilation strategies. We certainly need to gather and interpret information about factors impacting the indoor environmental quality in schools and to provide simple and economical means, based on sound scientific evidence, to counteract poor indoor air quality and thermal environment. In this manner, we believe that this project contributes particularly to UN SDG 3: Good health and well-being, and UN SDG 11: Sustainable cities and communities. The methodology and approach applied in this project can be used as a basis in other indoor environments on a global scale.

2. Method development

The project has four phases:

Phase 1. Selection and recruitment of schools
Phase 2. Ventilation systems and building characteristics
Phase 3. Investigation of indoor air quality - objective and subjective
Phase 4. Development of an assessment tool for school buildings.

2.1. Phase 1: Selection and recruitment of schools

The elementary schools that become a part of the investigation are selected in close cooperation with the municipal school property manager of Gothenburg, Lokalförvaltningen (LF). The school buildings of LF vary over a wide range regarding age (from 100+ years to new), construction material, ventilation system (natural vs. various types of mechanical ventilation) and recorded frequency of complaints related to the quality of the indoor environment. Workshops with the LF and individual school building managers are arranged to obtain information about the major problems with indoor air quality and thermal comfort. Information about technical problems and the nature and extent of complaints is collected. The schools are selected mainly according to the ventilation system(s) and year of construction; the frequency of indoor air quality and thermal comfort related complaints were secondary criterion to ensure a range of indoor environments (poor to good). The selected buildings are grouped into three main categories: A, B and C, see Table 1. The aim is to include both well-performing and poorly-performing buildings in each building category, as judged from LF's records on indoor air quality and thermal comfort related complaints. About 10 schools are recruited in each category and 2-3 classrooms in grades 4-6 are investigated in each school. We aim at classrooms of the fifth-grade pupils assuming the children are old enough to understand the questions in the questionnaire and to provide reasonable answers.

Table 1. Categories of the investigated schools according to ventilation system and year of construction.

Building category	Main features
A	Supply of untreated outdoor air. Natural or mechanical exhaust ventilation. Typically more than 50 years since construction.
B	Mechanical supply and exhaust with simple control (constant airflow rate during daytime). Typically 20-30 years since construction or major renovation.
C	Mechanical supply and exhaust with advanced control (variable airflow rates). Demand control based on temperature, occupancy, CO_2 and/or other gaseous pollutants). Typically less than 10 years since construction or major renovation.

2.2. Phase 2: Ventilation systems and building characteristics

In Phase 2 the ventilation systems in the selected classrooms (type, quality of filters, air change rate (ACR)) are examined, and other building characteristics are collected (year of construction, geographical location, main building material). ACR was determined by tracer gas decay. Occupant generated CO_2 after the children left the classroom was used as tracer gas in most cases. In the absence of pupils, CO_2 was dosed from a cylinder. Complementary data are collected by a variety of measurements, e.g. in-duct air flow rate measurements and air distribution (mixing conditions) in representative classrooms. These measurements are carried out in order to clarify a) whether the system operates according to design specification; b) whether the control function is judged suitable with respect to the assessed actual need for climate control.

2.3. Phase 3: Investigation of indoor air quality - objective and subjective

Indoor air quality in the school buildings is assessed by 1) measurements of indoor climate parameters; 2) questionnaire survey of perceived air quality.

2.3.1. Objective evaluation of the indoor environmental quality.

The measurements are performed during heating season (October – March) and they last one week in each classroom. Thermal conditions (temperature, relative humidity (RH)) and concentrations of CO_2 are measured with Wöhler CDL 210 sensors with 2-minute time resolution. Operative temperature in the occupied zone approximately 50 cm from the windows is measured with 5-minute interval using a a TinyTag TK-4023 temperature sensor and data logger placed in a 4 cm diameter sphere (ping pong ball). The measured air pollutants include nitrogen dioxide (NO_2), ozone (O_3), TVOCs (Total VOC), formaldehyde and particulate matter PM_{10} and $PM_{2.5}$. These have been selected because of the availability of guideline values [9]. Additional target pollutants specified in the report of IEA-Annex 68 [10], e.g. benzene, acetaldehyde, acrolein, and nonanal and decanal (markers of dermal bio-effluents [11]), are quantified. Nitric oxide (NO) is sampled in order to assess the contribution of traffic to the indoor air pollution. The gaseous air pollutants are measured using diffusive samplers during one school week, from Monday morning to Friday afternoon [12]. Particulate matter PM_{10} and $PM_{2.5}$, are measured continuously using the DustTrak DRX Aerosol Monitor 8533. Corresponding outdoor air data (temperature, RH, NOx, O_3, PM_{10}, $PM_{2.5}$) are obtained from the Gothenburg's local environmental administration through its ambient air monitoring program.

2.3.2. Subjective evaluation of the indoor environmental quality.

Subjective assessments of the perceived indoor air quality (PAQ) and thermal comfort are performed through a questionnaire distributed to the pupils (age 9-12 years) and their teachers at the start of a lesson on one day during the week of the objective measurements. The questionnaire survey is preferably performed on Wednesdays to avoid the effect of the beginning and the end of the school week on children's responses. The questionnaire contains questions about the acceptability of the air quality, odour intensity, building related acute non-clinical health symptoms (previously named Sick-Building-Syndrome - SBS) symptoms and thermal sensation. The format and language of the questions were carefully adapted to the age of the children. Thus, the well-established continuous acceptability scale for indoor air quality [13], the visual analogue scales for odour intensity and the building related symptoms [14] and the 7-point thermal sensation scale [15] were modified to category scales. Thermal preference is assessed on a 3-grade scale ("colder", "as it is", "warmer"). The questionnaires are answered by 18 – 30 children per classroom. The questionnaire survey and measurements of temperature will be also performed during the non-heating season. All measured data and coded answers from the questionnaires are collected in a project main database for further statistical analyses.

2.4 Development of an assessment tool for school buildings

The basis for the assessment tool is the Indoor Environmental Index (IEI), originally developed for office buildings [16]. We intend to use the approach in this project, using the IAQ guideline values suggested by Salthammer et al. [9] for schools. The IEI is a combination of Indoor Discomfort Index (IDI) related to temperature and relative humidity and Indoor Air Pollution Index (IAPI) related to concentrations of air pollutants. The index will be further developed by including PAQ and the outdoor air conditions.

Statistical methods will be applied to find correlations between the parameters. A multivariate model, including variables from the measurements, responses from the questionnaire survey and building characteristics, will be constructed.

3. Preliminary results

Selected results are presented to demonstrate the application of the methodology. Examples from the measurements and surveys in the 10 classrooms of the first five investigated schools are presented.

3.1. Selected measurement results from the heating season

Concentrations of formaldehyde during the heating season in schools with different ventilation systems are shown in Figure 1. The dashed red line indicates the chronic exposure limit value proposed in a French guideline [17]. The concentration of formaldehyde was lower in the schools with supply and exhaust ventilation with constant airflow rates and heat recovery then in the schools with natural ventilation.

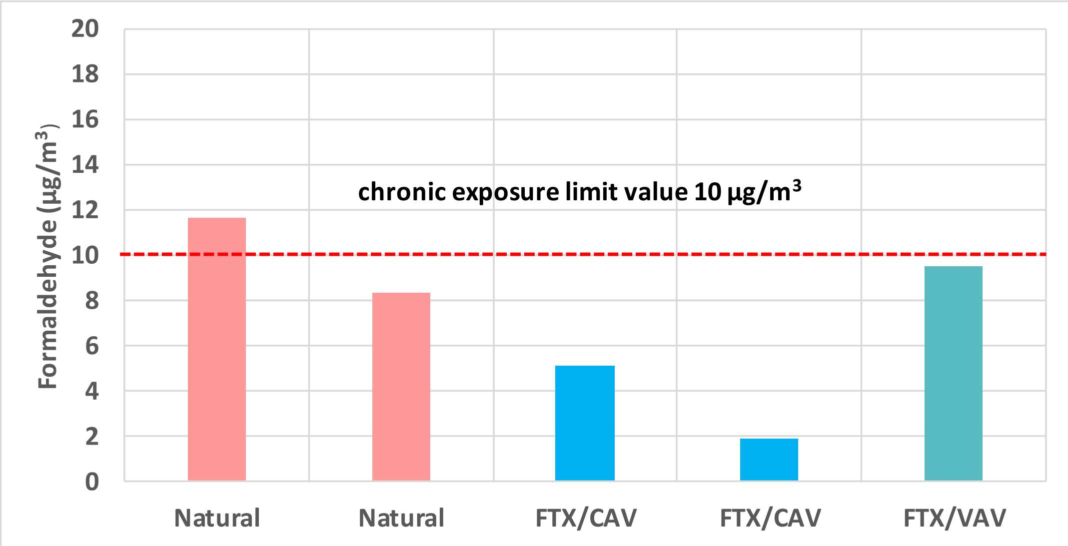

Figure 1. Concentration of formaldehyde in schools with different ventilation system. The value is an average of two classrooms in each school. (FTX – mechanical ventilation with heat recovery; CAV – constant airflow rates; VAV – demand-controlled ventilation with variable airflow rates).

The indoor-to-outdoor (I/O) ratios of NO_2 for the schools with the different ventilation systems are presented in Figure 2. Demand-controlled ventilation with constant flows appears to result in outdoor NO_2 being transported into the classroom. The correlation between ACR and the I/O ratios will be investigated at a later stage of the project.

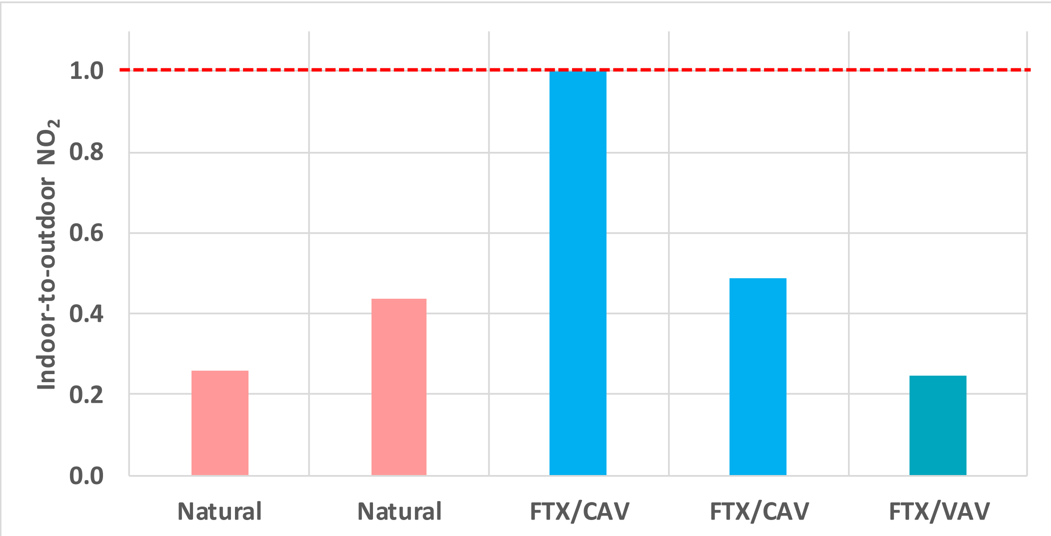

Figure 2. Indoor-to-outdoor ratio for NO_2 in schools with different ventilation systems. The indoor value is an average of two classrooms in each school; the outdoor value is an average over the same period as the corresponding indoor sampling (data provided by the City of Gothenburg ambient air quality monitoring office).

3.2. Survey results: thermal sensation in the non-heating season

Figure 3 shows the relationship between the children's thermal sensation vote and the operative temperature at the time of the survey. Seven out of ten surveys were conducted at temperatures between 22-24°C and children's mean thermal sensation ranged between neutral and slightly warm. The regression coefficient from all individual thermal sensation votes against the operative temperature is 0.34/°C, which means an increase in children's thermal sensation of one scale point (e.g. from neutral to slightly warm) when temperature increased by 3°C. The analysis using the entire dataset will allow us to explore the relationship between the children's thermal sensation and the different conditions investigated (e.g. season, ventilation system, IAQ parameters).

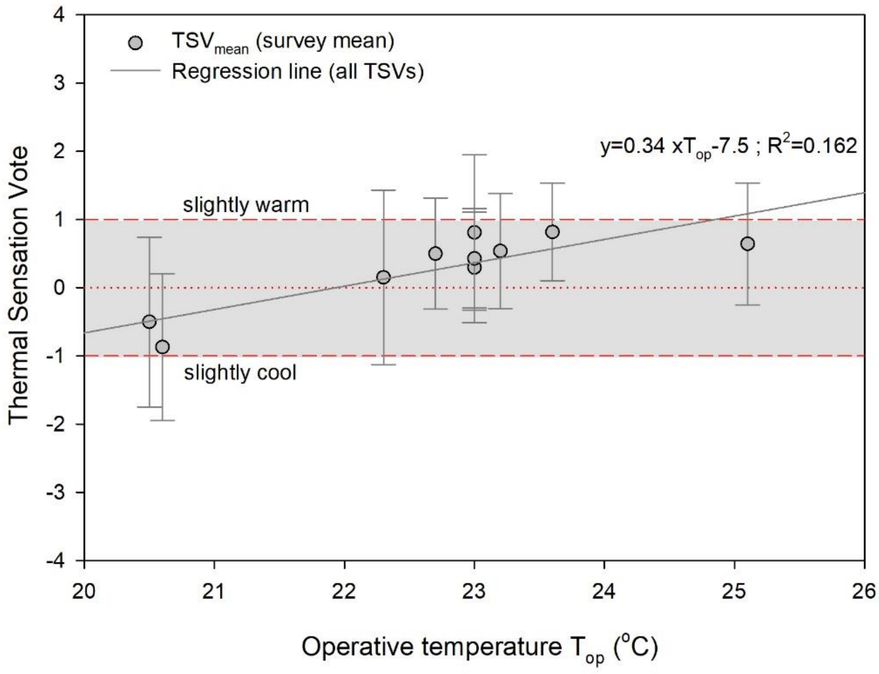

Figure 3. Children's mean thermal sensation vote against the operative temperature during the survey. Error bars indicate standard deviation. The regression line corresponds to all individual thermal sensation votes.

4. Conclusions

The paper presents the methodology which has been developed within the project "Ways to Improving Indoor Environmental Quality in Swedish Schools" for evaluating the indoor air quality and thermal environment in schools in a holistic way. The methodology is currently applied in 30 selected schools; thermal climate, indoor air quality measurements and questionnaire surveys during the heating season and questionnaire survey are ongoing. Temperature measurements and questionnaire surveys will be performed during the coming non-heating season.

Once the data from all schools are available, the overall assessment tool will be developed using the concept of the Indoor Environmental Index. The tool is intended to rank the schools based on the measured and perceived IC. It will serve as a basis for the development of guidelines for retrofitting, renovations and new construction of school buildings with good indoor environment.

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