Assessing ventilation strategies in a school with observed indoor air problems

Ulrika Uotila
Faculty of Built Environment, Tampere University, Tampere, Finland
Arto Saari
Department of Built Environment, Tampere University, Tampere, Finland
Juha-Matti Kalevi Junnonen
Faculty of Built Environment, Tampere University, Tampere, Finland, and
Lari Eskola
A-Insinöörit Suunnittelu Oy, Helsinki, Finland

Received 4 March 2021
Revised 22 May 2021
Accepted 19 June 2021

Abstract

Purpose – Poor indoor air quality in schools is a worldwide challenge that poses health risks to pupils and teachers. A possible response to this problem is to modify ventilation. Therefore, the purpose of this paper is to pilot a process of generating alternatives for ventilation redesign, in an early project phase, for a school to be refurbished. Here, severe problems in indoor air quality have been found in the school.

Design/methodology/approach – Ventilation redesign is investigated in a case study of a school, in which four alternative ventilation strategies are generated and evaluated. The analysis is mainly based on the data gathered from project meetings, site visits and the documents provided by ventilation and condition assessment consultants.

Findings – Four potential strategies to redesign ventilation in the case school are provided for decision-making in refurbishment in the early project phase. Moreover, the research presents several features to be considered when planning the ventilation strategy of an existing school, including the risk of alterations in air pressure through structures; the target number of pupils in classrooms; implementing and operating costs; and the size of the space that ventilation equipment requires.

Research limitations/implications – As this study focusses on the early project phase, it provides viewpoints to assist decision-making, but the final decision requires still more accurate calculations and simulations.

Originality/value – This study demonstrates the decision-making process of ventilation redesign of a school with indoor air problems and provides a set of features to be considered. Hence, it may be beneficial for building owners and municipal authorities who are engaged in planning a refurbishment of an existing building.

Keywords School, Ventilation, Building-related symptoms, Natural ventilation, Mechanical ventilation, Poor indoor air

Paper type Research paper

Facilities
Emerald Publishing Limited
0263-2772
DOI 10.1108/F-03-2021-0019

Introduction

The quality of the indoor air in schools is of particular public concern because it may have long-lasting consequences for both individuals and society (Chithra and Shiva Nagendra, 2018; Daisey *et al.*, 2003; Järvi *et al.*, 2018; Mendell and Heath, 2005). Children are particularly susceptible to indoor air pollution, compared to adults, because of their underdeveloped immune system and lungs and high inhalation rates per body mass (Mendell and Heath, 2005; Schwartz, 2004). The lowered quality of indoor air increases the possibility of health problems and decreases comfort (Mendell and Heath, 2005; Simoni *et al.*, 2010). Furthermore, poor indoor air in schools affects pupils' learning performances (Bakó-Biró *et al.*, 2012; Petersen *et al.*, 2016; Wargocki and Wyon, 2007) and the productivity of teachers (Kallio *et al.*, 2020; Schneider, 2003).

One of the most important factors contributing to indoor air quality is ventilation, as it both dilutes the pollutants originating in the building and removes them (Etheridge and Sandberg, 1996) by the process of exchanging polluted indoor air with cleaner outdoor air (Carrer *et al.*, 2015). Currently, multiple schools, all over the world, have inadequate ventilation. Even if a refurbishment of the ventilation system could improve the indoor air quality, refurbishment actions are typically challenging to implement and the effects of these actions on the indoor air quality are vague.

Studies concerning the technical aspects of alternative ventilation strategies or poor indoor air may assist in the choice of the ventilation strategy of a school with observed indoor air problems. However, they do not express widely the aspects that need to be addressed when replanning the ventilation strategy, especially of a school with noted health symptoms. This motivated the study of these features to be considered when redesigning ventilation for a school with poor indoor air and complaints of health symptoms. This study uses a case study approach to understand this complex issue. Firstly, the study investigates the origins of the poor indoor air of the school, examines the condition of the building and assesses the requirements related to the use of the building. Then, four alternative strategies to redesign the ventilation are generated and evaluated. The aim of the study is to assist in the decision-making when selecting a ventilation strategy for a school to be refurbished and to provide viewpoints to be considered when refurbishing the ventilation system of a building with indoor air problems.

Indoor air in schools

Indoor air problems in schools are often caused by both inadequate ventilation and pollutant sources, such as fungi, moulds and bacteria; formaldehyde; radon; volatile organic compounds; and dust. The problems caused by pollutant sources typically have an impact on the building users' health, whereas inadequate ventilation effects the users' performance and well-being in the short-term. Common health effects brought by pollutants on pupils are nasal congestion, rhinitis, shortness of breath, eye irritation and fatigue (Borràs-Santos *et al.*, 2013; Haverinen *et al.*, 1999; Meklin *et al.*, 2005; Sahakian *et al.*, 2008). In particular, pollutants originating from moisture damaged structures are also linked to repetitive flu infections, coughs and outbreaks of asthma (Chen *et al.*, 2014; Haverinen *et al.*, 1999). Many of these building-related health problems are caused by leaks, water damage and excessive moisture which originate from errors during construction; poor maintenance and delayed repairs; or inappropriate use of the building (Uotila *et al.*, 2019). In addition, indoor air pollution is also released from building materials and furnishings, while such pollution as traffic emissions enters from outdoors.

Inadequate ventilation often leads to an increased level of pollutants and high concentrations of carbon dioxide (CO_2) (Daisey *et al.*, 2003; De Giuli *et al.*, 2012; Santamouris *et al.*, 2008).

Even though regulations have been introduced regarding the quality of indoor air in schools, the indoor environment in classrooms quite often does not meet these requirements (Daisey *et al.*, 2003; De Giuli *et al.*, 2012; Pazold *et al.*, 2020; Santamouris *et al.*, 2008). The measured airflow in classrooms is, typically, lower than the design values and the concentrations of indoor air pollutants exceed the guidelines (Koiv, 2014; Pazold *et al.*, 2020; Shaughnessy *et al.*, 2012). This may be due to a lack of maintenance or ageing of the ventilation equipment (Pazold *et al.*, 2020; Shaughnessy *et al.*, 2012). Furthermore, as school buildings are rather old, the ventilation systems are unable to meet the current standards, especially when using natural ventilation (Shaughnessy *et al.*, 2012).

The ventilation strategies followed in schools vary between countries, given the variety of climatic conditions and the age of school buildings. Even though natural ventilation is still the most common ventilation strategy in schools, especially in the older building stock (Litiu, 2012; Morck and Erhorn, 2003; Seppänen *et al.*, 2012), a major share of schools are mechanically ventilated in cold climates (Seppänen *et al.*, 2012). Also, hybrid ventilation is gaining popularity when trying to improve the indoor air quality of schools. Irrespective of the selected strategy, proper operation of ventilation has a major impact on the quality of indoor air. Thus, it needs to be accurately designed, implemented, controlled and maintained to provide good circumstances for building users.

Currently, there is an increasing need for refurbishment in many school buildings due to their age and as a result of new teaching and learning concepts (Le *et al.*, 2018). Along with the refurbishment, the existing ventilation system typically needs to be modified, as refurbishment actions without considering indoor air quality may have an adverse effect on the indoor environment (Broderick *et al.*, 2017; Földváry *et al.*, 2017). Both alterations to the ventilation system and these refurbishment actions may cause changes in the pressure difference across the structures of a building (Leivo *et al.*, 2017), which may result in an infiltration of pollutants from the structures into the indoor air (Airaksinen *et al.*, 2004a; Seppänen and Fisk, 2004). In addition, a negative pressure indoors may introduce harmful pollutants, including fungal spores (Airaksinen *et al.*, 2004a). As ventilation interacts with the building envelope, it can also deteriorate the structures of a building (Seppänen and Fisk, 2004). Therefore, the air pressures should be maintained at a level that does not generate moisture loads on the structures. Typically, the extract airflow rate is designed to be slightly higher than the supply to prevent the exfiltration of moist indoor air into the structures (Vornanen-Winqvist *et al.*, 2018). Some studies have even shown that a positive pressure indoors may decrease the amount of harmful pollutants in the indoor air (Ferrantelli *et al.*, 2019; Vornanen-Winqvist *et al.*, 2018), but these ventilation interventions are, typically, only suitable as short-term solutions implemented before a major refurbishment. Furthermore, as many buildings are renovated to be more energy efficient by improving air tightness, the ventilation rates of these buildings have adversely decreased (Broderick *et al.*, 2017; Földváry *et al.*, 2017).

The effects of a ventilation system refurbishment on indoor air quality are presented in only a few studies. Stabile *et al.* (2019a, 2019b) report a positive effect on the quality of indoor air in an Italian classroom where manual airing was replaced by mechanical ventilation with heat recovery. Toftum and Wargocki (2018) and Heebøll *et al.* (2018) report on a study concerning pupils' well-being, symptoms and performance in classrooms that were retrofitted with four alternative ventilation solutions. Even though the study found no systematic effect of these retrofits on pupils' symptoms or performance, a significant link between the performance of some tasks and the classroom CO_2 concentration and temperature were discovered, and all of these retrofits improved the classroom conditions (Toftum and Wargocki, 2018). A research study, reported on by Morck and Erhorn (2003) and Kluttig and Morck (2005), addresses the energy retrofit measures in educational buildings in ten countries. The study highlights a great variation between the ventilation strategies that different countries follow. In Finland, the quality of indoor air was emphasised and the aim was to improve it by mechanical ventilation with heat recovery (Kluttig and Morck, 2005), whereas in Denmark and Norway, there was a tendency to replace mechanical ventilation with natural hybrid ventilation with fans (Kluttig and Morck, 2005). In Denmark, this ventilation retrofit improved the indoor comfort quality that the pupils and teachers perceived in the school.

Materials and methods

A case study approach was adopted to address the alternative solutions for organising the ventilation in a municipal school with poor indoor air. Several structures of the school building were noted to be in urgent need of refurbishment, and a major part of the building's technology was also at the end of its useful life. Furthermore, the building users had complained about poor indoor air quality and health symptoms, including persistent respiratory disorders, eye irritations, headaches, allergic symptoms, coughs and fatigue, when using the building. In addition, the building users had complained about high temperatures in rooms during the summer and coldness during the winter. Moreover, the ventilation rate was perceived to be inadequate. The use of the basement had been prohibited by the local authority because of an unpleasant smell. Due to the aforementioned reasons, municipal authorities initiated the project to plan a refurbishment of the building. This also included a plan to modify the existing ventilation strategy.

The data used for the analysis were based on the authors' observations during site visits as well as records of meetings with the authors, the condition assessment consultants, and the project team commissioned to plan the refurbishment. Furthermore, documents, including an assessment concerning ventilation alternatives produced by consultants; reports from investigations and health questionnaires; building documentation; and a sketch of refurbishment by designers were used as sources for the analysis.

Case study building

The case study building, built in 1955, is a primary school located in the metropolitan area in Southern Finland. It has a total floor area of 3,957 sq. m. The building is mostly a three-storey one but it has a wing for sport 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 children attend the school. In addition to this, approximately 50 faculty and staff members work in the building.

The two layered concrete foundation of the building is soil-based. The floor of the sport hall and, partially, the floor of the basement are 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 has a pitched roof with an attic space that is not in use. Despite the old age of the building, it has not yet been thoroughly refurbished. However, during the late 1980s, several refurbishment actions were implemented, such as the residential wing being refurbished for educational use and for the staff, and natural ventilation being partially replaced with mechanical ventilation (Figure 1).

Results

Building condition assessment results

Over the years, several investigations have been implemented to survey the condition and repair needs of the building. To assess the potential origins of the indoor air problems, these

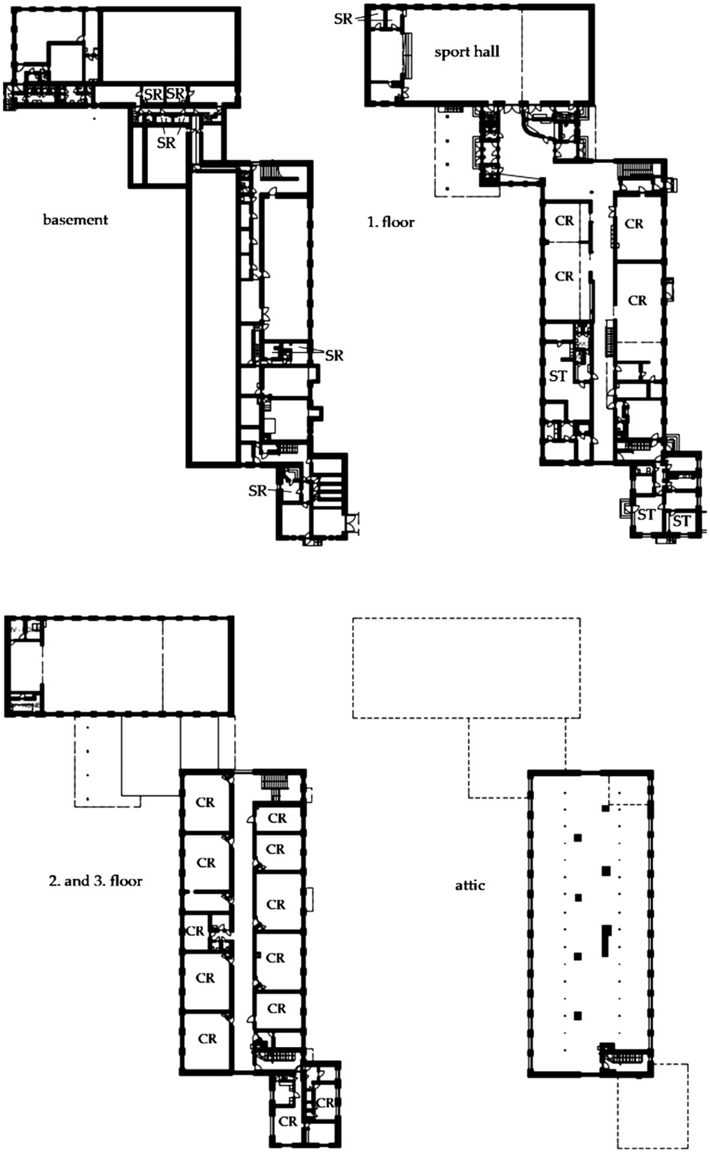

Figure 1.
Floors and classrooms (CR), staff rooms (ST) and shower rooms (SR) of the case building

investigations were scrutinised by recording the potential sources of poor indoor air and repair suggestions presented in these documents. Furthermore, the authors made site visits and had conversations with the condition assessment consultants, the project team and the users to verify these findings and identify future needs. The structures and systems with potential sources of indoor air problems, and the condition of these features are presented in Table 1. Moreover, the requirements related to the future use of the building, the functionality and repair needs are also presented in Table 1.

Structure/system	Consideration	Requirements
Basement	The basement is damaged in multiple locations. Excess moisture is measured and microbial smell noted in several places	The damaged structures of the basement need to be repaired. It must be ensured that the potential impurities, even when the basement is repaired, do not enter the upper floors through shafts. Primarily, facilities for active use should not be located in the basement. Instead, building services equipment or storages may be located there
External envelope	The external envelope might be microbially damaged	Due to potential microbes inside the envelope, negative air pressure in the rooms should be avoided, excluding the rooms with a moisture load. It is not possible to block up all of the air leakages
Two-layered intermediate floor	The intermediate floor contains organic filling, which might have become moist	It must be ensured that if the air pressure changes, the organic filling of the intermediate floors does not spread impurities, harmful for health, into the indoor air
Natural ventilation shafts	Ventilation shafts are located next to the doors of classrooms	
Air inlet	The size and the number of replacement air valves are deficient	
Ventilation	The residential wing has rooms without any ventilation system	
Heating system	The operation of the heating system is deficient	
Other technical building services	The majority of the building service equipment needs to be replaced. It might be possible to preserve heat pipes; radiators; and the exhaust shafts of natural ventilation	
Lift		The school needs to be accessible for disabled pupils and thus a lift must be built. However, the lift should not be built into the basement, as the potential impurities from the basement might enter into the upper floors
Attic		If air supply units are located in the attic, the incombustible floor needs to be taken down and the roofing deck requires steel holders
Shower rooms		Currently, cramped shower rooms are located in the basement. It must be explored whether the shower rooms could be located on the first floor. Thus, a lift will also not be needed in the basement
Classrooms	The existing classroom division is fairly suitable for new educational requirements	

Table 1.
Condition, requirements and considerations related to the rooms; structures; and systems affecting ventilation strategy

Besides the findings related to the condition of the structures and the systems, CO_2 concentrations were measured in classrooms three times, during a period of one and two weeks. The CO_2 level was mainly between 1,000 and 1,500 ppm during the occupied hours in the studied rooms, while in one classroom the maximum concentration exceeded 2,000 ppm almost every day. A Finnish standard specifies the maximum CO_2 concentration in a classroom at 800 ppm higher than the outdoor concentration of CO_2 (RT 07–11299, 2018). Typically, the outdoor CO_2 levels are 350–450 ppm (Halgamuge *et al.*, 2009). Furthermore, the investigation of air tightness revealed air leakages through exterior and interior walls and the intermediate floor in all three addressed rooms. Moreover, the measurements of air pressure across the building envelope showed that the studied rooms were under negative pressure for almost the entire measurement periods, and the highest measured value was −38 Pa. The indoor air quality was studied three times in several rooms but the levels of harmful pollutants, such as fungi, VOCs and microbes, did not exceed the normal level.

Currently, the building uses various ventilation techniques. The sports hall has mechanical supply-exhaust ventilation. The wing, which was originally planned for residential use, comprises rooms that use mechanical exhaust ventilation and rooms with no ventilation. The middle part of the building has natural ventilation. However, some rooms in the middle part have mechanical exhaust or supply-exhaust ventilation. This creates a risk that the negative air pressure, caused by mechanical exhaust ventilation, will reverse the direction of air flow in the shafts of the natural ventilation. Hence, air is led in by the exhaust air drafts of natural ventilation. Furthermore, the inlet of outdoor air is currently mainly based on opening a ventilation window because external walls lack replacement air valves.

Alternative ventilation strategies

On the basis of the assessment of the building condition, the requirements and the potential sources of the poor indoor air, four alternative solutions for redesigning the ventilation were formulated. These alternative strategies are: natural ventilation (alternative 1); hybrid ventilation (alternative 2); mechanical exhaust ventilation with supply air (alternative 3); and mechanical supply air ventilation with centralised exhaust air (alternative 4). A brief description of the operation of each alternative and the required alteration work to implement the ventilation system into the school are presented in Table 2. Moreover, the number of users that each alternative permits is displayed. This number is calculated by estimating the rated value of air flow of each technique and by considering the Finnish ventilation standard that requires a ventilation rate of 6 l/s per occupant of a classroom. The size of the classroom this calculation refers to is 60 sq. m. Furthermore, a summary of the benefits and downsides of each solution are presented in Table 2.

The variation in the number of persons in the rooms that alternatives three and four enable, see Table 2, depends on the chosen target value for indoor air quality. The indoor air category S2 describes a good indoor environment, whereas the S3 class defines the indoor air environment of a room that meets the minimum requirements set by the building code. As the requirements of the S3 class are lower, it allows a higher number of persons in a room.

Due to the risks related to the quality of indoor air in the building, the authors present the following key propositions:

- Facilities for active use should not be located in the basement;
- It must be ensured that the impurities in the basement do not enter the indoor air of the upper floors;
- A lift should not be built into the basement;

Table 2.
Summary of the alternative ventilation strategies

Alternative	Operation	No. of users	Alteration work	Benefits	Downsides
Alternative 1 (A1)	Natural ventilation in the middle part of the building; and Mechanical supply air ventilation with heat recovery in sanitary facilities and staff room	Max 20 persons in a classroom, 400 persons in the building	Replacement air valves and powered replacement air hatches; Mechanical supply/air ventilation with heat recovery in sanitary facilities and staff room; and Potentially, the existing shafts need to be replaced with larger shafts	Inexpensive operating costs	A draught of air in a cold climate; Impurities enter indoor air because of nearby traffic; Lack of heat recovery (classrooms); Rooms that require mechanical exhaust ventilation, such as home economics, are challenging to place in the building with natural ventilation; A small number of pupils allowed; A need for a large number of shafts; even 2 sq. m per classroom; Traffic noise; and Relatively high installation costs, if shafts need to be replaced
Alternative 2 (A2)	Hybrid – fan assisted natural ventilation, heating and filtering the supply air, powered boost adjustment Centralised supply air Mechanical supply/exhaust ventilation with heat recovery in sanitary facilities and social rooms	Max 25 persons in a classroom, 500 persons in the building, air flow rate of 0.7 m3/s	Individual room shafts ∅ 400 mm for supply air and exhaust air; Electric filtering and radiators in the basement; Individual room shafts for supply air; and Mechanical supply/exhaust ventilation with heat recovery for exhaust air in sanitary facilities and staff room	The building will not maintain negative pressure inside; and Relatively large number of pupils	Challenges in placing air inlets due to a nearby road, a parking lot and a service road into the kitchen of the campus; Challenges in organising an exhaust air duct large enough into the basement; Almost a constant need to use mechanical ventilation; and Lack of heat recovery (classrooms)

(*continued*)

Alternative	Operation	No. of users	Alteration work	Benefits	Downsides
Alternative 3 (A3)	Mechanical exhaust ventilation with supply air	25/30 persons in a classroom, (S2/S3), 500/600 persons in the building, air flow of the ventilation unit 6 m3/s	Air supply units in the basement; Vertical shaft for air distribution; Exhaust air units into the attic; Exhaust air shafts Individual room adjustment for boost, occupancy sensors + on/off plates for boost; Sanitary facilities and staff room integrated with mechanical exhaust air units of classrooms; and Liquid heat recovery	Large number of pupils; and Savings in energy consumption because the air flow can be adjusted in each room separately	High operating costs but automatic adjustment is used as the base of the use; Challenges in keeping the pressure difference between indoor air and outdoor air constantly small to minimise air leakages through structures. A need for constant measurements and adjustments of pressure differences; Design requires high expertise; Challenges in placing air inlets; and About 1 sq m of space is needed for shafts in each classroom
Alternative 4 (A4)	Mechanical exhaust ventilation with supply air. Mechanical supply/exhaust ventilation with centralised exhaust ventilation through the roof of the third floor	25/30 persons in a classroom, (S2/S3), 500/600 persons in the building, air flow of the ventilation unit 4.5 – 5 m3/s	Mechanical supply air units; Centralised exhaust ventilation from the roof of the third floor’s corridor; Air ventilation and increased adjustment individually in rooms; Liquid heat recovery; Transfer air devices; and Sanitary facilities integrated into the same mechanical ventilation units	High modifiability: interior walls between classrooms and corridors can be removed without the need to modify ventilation equipment; Large number of pupils; and Energy savings by using individual room adjustments of air flow	Same challenges with the location of air inlets and maintenance of air pressure differences are connected to alternative 4 as alternative 3 has; Large transfer air devices are needed in the wall between classrooms and corridors; and Lower total air flow compared to alternative 3, the rating is based on the number of users, not square metres

Table 2.

- Negative air pressure should be avoided in rooms without special ventilation needs to reduce the risk of any pollution spread from structures;
- Placing classrooms with high requirements for ventilation in the school is challenging; and
- Sanitary facilities require mechanical ventilation. If natural ventilation is selected, antechambers are needed when accessing these rooms.

Even though the benefits, downsides and risks of the alternative strategies were not accurately weighted and compared to the requirements, the evaluation indicates that A3 might be the most suitable strategy. This mechanical ventilation strategy enables the largest number of pupils in the school together with A4, and it provides demand-controlled ventilation. In addition, savings in energy costs might be achieved when using heat recovery. The main downside of A4 is the large space it requires, which results in a major refurbishment. A1 is not suitable in this location because there is high traffic density near the school. A2 is challenging to implement in the school, as it requires spacious shafts to avoid constant use of mechanical assistance.

Before concluding the selection of the strategy, the authors highlight the following features still to be considered:

- The flexibility and subsequent modifications in rooms should be considered in the ventilation design;
- The management of air flows through structures requires high accuracy especially when using mechanical ventilation;
- The attic may be used as a location for mechanical ventilation units. However, more accurate calculations of the suitability and load capacity of the attic are needed;
- More accurate calculations of the installation and operational costs of the alternative strategies are needed; and
- Simulation modelling is required, especially, when designing A1 or A2.

Discussion

When choosing the ventilation strategy for a building with noted indoor air problems, a thorough assessment of the origins of the indoor air problems is important to provide a healthy environment for building users. A redesign of ventilation alone cannot, typically, provide a healthier indoor environment, if the root causes, such as moisture damaged structures and mould, are not eliminated first. In addition, a proper survey of the potential risks related to the redesign of ventilation, including the structures and locations with potential impurities, is required, as a major modification or replacement of the original ventilation system often effects pressure differences over structures, which may lead to high concentrations of microbes in the air (Airaksinen *et al.*, 2004a, 2004b; Leivo *et al.*, 2017).

The potential sources of indoor air problems of the case school are consistent with previous studies. The operation of natural ventilation was deficient and unable to meet the current standards with the current number of pupils in classrooms. Furthermore, the system was disturbed by mechanical exhaust ventilation. Hence, it was suggested that this inadequate ventilation contributed to the poor indoor air in the school. Naturally ventilated classrooms are connected to an inadequate ventilation rate in several other studies, including a study by Canha *et al.* (2013) and Hou *et al.* (2015). However, the harmful effect of local exhaust ventilation to the functionality of natural ventilation has not been previously presented in literature. The results of the condition assessment reports indicated that indoor air problems in the school are also associated with the basement. This was not a surprise, as moisture and mould damage are common in structures with soil contact, including basements or spaces on ground floors (Annila *et al.*, 2018). Excess moisture was measured in several locations in the basement of the school. A moisture damaged and damp indoor environment, resulting in high concentration of microbes, is widely connected to poor indoor air and health symptoms, e.g. in the studies of Meklin *et al.* (2005) and Jacobs *et al.* (2014). In addition, the use of the basement was prohibited due to the unpleasant smell of microbial origin. A thorough refurbishment of the structures of the basement may reduce indoor air problems in the future. However, because of the challenging environmental conditions and highly demanding refurbishment actions, these structures require regular observation. Hence, it might be beneficial not to place actively used rooms in the basement. Moreover, it might be appropriate to isolate the ventilation of the basement to minimise the risk of potential impurities from the basement entering the upper floors.

The assessment of the alternative solutions shows that the ventilation strategy has a major effect on the number of pupils allowed in the classrooms. When a ventilation system with mechanical exhaust and support air (A3) and a centralised mechanical exhaust ventilation with support air (A4) enable 25–30 persons per classroom, only 20 persons are allowed to use a naturally ventilated (A1) classroom. In the estimates, the number of pupils near the case school will increase in the future. From this aspect, it would be beneficial to choose ventilation strategies A3 or A4, which permit 500–600 persons in the school, instead of A1 which permits only 400 persons.

In addition to the large number of pupils that A3 and A4 permit, these strategies provide a better quality of indoor air if they work as designed. Whereas the air rate of naturally ventilated classrooms depends on weather, mechanical ventilation offers a higher comfort of indoor air environment continuously. In addition, mechanical ventilation can be demand-controlled. The choice of mechanical ventilation, instead of natural ventilation, is also supported by a high ventilation rate, which is effective in reducing harmful health symptoms caused by poor indoor air. For example, Seppänen (1999) suggest that a ventilation rate of under 10 l/s per person results in health symptoms, whereas Sundell *et al.* (2011) and Wargocki *et al.* (2002) provide as high a rate as 25 l/s per person to reduce symptoms. These numbers are much higher than the minimum air rate regulation demands. Even though the mechanical ventilation strategies (A3 and A4) provide several benefits, they also contain serious downsides to be considered in a building with indoor air problems. As not all of the microbes and impurities can be removed from the structures, there is a high risk that a poorly operating ventilation system may spread harmful pollutants into the indoor air. Therefore, the design, installation, use and maintenance of A3 and A4 require particular accuracy, and the air pressures indoors need to be well-managed and regularly observed.

The costs of the alternative ventilation strategies were only evaluated at a rough level in this study. However, it was estimated that there is great variation in the installation and operating costs between the alternative strategies. Most likely, natural ventilation has the lowest costs in both installation and, at least, in use. The scale of the installation costs of alternatives two, three and four will probably be about the same, whereas the operational costs will probably be remarkably less for A2 compared to strategies A3 and A4. For example, Chenari *et al.* (2016) has highlighted significant energy savings with hybrid ventilation compared to mechanical ventilation, which supports the cost savings presented in this study. However, it must also be noted that several authors, including Mysen *et al.* (2005), Merema *et al.* (2018) and Wachenfeldt *et al.* (2007), have reported remarkable savings in total energy consumption and heat loss when using a demand-controlled mechanical ventilation with heat recovery compared to the use of a constant air volume system. Still, a more accurate calculation of costs is needed to increase the validity of the evaluation.

The size of the space required for both shafts and equipment of the alternative solutions varies remarkably. As the building has a large-sized attic and basement with no use, the placement of the ventilation units and heat recovery equipment of A3 is rather simple, whereas the equipment for air transferring in A4 needs to be located between the classrooms and corridors. Hence, this alternative would reduce the size of classrooms or corridors and require major refurbishment actions. Furthermore, A2 requires larger sized shafts than the other alternatives. Thus, the implementation of this strategy also requires major actions. In addition, even if natural ventilation remains, the existing shafts are potentially too small for current use and need to be replaced with larger ones. Furthermore, the potential location of ventilation units and ducts still need to be assessed more closely before the final decision.

As the intermediate floors and the envelope may contain microbes and other pollutants that are harmful to health, it might be beneficial to avoid negative air pressure indoors. This reduces the risk of spreading the pollutants from structures into the indoor air. A positive air pressure of 5–7 Pa has been shown to be effective in decreasing symptoms and discomfort in a building with indoor air problems in a study by Vornanen-Winqvist *et al.* (2018). In addition, the results of the study by Ferrantelli *et al.* (2019) imply that a positive air pressure does not induce negative effects on the structures' moisture content in normally ventilated classrooms.

Even though the parameters of the alternatives, presented in the evaluation, were not accurately prioritised, the results indicate that the mechanical ventilation strategy, i.e. alternative 3, should be advocated. It permits a large number of pupils in classrooms and allows later modifications in use. Considering learning outcomes, this strategy is supported by the study of Toftum *et al.* (2015), which reported higher learning outcomes for pupils in classrooms with mechanical ventilation compared to naturally ventilated classrooms. This strategy allows a better quality of indoor air, compared with natural ventilation, especially in this location where nearby traffic causes a high concentration of pollutants outdoors. However, if A3 was to be implemented, the system requires proper maintenance and the air pressure indoors needs to be regularly followed to reduce the risks of pollution entering the indoor air from the structures.

The findings of this study aim to assist decision-making regarding refurbishment actions by providing ventilation system alternatives and presenting considerations related to the redesign. At the next stage, the placement of ventilation units and ducts needs to be assessed and both the installation and operating costs evaluated. Moreover, the operation of the systems should be examined with a simulation. Then, the final decision regarding the strategy can be made.

The case study implies that the choice of the appropriate ventilation strategy for a school building with poor indoor air is a complex task that requires a high level of understanding of structures and their performance, air pressure; characteristics of alternative ventilation strategies and risks. Irrespective of the selected strategy, it might be appropriate to choose a solution that permits modifications in the use of the rooms afterwards. Hence, the ventilation of the rooms should not be designed strictly for the current use only. On the basis of the findings of this study, the authors provide the following viewpoints to facilitate the planning of the ventilation strategy of a school with low quality indoor air:

- The starting point of a ventilation redesign is a thorough investigation of the sources of poor indoor air quality and the occupants' symptoms;
- Compared to natural ventilation, mechanical ventilation permits a much larger number of pupils in classrooms;
- The air flow rate and level of pollutant concentrations are easier to control by using mechanical ventilation compared to natural ventilation;

- Natural ventilation has small operating costs and low energy usage compared to other ventilation strategies;
- The use of mechanical ventilation requires regular maintenance and monitoring air pressure differences;
- The functionality of natural ventilation is often poor if it is disturbed by local exhaust ventilation; and
- Future modifications in the use of rooms and the flexibility of technology and equipment should be considered when planning the ventilation strategy.

Conclusions

Alternative strategies to redesign ventilation in a school with indoor air problems were studied by conducting a case study. Four alternative strategies were generated and evaluated for decision-making regarding refurbishment in an early project phase of the studied case project. The notable viewpoint with these alternative solutions for organising ventilation in the school is the great variation in the number of users that each solution permits. Mechanical ventilation strategies may permit a number of occupants in a classroom up to 50% higher compared to a naturally ventilated classroom. Compared to hybrid ventilation, mechanical ventilation may permit 20% more occupants. Although this feature is useful in areas of growing population, mechanical ventilation strategies also contain serious challenges, which need to be managed in a building with indoor air problems. Faulty functionality of the systems may increase indoor air problems, as harmful pollutants, such as microbes, may enter from structures into the indoor air as a result of changes in air pressures over structures. Thus, the adoption of mechanical ventilation requires high expertise in the design and use and regular monitoring of air pressures. The total costs vary greatly between the alternative strategies. The operational and maintenance costs of natural ventilation are marginal compared with the cost of mechanical ventilation. However, heat recovery and demand-controlled ventilation brings savings in energy costs in mechanical ventilation.

As the study seeks to demonstrate the decision-making process in ventilation redesign, the results are based on the data gathered at the project planning phase instead of realised values. The research provides a set of features to be considered and addressed when planning a ventilation strategy in the early project phase. Hence, it may be beneficial to building owners and municipal authorities who are engaged in planning a refurbishment of a building with indoor air problems.

References

Airaksinen, M., Kurnitski, J., Pasanen, P. and Seppänen, O. (2004a), “Fungal spore transport through a building structure”, *Indoor Air*, Vol. 14 No. 2, pp. 92-104.

Airaksinen, M., Pasanen, P., Kurnitski, J. and Seppänen, O. (2004b), “Microbial contamination of indoor air due to leakages from crawl space: a field study”, *Indoor Air*, Vol. 14 No. 1, pp. 55-64.

Annila, P.J., Lahdensivu, J., Suonketo, J., Pentti, M. and Vinha, J. (2018), “Need to repair moisture- and mould damage in different structures in finish public buildings”, *Journal of Building Engineering*, Vol. 16, pp. 72-78.

Bakó-Biró, Z., Clements-Croome, D.J., Kochhar, N., Awbi, H.B. and Williams, M.J. (2012), “Ventilation rates in schools and pupils’ performance”, *Building and Environment*, Vol. 48, pp. 215-223.

Borràs-Santos, A., Jacobs, J.H., Täubel, M., Haverinen-Shaughnessy, U., Krop, E.J.M., Huttunen, K., Hirvonen, M.R., Pekkanen, J., Heederik, D.J.J., Zock, J.P. and Hyvärinen, A. (2013), “Dampness and mould in schools and respiratory symptoms in children: the HITEA study", *Occupational and Environmental Medicine*, Vol. 70 No. 10, doi: 10.1136/oemed-2012-101286.

Broderick, A., Byrne, M., Armstrong, S., Sheahan, J. and Coggins, A.M. (2017), "A pre and post evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted co-operative social housing", *Building and Environment*, Vol. 122, pp. 126-133.

Canha, N., Almeida, S.M., Freitas, M.C., Täubel, M. and Hänninen, O. (2013), "Winter ventilation rates at primary schools: comparison between Portugal and Finland", *Journal of Toxicology and Environmental Health, Part A*, Vol. 76 No. 6, pp. 400-408.

Carrer, P., Wargocki, P., Fanetti, A., Bischof, W., De Oliveira Fernandes, E., Hartmann, T., Kephalopoulos, S., Palkonen, S. and Seppänen, O. (2015), "What does the scientific literature tell us about the ventilation-health relationship in public and residential buildings?", *Building and Environment*, Vol. 94, pp. 273-286.

Chen, C.H., Chao, H.J., Chan, C.C., Chen, B.Y. and Guo, Y.L. (2014), "Current asthma in school children is related to fungal spores in classrooms", *Chest*, Vol. 146 No. 1, pp. 123-134.

Chenari, B., Dias Carrilho, J. and Gameiro Da Silva, M. (2016), "Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: a review", *Renewable and Sustainable Energy Reviews*, Vol. 59, pp. 146-1447.

Chithra, V.S. and Shiva Nagendra, S.M. (2018), "A review of scientific evidence on indoor air of school building: pollutants, sources, health effects and management", *Asian Journal of Atmospheric Environment*, Vol. 12 No. 2, pp. 87-108.

Daisey, J.M., Angell, W.J. and Apte, M.G. (2003), "Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information", *Indoor Air*, Vol. 13 No. 1, doi: 10.1034/j.1600-0668.2003.00153.x.

De Giuli, V., Da Pos, O. and De Carli, M. (2012), "Indoor environmental quality and pupil perception in Italian primary schools", *Building and Environment*, Vol. 56, pp. 335-345.

Etheridge, D.W. and Sandberg, M. (1996), *Building Ventilation: Theory and Measurement*, John Wiley and Sons Chichester Vol. 50.

Ferrantelli, A., Vornanen-Winqvist, C., Mattila, M., Salonen, H. and Kurnitski, J. (2019), "Positive pressure effect on moisture performance in a school building", *Journal of Building Physics*, Vol. 43 No. 2, pp. 121-142.

Földváry, V., Bekö, G., Langer, S., Arrhenius, K. and Petráš, D. (2017), "Effect of energy renovation on indoor air quality in multifamily residential buildings in Slovakia", *Building and Environment*, Vol. 122, pp. 363-372.

Halgamuge, M.N., Chan, T.K. and Mendis, P. (2009), "Ventilation efficiency and carbon dioxide (CO2) concentration", *PIERS Online*, Vol. 5 No. 7, pp. 637-640.

Haverinen, U., Husman, T., Toivola, M., Suonketo, J., Pentti, M., Lindberg, R., , Leinonen, J., Hyvärinen, A., Meklin, T. and Nevalainen, A. (1999), "An approach to management of critical indoor air problems in school buildings", *Environmental Health Perspectives*, Vol. 107 No. suppl 3, pp. 509-514.

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", *Science and Technology for the Built Environment*, Vol. 24 No. 6, pp. 626-637.

Hou, Y., Liu, J. and Li, J. (2015), "Investigation of indoor air quality in primary school classrooms", *Procedia Engineering*, Vol. 121, pp. 830-837.

Jacobs, J., Borràs-Santos, A., Krop, E., Täubel, M., Leppänen, H., Haverinen-Shaughnessy, U., Pekkanen, J., Hyvärinen, A., Doekes, G., Zock, J.P. and Heederik, D. (2014), "In dust in primary schools and respiratory health in schoolchildren across Europe", *Occupational and Environmental Medicine*, Vol. 70 No. 10, pp. 681-687.

Järvi, K., Vornanen-Winqvist, C., Mikkola, R., Kurnitski, J. and Salonen, H. (2018), "Online questionnaire as a tool to assess symptoms and perceived indoor air quality in a school environment", *Atmosphere*, Vol. 9 No. 7, p. 270.

Kallio, J., Vildjiounaite, E., Koivusaari, J., Räsänen, P., Similä, H., Kyllönen, V., Muuraiskangas, S., Ronkainen, J., Rehu, J. and Vehmas, K. (2020), "Assessment of perceived indoor environmental quality, stress and productivity based on environmental sensor data and personality categorization", *Building and Environment*, Vol. 175, doi: 10.1016/j.buildenv.2020.106787.

Kluttig, H.E. and Morck, O. (2005), "Energy-efficient renovation of educational buildings", PEB exchange", *Programme on Educational Building 2005/09*, doi: 10.1787/562284354371.

Koiv, T. (2014), "The indoor climate and energy consumption of renovated schools", *WSEAS Transactions on Environment and Development*, Vol. 10, pp. 100-105.

Le, A.T.H., Park, K.S., Domingo, N., Rasheed, E. and Mithraratne, N. (2018), "Sustainable refurbishment for school buildings: a literature review", *International Journal of Building Pathology and Adaptation*, Vol. 39 No. 1, pp. 5-19.

Leivo, V., Prasauskas, T., Turunen, M., Kiviste, M., Aaltonen, A., Martuzevicius, D. and Haverinen-Shaughnessy, U. (2017), "Comparison of air pressure difference, air change rates, and CO2 concentrations in apartment buildings before and after energy retrofits", *Building and Environment*, Vol. 120, pp. 85-92.

Litiu, A. (2012), "Ventilation system types in some EU countries", *REHVA Journal*, No. 1, pp. 18-23.

Meklin, T., Potus, T., Pekkanen, J., Hyvarinen, A., Hirvonen, M.R. and Nevalainen, A. (2005), "Effects of moisture-damage repairs on microbial exposure and symptoms in schoolchildren", *Indoor Air-*, Vol. 15 No. s10, pp. 40-47.

Mendell, M.J. and Heath, G.A. (2005), "Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature", *Indoor Air*, Vol. 15 No. 1, pp. 27-52.

Merema, B., Delwati, M., Sourbron, M. and Breesch, H. (2018), "Demand controlled ventilation (DCV) in school and office buildings: lessons learnt from case studies", *Energy and Buildings*, Vol. 172, pp. 349-360.

Morck, O. and Erhorn, H. (2003), "IEA ECBCS annex 36-CaseStudy reports", *ECBCS Bookshop, Birmingham*.

Mysen, M., Berntsen, S., Nafstad, P. and Schild, P.G. (2005), "Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools", *Energy and Buildings*, Vol. 37 No. 12, pp. 1234-1240.

Pazold, M., Winkler, M. and Antretter, F. (2020), "Investigating overheating by measurement and simulation in classrooms", *E3S Web of Conferences*, Vol. 172, doi: 10.1051/e3sconf/202017203005.

Petersen, S., Jensen, K.L., Pedersen, A.L.S. and Rasmussen, H.S. (2016), "The effect of increased classroom ventilation rate indicated by reduced CO2 concentration on the performance of schoolwork by children", *Indoor Air*, Vol. 26 No. 3, pp. 366-379.

RT 07-11299 (2018), *Sisäilmastoluokitus 2018 [Finnish Classification of Building Climate 2018]*, Rakennustieto.

Sahakian, N.M., White, S.K., Park, J.H., Cox-Ganser, J.M. and Kreiss, K. (2008), "Identification of mold and dampness-associated respiratory morbidity in 2 schools: comparison of questionnaire survey responses to national data: research article", *Journal of School Health*, Vol. 78 No. 1, pp. 32-37.

Santamouris, M., Synnefa, A., Asssimakopoulos, M., Livada, I., Pavlou, K., Papaglastra, M., Gaitani, N., Kolokotsa, D. and Assimakopoulos, V. (2008), "Experimental investigation of the air flow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation", *Energy and Buildings*, Vol. 40 No. 10, pp. 1833-1843.

Schneider, M. (2003), *Linking School Facility Conditions to Teacher Satisfaction and Success*, ERIC Publications.

Schwartz, J. (2004), "Air pollution and children's health", *Pediatrics*, Vol. 113 No. 3, pp. 1037-1043.

Seppänen, O.A. (1999), "Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings", *Indoor Air*, Vol. 9 No. 4, pp. 226-252.

Seppänen, O.A. and Fisk, W.J. (2004), "Summary of human responses to ventilation", *Indoor Air*, Vol. 14 No. s7, doi: 10.1111/j.1600-0668.2004.00279.x.

Seppänen, O., Brelih, N., Goeders, G. and Litiu, A. (2012), "Existing buildings, building codes, ventilation standards and ventilation in Europe", *Final HEALTHVENT WP5 Report*.

Shaughnessy, R., Toyinbo, O., Turunen, M., Kurnitski, J. and Haverinen-Shaughnessy, U. (2012), "Indoor environmental quality in finish elementary schools and its effects on students' health and learning".

Simoni, M., Annesi-Maesano, I., Sigsgaard, T., Norback, D., Wieslander, G., Nystad, W., Cancianie, M., Sestini, P. and Viegi, G. (2010), "School air quality related to dry cough, rhinitis and nasal patency in children", *European Respiratory Journal*, Vol. 35 No. 4, doi: 10.1183/09031936.00016309.

Stabile, L., Buonanno, G., Frattolillo, A. and Dell'Isola, M. (2019a), "The effect of the ventilation retrofit in a school on CO 2, airborne particles, and energy consumptions", *Building and Environment*, Vol. 156, pp. 1-11.

Stabile, L., Massimo, A., Canale, L., Russi, A., Andrade, A. and Dell'Isola, M. (2019b), "The effect of ventilation strategies on indoor air quality and energy consumptions in classrooms", *Buildings*, Vol. 9 No. 5, p. 110.

Sundell, J., Levin, H., Nazaroff, W.W., Cain, W.S., Fisk, W.J., Grimsrud, D.T., Gyntelberg, F., Li, Y., Persily, A.K., Pickering, A.C., Samet, J.M., Spengler, J.D., Taylor, S.T. and Weschler, C.J. (2011), "Ventilation rates and health: Multidisciplinary review of the scientific literature", *Indoor Air*, Vol. 21 No. 3, pp. 191-204.

Toftum, J. and Wargocki, P. (2018), "Retrofit of school ventilation and pupil well-being and performance being and performance–ASHRAE RP1624", *15th Conference of the International Society of Indoor Air Quality and Climate*.

Toftum, J., Kjeldsen, B.U., Wargocki, P., Menå, H.R., Hansen, E.M.N. and Clausen, G. (2015), "Association between classroom ventilation mode and learning outcome in Danish schools", *Building and Environment*, Vol. 92, pp. 494-503.

Uotila, U., Saari, A. and Junnonen, J.M. (2019), "Municipal challenges in managing a building with noted health symptoms", *Facilities*, Vol. 38 Nos 5/6, pp. 365-377.

Vornanen-Winqvist, C., Järvi, K., Toomla, S., Ahmed, K., Andersson, M.A., Mikkola, R., Marik, T., Kredics, L., Salonen, H. andKurnitski, J. (2018), "Ventilation positive pressure intervention effect on indoor air quality in a school building with moisture problems", *International Journal of Environmental Research and Public Health*, Vol. 15 No. 2, p. 230.

Wachenfeldt, B.J., Mysen, M. and Schild, P.G. (2007), "Air flow rates and energy saving potential in schools with demand-controlled displacement ventilation", *Energy and Buildings*, Vol. 39 No. 10, pp. 1073-1079.

Wargocki, P. and Wyon, D.P. (2007), "The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children (RP-1257)", *HVAC&R Research*, Vol. 13 No. 2, pp. 193-220.

Wargocki, P., Lagercrantz, L., Witterseh, T., Sundell, J., Wyon, D.P. and Fanger, P.O. (2002), "Subjective perceptions, symptom intensity and performance: a comparison of two independent studies, both changing similarly the pollution load in an office", *Indoor Air*, Vol. 12 No. 2, pp. 74-80.

Corresponding author

Ulrika Uotila can be contacted at: ulrika.uotila@tuni.fi