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Determining ventilation strategies to relieve health symptoms among school occupants

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Abstract

Purpose – Poor indoor air quality (IAQ) contributing to occupants' health symptoms is a universal, typically ventilation-related, problem in schools. In cold climates, low-cost strategies to improve IAQ in a naturally ventilated school are rare since conventional methods, such as window opening, are often inappropriate. This paper aims to present an investigation of strategies to relieve health symptoms among school occupants in naturally ventilated school in Finland.

Design/methodology/approach – A case study approach is adopted to thoroughly investigate the process of generating the alternatives of ventilation redesign in a naturally ventilated school where there have been complaints of health symptoms. First, the potential sources of the occupants' symptoms are identified. Then, the strategies aiming to reduce the symptoms are compared and evaluated.

Findings – In a naturally ventilated school, health symptoms that are significantly caused by insufficient ventilation can be potentially reduced by implementing a supply and exhaust ventilation system. Alternatively, it is possible to retain the natural ventilation with reduced number of occupants. The selected strategy would depend considerably on the desired number of users, the budget and the possibilities to combine the redesign of ventilation with other refurbishment actions. Furthermore, the risk of poorer indoor air caused by the refurbishment actions must also be addressed and considered.

Practical implications – This study may assist municipal authorities and school directors in decisions concerning improvement of classroom IAQ and elimination of building-related symptoms. This research provides economic aspects of alternative strategies and points out the risks related to major refurbishment actions.

Originality/value – Since this study presents a set of features related to indoor air that contribute to occupants' health as well as matters to be considered when aiming to decrease occupants' symptoms, it may be of assistance to municipal authorities and practitioners in providing a healthier indoor environment for pupils and teachers.

Keywords Ventilation, Indoor air, School, Health, Ventilation redesign, Ventilation strategy

Paper type Research paper

Introduction

Pupils and teachers are exposed to multiple features affecting their health when they are at school (Fisk, 2017; Peng *et al.*, 2017; Vornanen-Winqvist *et al.*, 2018a, 2018b). Even though the majority of the occupants' symptoms are short term, the symptoms may also have a

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long-lasting effect on occupants' health. A wide spectrum of these symptoms and diseases are linked to indoor air and ventilation in schools (Seppänen and Fisk, 2004). The indoor air quality (IAQ) is of special concern in the school environment because children are particularly susceptible to indoor air pollution compared to adults because of their underdeveloped immune system and lungs, as well as their high inhalation rates per body mass (Mendell and Heath, 2005; Zuraimi *et al.*, 2007). Currently, a large number of schools have poor IAQ, and multiple pupils and teachers complain of neurophysiologic symptoms (Muscatiello *et al.*, 2015); respiratory symptoms (Borràs-Santos *et al.*, 2013; Meklin *et al.*, 2002; Uotila *et al.*, 2019); and poor general health (Shaughnessy *et al.*, 2012) when using these buildings.

Prior studies have found connections between the selected ventilation strategy and occupants' health symptoms. For example, mechanical ventilation compared to natural ventilation is connected to a higher risk of current rhinitis among children (Zuraimi *et al.*, 2007) and a higher prevalence of nasal symptoms (Walinder *et al.*, 1999). Whereas living in a naturally ventilated house is connected to a higher prevalence of general symptoms compared to a mechanically ventilated house (Smedje *et al.*, 2017). However, occupants' symptoms are more related to the IAQ the selected strategy provides than the selected strategy itself.

Worldwide, multiple low-cost interventions have been experimented for improving IAQ in naturally ventilated school. Telejko and Zender-Ś wiercz (2017) reported on the pursuit of improving IAQ by increasing the stream of supply air. The increase from 150 to 360 m^3/h resulted in reduction of the maximum CO_2 concentration in Polish classrooms from 2,700 to 1,700 ppm (Telejko and Zender-Ś wiercz, 2017). The increase of airflow into 540 m^3/h resulted in further reduction of the CO_2 concentration but also caused feeling of draft and had a negative effect on the energy balance of the building (Telejko and Zender-Ś wiercz, 2017). In Italy, IAQ of naturally ventilated classroom was tended to improve by using a low-cost CO_2-based visual-alerting system. The system had a positive effect on IAQ, but its effectiveness was highly dependent on the occupants, and the system is more likely to be used with mild outdoor temperatures (Avella *et al.*, 2021a, 2021b). In Switzerland, CO_2 concentrations of naturally ventilated classrooms were remarkably reduced by the intervention in which the ventilation took place exclusively during breaks between lessons (Vassella *et al.*, 2021). In Portugal, the impact of refurbishment including an experimental demand controlled ventilation system was monitored and assessed by survey. The refurbishment was proved to have positive effect on IAQ in classrooms by both methods (Almeida and de Freitas, 2015).

Even the great number of studies have presented interventions with positive affect on IAQ, the alternatives for improving IAQ in naturally ventilated school in cold climates are still not completely understood. As common method for improving IAQ in mild climate is to increase supply air, in cold climates this strategy may cause draft (Duarte *et al.*, 2017), lower the indoor temperature (Heebøll *et al.*, 2018), reduce energy efficiency (Schibuola *et al.*, 2016) and has a significant negative affect on heating costs. Furthermore, replacement of natural ventilation with mechanical ventilation can be a poor option because of its energy-intensiveness (Ben-David and Waring, 2016) and high costs (Almeida and De Freitas, 2014; Duarte *et al.*, 2017). In addition, in an old building with leaking structures it may cause IAQ problems and work improperly (Vornanen-Winqvist *et al.*, 2018a, 2018b).

Moreover, the prior studies concerning IAQ improvements have mainly focused on technical point of view, and the economic aspects have been excluded. Since municipalities have challenges in funding the refurbishment of public buildings (Korhonen *et al.*, 2018;

Valen and Olsson, 2012), even the ones with complains of health symptoms (Uotila *et al.*, 2019) and inadequate financial resources for the maintenance (Wargocki and Wyon, 2013), also the low-cost alternatives to manage this prevalent problem are vitally needed.

To fill this apparent gap, this study aims to provide alternative strategies for improving IAQ in naturally ventilated school in cold climate. This study uses a case study approach to assist the search for ventilation strategies. Case study is selected as the aim of the study is to gather a thorough understanding of this complicated problem within its real-life context. First, the potential reasons for the occupants' symptoms in the case school are established. Then, the study compares two differently priced strategies relieve the symptoms: implementing supply and exhaust ventilation and preserving the current natural ventilation strategy with a lower number of users.

Indoor air features and parameters contributing to symptoms

Pupils and teachers' health symptoms related to the use of a school building originate from a varying set of sources. Building-related pollutant sources, including microbes, fungi and bacteria, are typically caused by leaks and excessive moisture in structures (Annila *et al.*, 2017; Haverinen-Shaughnessy, 2012; Meklin *et al.*, 2002). These moisture problems are, usually, the result of errors during construction; poor maintenance and delayed repairs, or the inappropriate use of a building (Meklin *et al.*, 2002; Täubel and Leppänen, 2017). Volatile organic compounds (VOCs) are often released from building materials (Liu *et al.*, 2013). Furthermore, some pollutant sources, such as traffic emissions and radon, enter the indoor air from outdoors. In addition, the occupants of a school generate an adverse level of biological pollutants, such as CO_2, themselves, especially in classrooms with inadequate ventilation.

A summary of the indoor air features and parameters associated with pupils and teachers' health reported in literature is presented in Table 1. Features causing chronic health effects after long-lasting exposure, such as radon, are excluded from the table. The presented features are significantly inferred from case studies, and the results may be affected by other factors that cannot be controlled. Therefore, these studies mainly report on association between specific features and health but do not identify causal relationships. In addition, these studies have several limitations, which may have affected their results. For example, the occupants' symptoms are typically self-reported instead of clinically verified, the contaminations of all indoor air pollutants are not measured, and the measurement periods are typically relatively short.

Ventilation strategies in schools

Prior studies have indicated that poor indoor ventilation may lead into higher levels of indoor pollutants, which can reduce occupants' comfort and cause symptoms. Hence, the extent, volume and intensity of occupants' health symptoms in schools can be significantly affected by ventilation. The ventilation both dilutes and removes the pollutants originating in the building (Etheridge and Sandberg, 1996) with the process of exchanging polluted indoor air with cleaner outdoor air (Carrer *et al.*, 2015). However, indoor air concentrations of some pollutants from outdoor air, including ozone and outdoor air particles, may also increase with higher ventilation rates (Fisk, 2017). Hence, outdoor air quality has to be considered when designing ventilation systems. Generally, three key methods are used to ventilate a building:

(1) natural ventilation;

(2) mechanical ventilation; and

(3) hybrid ventilation (Chenari *et al.*, 2016; Litiu, 2012).

Table 1. Indoor air parameters associated with health outcomes in schools

Feature	Health outcomes	Target value/guidelines
Ventilation rate	Increased ventilation rates were associated with decreased illness absence (Mendell *et al.*, 2013)	According to EN 16798–1 (European Committee for Standardization, 2019), the total ventilation rate must never be lower than 4 l/s per person. The Finnish standard specifies the minimum ventilation rate per person 6 l/s in schools (Finnish Ministry of The Environment, 2017)
	Higher ventilation rates, even up to 15 l/s per person or higher, in classrooms were consistently associated with decreased illness absence (Mendell *et al.*, 2013)	
	A small increase in reported eye symptoms at the higher ventilation rates were found but no association with other self-reported symptoms (Petersen *et al.*, 2016)	
	Increased ventilation rate was significantly associated with decreased odds of suffering from eye and skin disorders (Baloch *et al.*, 2020)	
CO_2	A CO_2 concentration above 1,000 ppm in classrooms was associated with considerable increases in dry cough and rhinitis (Simoni *et al.*, 2010)	A European standard specifies the maximum CO_2 concentration in a classroom with moderate indoor air quality of 600–1000 ppm (CEN European Committee for Standardization, 2004). According to a Finnish standard (Finnish Ministry of The Environment, 2017), the maximum CO_2 concentration in a new building is 800 ppm above the level of CO_2 outdoors
	CO_2 concentration was negatively correlated with general symptoms and mucosal symptoms (Zhang *et al.*, 2011)	
	Higher level of CO_2 was associated with itchiness and nasal congestion (Fernández-Agüera *et al.*, 2019)	
	Allergies, nose irritation and fatigue were significantly positively correlated to the levels of CO_2 concentrations (Dorizas *et al.*, 2015)	
	Ocular, nasal and throat symptoms, breathlessness, headache and tiredness were significantly more common at higher CO_2 levels (Norbäck and Nordström, 2008)	
	Increased classroom CO_2 had a relatively small, but significant, effect on wheezing but not on other health problems, e.g. headaches (Kim *et al.*, 2011)	
	Current asthma, asthma attacks and asthma medication were positively associated with CO_2 (Mi *et al.*, 2006)	
	Teachers' neuro-physiologic (i.e. headache, fatigue, difficulty concentrating) symptoms significantly increased for every 100 ppm increase in maximum classroom CO_2 concentrations	

(*continued*)

Table 1.

Feature	Health outcomes	Target value/guidelines
	and were nonsignificantly increased in classrooms with above-median proportions of CO_2 concentrations greater than 1,000 ppm (Muscatiello *et al.*, 2015) Higher level of CO_2 was associated with an increased incidence of mucosal symptoms and general symptoms (Zhang *et al.*, 2014) CO_2 values higher than 2,100 ppm were associated with exercise-induced wheezing and night cough among pupils (Fraga *et al.*, 2008) Higher levels of CO_2 in schools were connected with a higher risk of experiencing upper, lower airways and systemic outcomes (Baloch *et al.*, 2020)	
Air pressure	Positive air pressure (5–7 Pa) decreased nose irritation, dryness of facial skin and tiredness in a school, where occupants' symptoms were suspected to be related to the impurities leaked indoors through the building envelope (Vornanen-Winqvist *et al.*, 2018a, 2018b)	According to the National Building Code of Finland, in a new building, positive air pressure should not cause long-term moisture load into the structures and negative air pressure should not allow harmful contaminant to enter into indoor air (Finnish Ministry of The Environment, 2017)
Air humidity	Modest increase in respiratory symptoms over both at low (<30%) and high RH (>50%) among teachers (Angelon-Gaetz *et al.*, 2016) Current asthma, asthma attacks and asthma medication were positively associated with indoor relative air humidity (Mi *et al.*, 2006) Relative humidity was associated with increased odds of suffering from lower airways and systemic disorders among schoolchildren (Baloch *et al.*, 2020)	
Room temperature	Increased room temperature was related to nasal and throat symptoms, headache and tiredness (Norbäck and Nordström, 2008) Room temperatures above 22 °C increased mucosal irritation and general symptoms such as headache and tiredness may occur in temperate climates (Zhang *et al.*, 2011)	In Finland, target value for room temperature is 20°C– 23°C during heating season (Finnish Ministry of the Environment, 2012)
NO_2	An increase in indoor NO_2 was associated with current asthma and asthma medication. Outdoor NO_2 was associated with current asthma (Mi *et al.*, 2006) NO_2 might be related to mucosal symptoms, and skin symptoms (Zhang *et al.*, 2011) Pupils reported more wheezing at increased outdoor level of NO_2 (Kim *et al.*, 2011)	The WHO guideline value is 200 μg/m3 for 1-h NO_2 concentration (World Health Organization, 2010)
SO_2	SO_2 might be related to general symptoms, mucosal symptoms and skin symptoms (Zhang *et al.*, 2011) Both indoor and outdoor SO_2 were positively associated with prevalence of school-related symptoms (Zhang *et al.*, 2014)	The 24-h average WHO guideline value for SO_2 is 20 μg/m3 (World Health Organization, 2006)

(*continued*)

Table 1.

Feature	Health outcomes	Target value/guidelines
O_3	Indoor O_3 was positively associated with prevalence of skin symptoms (Zhang *et al.*, 2014)	The daily maximum 8-h mean of WHO guideline value for O_3 is 100 μg/m3 (World Health Organization, 2006)
	Elevated levels of ozone were significantly related to a variety of symptoms (Baloch *et al.*, 2020)	
VOC	Pupils exposed to higher total VOC concentrations (the median concentration of 140.3 $\mu g/m^3$) had a twofold increased risk of having asthma-related symptoms (Madureira *et al.*, 2015)	WHO recommendation is 100 $\mu g/m^3$ (30 min) (World Health Organization, 2010). Finnish standard recommends the action level of 400 $\mu g/m^3$ (Valvira, 2016)
	Increased number of VOCs was connected to a higher risk for upper and lower airways and systemic disorders (Baloch *et al.*, 2020)	
Formaldehyde	Indoor exposure to formaldehyde was related to asthma-like symptoms among pupils (Madureira *et al.*, 2015)	WHO and Finnish standard specify the maximum short-term (30 min) guideline of 0.1 mg/m3 (Finnish Ministry of the Environment, 2012; World Health Organization, 2010)
	A high prevalence of rhinoconjunctivitis in the past year was found in children using classrooms with high levels of formaldehyde (Annesi-Maesano *et al.*, 2012)	
Particulate matters ($PM_{2.5}$ and PM_{10}): contaminants, including viruses, bacteria, allergens, fungi and traffic emissions	Both indoor and outdoor PM_{10} was associated with increased incidence and decreased remission of most types of SBS symptoms such as facial and hand rash or itching; eye irritation; nasal catarrh and obstruction; dryness in the throat; sore throat; irritating cough; headache (Zhang *et al.*, 2014)	The WHO health based standard for PM_{10} is a maximum of 50 $\mu g/m^3$ as a 24-h mean value (World Health Organization, 2006). According to the Finnish standard, the maximum design value is also 50 μg/m3 for PM_{10} and 25 μg/m3 for $PM_{2.5}$ (Finnish Ministry of the Environment, 2012)
	The indoor median concentration of PM2.5 and PM10 that exceed the 25 $\mu g/m^3$ and 50 $\mu g/m^3$ levels of WHO air quality guidelines for a sampling period of 24 h increased the odds of asthma-like symptoms among pupils (Madureira *et al.*, 2015) High fungal concentrations were associated with respiratory symptoms of children in concrete/brick schools but not in wooden schools (Meklin *et al.*, 2002) Certain moulds were associated with the respiratory symptoms of children (Simoni *et al.*, 2011)	

A natural ventilation is based on a variety of different ventilation strategies: stack ventilation is operated through thermal buoyancy, whereas cross and single-sided ventilations are based on wind (Ghiaus and Roulet, 2012). Mechanical ventilation is based on air distribution by fans. Different methods of room air distribution may be categorized into various types, including mixing ventilation, displacement ventilation and jet ventilation (Ren *et al.*, 2015). Hybrid ventilation combines the different features of both natural and mechanical ventilation at different times of the day or seasons of the year. Hybrid ventilation may be defined in three main concepts: alternating use of natural and mechanical ventilation; fan assisted natural ventilation; and stack and wind supported mechanical ventilation (de Gids and Jicha, 2010).

The ventilation strategies of schools vary between countries. These differences are likely to result mainly from the variety of climatic conditions, the age of school buildings and different priorities, such as the quality of indoor air and costs, that different countries have. The majority of schools worldwide are ventilated naturally, especially the older building stock (Litiu, 2012; Morck and Erhorn, 2003; Seppänen *et al.*, 2012), but in colder climates, a large portion of schools are mechanically ventilated (Seppänen *et al.*, 2012). Hybrid ventilation is also used (Litiu, 2012; Vornanen-Winqvist *et al.*, 2018a, 2018b). Irrespective of the selected strategy, the proper operation of the ventilation system has a major effect on the quality of indoor air. Thus, it needs to be accurately designed, implemented, controlled and maintained to provide good circumstances for building users.

Materials and methods

This study adopts a case study approach to assist the search of ventilation strategies for providing a healthier indoor environment for school occupants. The occupants of the case school building have complained of health symptoms when using the building. Moreover, the building is in major need of renovation because of the aging of the structures and systems. Therefore, refurbishment of the building is under consideration.

Multifarious data, including health questionnaires and condition assessments, are used to gather a comprehensive understanding of the situation and the potential reasons for the health symptoms. The municipal authors purchased a survey of the occupants' health symptoms and perceived indoor air of the school. All the pupils and teachers of the school were asked to fill in an anonymous Örebro (MM-40) questionnaire concerning prevalence and frequency of various features of indoor environment. In addition, in this established and validated practise (Andersson, 1998), the respondents were asked to report their health symptoms in past 3 months and diseases diagnosed by doctor. These surveys were implemented by the University of Turku in 2017–2019 for teachers and 2018 for pupils. In 2018, 126 pupils and 26 staff members responded to the survey. The congruent results indicate the indoor air problems in the building as they significantly diverged from the point of reference, especially with records of stuffiness, unpleasant smells, draught and poor air change, and the perceived health symptoms. The most commonly reported symptoms, which appeared to a significantly large extent compared to the reference material, were nasal congestion, tiredness, skin symptoms and rash. Furthermore, staff reported, notably, on eye irritation.

The municipalities purchased also a condition assessment, on the authors initiative, to research the potential sources of the symptoms. This study included material sampling from base floor and external wall for microbial analysis, moisture measurements with a portable device (GANN Hydromette UNI 1) for logging relative humidity from boreholes and cuts under floor covering and ventilation system mapping. In addition, base floor, intermediate floor and external wall condition was also surveyed by boreholes. Moreover, the prior surveys covered air samples for evaluating microbe contamination and differential pressure measurements. Smoke tracer tests were used for investigating air leaks of the base floor, interior and exterior walls and the roof structure and for tracking the air flow of air ducts. Also, the CO_2 content was measured continuously for two weeks in six classrooms, and temperature and relative humidity was measured for 16 days in three classrooms.

The authors addressed the potential sources of the building users' symptoms first by scrutinizing the condition assessments and the reports of health questionnaires. The potential sources of health symptoms are determined by comparing the measured values of indoor air parameters to the values presented in the literature and guidelines. In addition, conclusions of the condition assessment reports and the analysis of the alternative strategies produced by the indoor air consultants are ruled in.

Case study building

The case study building is a primary school located in the metropolitan area in Southern Finland. It was built in 1955 and has a total floor area of 3,957 sq m. The building is mostly three-storey high, but it has a wing for sports activities and a club room, which comprises two floors. Besides the rooms designed for educational use, the building has a residential wing, which is nowadays mainly used by the staff. Currently, approximately 300 pupils, mainly between 13 and 15 years of age, attend the school and approximately 50 faculty and staff members work in the building (Figure 1).

The building has a soil-based two-layered concrete foundation. The floor of the sports hall and, partially, the floor of the basement is raised by wooden structures. The frame is built on solid bricks with an air cavity. The intermediate floors contain two concrete slabs and some of these intermediate floor structures use organic filling as insulation.

The building currently uses various ventilation techniques. The sports hall has mechanical supply-exhaust ventilation based on the principle of mixed ventilation. The system does not adopt heat recovery but uses recirculated air. The wing, originally planned for residential use, comprises rooms that use mechanical exhaust ventilation and rooms with single-side ventilation through open windows. The middle part of the building is mainly naturally ventilated by using stack ventilation, but the replacement air vents are very few and too small for current use according to the inspection. Furthermore, the windows cannot be kept open for long times during the winter because of the low outdoor temperatures. The exhaust air ducts are original and located next to the entrances of the classrooms. In the

Figure 1.
Case building

middle part, some rooms such as toilets, chemistry classrooms and the basement, use mechanical exhaust or supply-exhaust ventilation.

Results

Potential sources of the occupants' symptoms

It was not possible to measure the ventilation rates of the building reliably or to a large extent since natural ventilation is highly affected by external environmental conditions and varies significantly during different times. However, surveys of air flow in ducts prove that the mechanical exhaust ventilation in the middle part of the building causes the negative air pressure, which has reversed the direction of the air flow in the natural ventilation shafts. Hence, air comes in through the exhaust air shafts of the natural ventilation. Furthermore, the inlet of outdoor air is currently mainly based on the opening of ventilation windows since the external walls lack replacement air valves. The window ventilation is challenging especially during the winter, as the windows cannot be kept open for a long time because of cold outdoor temperature.

The ventilation rate of classrooms was estimated by calculation based on the CO_2 and the number of occupants in accordance with ventilation calculation guide by Finnish Ministry of the Environment (Finnish Ministry of The Environment, 2018). The outdoor concentration of $CO_2$was assumed to be 400 ppm in this calculation since the aforementioned guide recommends using this value if measured values are not available. In addition, the outdoor air quality around the school is estimated to mainly be at a satisfying level according to the open data of measured concentrations of a set of various air pollutants (HSY, 2022). According to this calculation, the ventilation rate of the classrooms is about 2.7 l/m^3 per person which is significantly lower than the typical standard values, 4–6 l/m^3.

Excessive moisture values were measured in the base floor, but no indication of fungi or mold as being the source of health symptoms was found. In addition, the measured content of particular matters placed under a rather normal range. Hence, these were excluded from the potential sources of symptoms.

The features potentially having an effect on occupants' symptoms in this case building are summarized in Table 2. These data, gathered from the condition assessment reports and other surveys, are compared to the values associated with health symptoms in literature and the values prescribed by guidelines and standards.

The measured as well as the calculated CO_2 values are significantly higher than the recommended values. In addition, the health symptoms found by the health questionnaire were similar with the symptoms associated with high CO_2 concentrations in literature. Furthermore, the ventilation was detected as being inoperative in the condition assessment. Therefore, the most potential sources for the users' health symptoms in this case building are inferred to be:

- inoperative ventilation system; and thus
- a high level of CO_2.

Alternative ventilation strategies

As insufficient ventilation and a high level of CO_2 were concluded to have substantial contribution to health symptoms, there was a need to improve IAQ. Interventions increasing the supply air flow were excluded, since these strategies, most likely, will lower indoor temperature, cause draught and raise energy consumption. In addition, because of the listed façade of the building, visible alterations of façade are prohibited. The first alternative

Feature	Measured/evaluated value	Comparison to guidelines
Ventilation rate	The condition assessment reports estimate the ventilation rates to be much lower than the design values. Furthermore, air flow in some of the natural ventilation air shafts has reversed the direction of the ventilation. Hence, air flows from the attic to the classrooms. The calculated value for ventilation rate is 2.7 dm^3/s per person	The calculated ventilation rate is much less than Finnish recommendations (6 dm^3/s per person)
CO_2	CO_2 varied between 1,000 and 2,000 ppm during the occupied hours (8–16) in the studied rooms, while in three classrooms the maximum concentration reached 2,000 ppm almost every day	Much above the standard values (600–1,000 ppm)
Air pressure	The building was under negative pressure for almost the whole of the measurement periods (measured in February and March). Range +28 to −40 Pa, range of averages −2.8 to −11.8 Pa	The building is designed to be under slight negative pressure. The variation of values can be mainly ascribed to opening windows and operating times of mechanical ventilation
Air humidity	Range of RH values 14%–42% (measured in spring)	Mainly within the range of normal level
Room temperature	Range of room temperatures 17.7 °C −24.5 °C (measured in spring)	Mainly within the range of normal level
NO_2	Not measured	
SO_2	Not measured	
O_3	Not measured	
VOC	111 μg/m3 (measured in one classroom)	Slightly above WHO guideline but within the normal range according to Finnish guide. The concentrations of the individual compounds contributing to total VOC substances remained below the recommended action level
Particulate matters	The measured levels of harmful pollutants, such as fungi and microbes, were less than 100 spores/g The concentration of mineral wool fibre was lesser than 0.1 fibre/cm^2 (14 days)	The values do not exceed the normal level defined in Finnish guidelines
Formaldehyde	Not measured	

Table 2. Potential sources of occupants' symptoms in the case building

strategy to relieve the occupants' symptoms is refurbishing the natural ventilation for supply and exhaust ventilation. This strategy is rather common in Finland, but expensive, laborious and includes risks related to the old structures and materials. Hence, also nondestructive alternative – preserving the natural ventilation but reducing the number of users – was generated.

The supply and exhaust ventilation would permit much higher ventilation rates than the current system provides and the higher ventilation rates would retain the CO_2 values at a tolerable level. This ventilation refurbishment would potentially reduce the occupants' symptoms significantly. However, the replacement of natural ventilation by supply and exhaust ventilation would be rather expensive and require a high level of expertise in design, implementation and maintenance to work properly. Furthermore, there is a high risk of impurities entering through the leaking structures and it would be a challenge to balance the ventilation as the structures are not tight. Thus, the system needs to be designed to maintain the air pressure difference of indoor air and outdoors as low as possible. This also requires constant measuring of air pressure as well as continuous adjustment. Moreover, the new ducts and devices would slightly diminish the usable area of rooms. However, the placement of exhaust and air supply units is rather simple, as these machines could be installed in the attic and the basement which are not occupied.

On the basis of the analysis of the sources of health symptoms, the main challenge is the high levels of CO_2 caused by the inadequate ventilation in relation to the number of occupants. Therefore, the current ventilation system could, probably, provide adequate IAQ if the number of users was reduced substantially. The number of pupils, with which the CO_2 concentration of classrooms would remain under the acceptable level, was estimated by calculation. By reducing the number of pupils from 26 to 15, the CO_2 concentration of the classroom would remain constantly under 1,350 ppm. This strategy has much lower implementation, use and maintenance costs compared to the supply and exhaust ventilation strategy. However, lowering the number of building users might not be cost-effective at the municipal level, as the rooms would not be used efficiently, and a considerable number of pupils would, currently, need to be relocated to other buildings. In addition, the activity of the occupants may affect on the real CO_2 concentration of the classrooms.

The implementation costs of the alternative strategies are calculated by using a tool of target cost estimates of TAKU^{TM} Cost Estimation 2019 software (TAKU, 2019). This software is commonly used in Finland for evaluating the costs of building and renovation projects. The calculations employ the cost level of July 2021. The implementation of supply and exhaust ventilation, including renovation of electric systems, to the second and third floor of the middle section of the building, where the classrooms and workrooms are mainly located, costs approximately €850 per sq m of net internal area with the renovation rate of 29%. It must be noted that even if the natural ventilation would be preserved, the building would still have major renovation needs. The scheme of renovation is not defined yet, but the complete overhaul would cost about €3,000 per sq m of net internal area. This is about the same as the cost of a new building with similar rooms. The complete overhaul of the second and third floor of the middle section of the building would cost about €1,600 per sq m of net internal area with the renovation rate of 54%.

Both of these strategies have multiple risks. These risks as well as the summary of the advantages and downsides of both generated strategies are presented in Table 3.

The number of pupils each strategy would enable is based on the calculated estimates of ventilation rates and measured classroom size. The presented features of mechanical ventilation, such as air flow adjustment and thermal control, are inferred from the characteristics this strategy typically provides. The characteristics of the natural ventilation strategy are mainly based on the information presented in the condition assessment reports and the analysis produced by consultants. The risks and potential health effects of the strategies are concluded from literature review and the condition assessment reports.

As both of these strategies could possibly enable a healthy indoor environment for the occupants, the final decision depends on the decision-makers' priorities. Hence, the following features could be taken into account when considering the strategy:

- the demand regarding the number of building users;
- the target range of indoor environmental quality (IEQ);
- the budget – implementation, use and maintenance costs;

Table 3. Evaluation of the alternative strategies in the case building

Strategy	Supply and exhaust ventilation	Preserving the current ventilation strategy with lower number of users
Advantages	The high number of pupils, 25 – 30, in each classroom, and approximately 500–600 users in the entire building; Ventilation can be adjusted based on the use; and The new system can be used to control the thermal environment and humidity in the building	Minor design and implementation costs and minor maintenance costs
Downsides	High design and implementation costs; High use and maintenance costs; New ducts and devices diminish the room space of each classroom by about 1–2 sq m; and The need of a high level of expertise in design and implementation	Low space utilisation rate – only about 15 pupils in each room and approximately 400 users in the entire building; challenging to adjust the ventilation rate; and for ensuring the functionality of the system, it might be worthwhile to isolate the rooms with exhaust ventilation or not to use the mechanical ventilation at all
Health effects/ Risks	High ventilation rates could lower the levels of CO_2; the thermal environment and humidity level could be improved by adjusting the ventilation system; and the risk of pollution entering from structures due to the air pressure changes	Window ventilation is still needed, and it could improve indoor air quality but lower the room temperature unpleasantly during winter, cause draught and reduce energy efficiency; Thermal discomfort will remain: overheating in summer and overcooling in winter; and The potential health symptoms caused by negative air pressure may remain

- possibilities and challenges in combining ventilation refurbishment actions with other refurbishment actions;
- the schedule; and
- risks of poorer indoor air because of the changes in air pressure over rooms caused by the refurbishment actions.

Discussion

Often, the IAQ of naturally ventilated schools in Finland does not meet the current standards (Toyinbo *et al.*, 2016). This may because of the higher number of pupils in rooms than designed. In addition, later changes in ventilation strategy, including implemented extract ventilation systems in the classrooms of home economics and chemistry, may impair the functionality of natural ventilation. Poor IAQ contributing to occupants' health symptoms generate consideration of the need of a ventilation system redesign, especially, in naturally ventilated buildings. Often a major ventilation refurbishment, such as implementing mechanical supply and exhaust ventilation, improve IAQ. However, these actions might be challenging to implement in listed buildings. Also, mechanical ventilation units may be demanding to place in existing rooms and intense air flow may transfer impurities into indoor air from structures (Vornanen-Winqvist *et al.*, 2018a, 2018b). Moreover, the budget appears to limit the alternatives for ventilation strategy redesign as previous studies have stated municipalities to delay refurbishment actions because of lack of allocation (Uotila *et al.*, 2019). Wargocki and Wyon (2013) have also recognized the challenge of inadequate financial resources for the maintenance and refurbishment and have suggested to use hybrid ventilation systems and the installation of energy recovery and air-cleaning technologies for improving classroom IEQ. Furthermore, they point out that changes in the design and operation of classrooms that are made in the name of sustainability must improve classroom conditions before attempting to save energy. Since the implementation of mechanical ventilation may increase the energy consumption of school building, the operating costs may soar above tolerable level. This can lead to switching off the ventilation, as has occurred in Portuguese schools (Almeida and De Freitas, 2014). Hence, low-cost and nondestructive strategies are essentially needed to relieve occupants' health symptoms.

The first step of ventilation strategy redesign involves investigating the occupants' symptoms and addressing the sources of these health problems. This includes measurements of indoor air parameters and condition assessments of structures and systems. Also, other indoor factors, including lighting (Figueiro *et al.*, 2019) and noise (Palumbo *et al.*, 2018), should be surveyed as these sources are also associated with symptoms and are treated with different strategies. In this case study, inoperative ventilation system and thus a high level of CO_2 were concluded to be the sources of the symptoms. However, since the built environment and its indoor environment with occupants is a complex system, all the different aspects, including physical, physiological, personal, psychological and social aspects, are challenging to taken into account in a real-life context. Hence, some contributors to symptoms might have been excluded from this case.

It must be noted that if the symptoms are caused by pollutions produced by mold or fungi or emitted from materials, these harmful structures and materials need to be replaced or refurbished to eliminate the source of the symptoms. In these situations, ventilation refurbishment alone is an inadequate strategy to provide a healthy environment in the long term. At the second phase, alternative ventilation strategies are generated and evaluated. Typically, these strategies may comprise alternatives of natural; supply and exhaust; and hybrid ventilation (Uotila *et al.*, 2021). Finally, the decision of the selected strategy can be made based on the budget, schedule, the characteristics of the building and the future needs. In addition, the risks related to the refurbishment and potential combination with other renovation actions, may affect the decision.

Enhanced ventilation rates, usually, decrease occupants' health symptoms. However, these also raise use and maintenance costs because of increased energy use and need of higher maintenance. However, in contrast, by using an energy recovery ventilation system, energy costs may be reduced significantly. In the case building, the replacement of natural ventilation with supply and exhaust ventilation costs approximately €850 per sq m of net internal area. Moreover, the total costs of the replacement are even higher because of the need of temporary spaces during the major refurbishment when the school cannot be occupied. However, it must be noted that since the building has major refurbishment needs, the temporary spaces are needed irrespective of the selected ventilation strategy. Furthermore, if the ventilation renovation assignments are implemented together with other refurbishment actions, the share of ventilation redesign costs of the total refurbishment cost is probably lesser than the cost of the ventilation replacement alone. Since there is a big difference in the costs of the alternative strategies, the total long-term costs of each strategy need to be evaluated properly to obtain accurate information for decision-making.

Finnish standard recommends ventilation rate per student of 6 l/s or higher (FINVAC, 2020). However, this value is rarely reached as results of study containing 108 classrooms in 60 Finnish schools show that the standard level was not reached in any of the classrooms with passive stack ventilation or with mechanical exhaust only (Toyinbo *et al.*, 2016). In addition, listed and historic buildings do not typically meet the current energy-efficiency and ventilation rate standards in their current use (Avella *et al.*, 2021a, 2021b; Kalamees *et al.*, 2015). This has led to installation of new ventilation systems and other changes, which have followed by building damage and led to expensive remediations and loss of historical values. Because of the architectural and historic heritage aspects (Rieser *et al.*, 2021) and the components and materials deviating from the currently used structures, ventilation refurbishment of historic building might be challenging to implement. Preserving current natural ventilation but reducing numbers of users could be useful strategy to prolong the usage of these buildings without the risk of ruining their hygrothermal performance or historical values.

Currently, the number of pupils in Finnish rural areas is progressively reducing. In the schools of these rural areas, in which occupants' symptoms are caused by inadequate ventilation, it might be beneficial to preserve the current ventilation system instead of implementing an expensive new system. As the number of occupants reduces, the IAQ may improve, and the complaints of symptoms potentially also fade over the years. These naturally ventilated schools are typically rather old, built before the 1960s and follow the traditional layout with similar, adjacent, classrooms. If the number of occupants in the classrooms with inadequate ventilation should be limited to an inconvenient level, also the strategy of combining two classrooms by taking down the partition wall between these rooms, if it is possible within the load-bearing capacity, could be considered. This strategy might improve IAQ with rather low refurbishment costs. In Finland, the number of pupils, 7–12 years of age, in a class is typically between 20 and 22 in cities and a bit less in rural municipalities (Ministry of Education and Culture, 2019). Lately, there has been a tendency to reduce the number of pupils in classrooms the aim of providing better teaching, and this effort has been supported by a state grant. If this trend continues, it might help in decreasing occupants' symptoms in classrooms with poor IAQ since because of the lowered number of occupants, the CO_2 concentration is reduced.

Reducing the number of occupants in classrooms may decrease the symptoms rapidly since the CO_2 concentration remains at an appropriate level. However, the development of the prevalence of symptoms needs to be followed for ensuring the progress. This strategy might be challenging to realize in a fast schedule as other spaces suitable for classrooms are needed to replace the classrooms with the reduced number of pupils. Moreover, this also requires changes to be made to groups. In addition, the number of teachers may need to be increased if group sizes are reduced. Hence, it is beneficial to start the process of ventilation redesign at a very early phase and reckon with these long-term effects more broadly in the management of the municipal building stock. If the strategy of implementing supply and exhaust ventilation is selected, it is often beneficial to realize it together with other refurbishment actions. Thus, the refurbishment needs of the building can be addressed on a broader scale and the actions can be combined. This is potentially beneficial financially and also brings saving in running times. In summary, by using a long-term strategy concerning the public building stock and its refurbishment, major financial savings can potentially be achieved.

Even though low ventilation rates are in many studies, including Wargocki (2013) and Carrer *et al.* (2015), associated with decreased well-being and a higher level of symptoms, some studies have indicated that an enhanced ventilation rate may not always decrease the symptoms. Contrary, the study by Maddalena *et al.* (2015) has shown that lower ventilation rates were associated with decreased severity of occupants' eye symptoms. In addition, it must be noted that health symptoms associated with a building is a rather complex and manifold topic because of the great variation between individuals' responses and symptoms and the uncertainty of the limit values of the pollutant concentrations and other air features. Furthermore, since psychological factors may significantly affect the perceived symptoms of individuals (Selinheimo *et al.*, 2019), improved IAQ may not directly correlate with a decreased volume and extent of the symptoms.

Conclusions

Even though, multiple studies have addressed the methods to improve IAQ in naturally ventilated schools, still little is known of the low-budget strategies to use in cold climate. This study investigated the strategies to improve classroom IAQ in cold climate. In this study, implementation of mechanical supply and exhaust ventilation and preserving the current ventilation strategy with lower number of users were compared. Also, financial aspects of the strategies were considered.

In naturally ventilated schools, current ventilation rates are often inadequate to provide a healthy environment for the existing number of pupils. Even though ventilation refurbishment may decrease the extent and volume of symptoms, major actions might be challenging to implement in listed buildings and in municipalities in a challenging economic situation. Therefore, also low-cost and nondestructive strategies should be considered when planning the ventilation redesign of a school with poor IAQ. This study highlights the generation and evaluation of alternative ventilation strategies, besides a major refurbishment or replacement, as municipalities' budget of building refurbishment are often rather small and characteristics of buildings may not easily allow major refurbishment actions. As the results of this research show, all the strategies do not require high costs, as reducing the number of occupants in classrooms may also provide advantageous results.

This study suggests starting the selection of the strategy with assessing the symptoms and their sources. Potential sources may be investigated by implementing a condition assessment and measuring indoor air and environment parameters. These measured contents can be compared to guideline values and values linked with symptoms in literature. After establishing the initial details, the alternative ventilation strategies can be generated and evaluated based on the criteria, including cost of implementation, maintenance and use; project schedule; and the demand regarding the number of occupants. Furthermore, the risks related to the strategies need to be considered. It must be noted that the ventilation redesign alone is sufficient only when the health symptoms are caused by inadequate ventilation rates, whereas symptoms caused by fungi or mold also require the removal of these sources.

As this study provides matters to be considered when making a decision regarding ventilation strategy redesign in a school with poor IAQ, it might assist municipal authorities to find new solutions to eliminate pupils' and teachers' symptoms. Moreover, it may assist in considering this issue in a broader view, including taking into account the alternative perspectives of economic aspects and risks related to major refurbishment actions. However, since this study was a case study concerning only one school building, the presented alternative solutions may not be suitable for another school even with rather similar conditions. This study has also other limitations. Measurements of indoor air parameters exposure were conducted for only short periods of times, which may not be representative of long-lasting exposure. In addition, as the school occupants do not spend all of their time in the school, it might be difficult to separate symptoms caused by the indoor air of the school from other contributions. Furthermore, the validity of the occupants' health symptoms could still be improved by cross-checking the responses with health checks and reports. Moreover, this study focused on only two alternative strategies even though more suitable solutions, such as hybrid ventilation and improvement of natural ventilation, also exist. Still, further studies are needed to investigate more low-cost alternatives for improving IAQ in naturally ventilated school in cold climate. In addition, more research is needed to measure the impact of these varied strategies on health symptoms, in real-life context. The realized implementing and operative costs of these strategies should be also further investigated.

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