Impact of weather conditions and building design on contaminant infiltration from crawl spaces in Swedish schools—Numerical modeling

(article starts on next page)

Research Article

Impact of weather conditions and building design on contaminant infiltration from crawl spaces in Swedish schools—Numerical modeling using Monte Carlo method

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Abstract

Some Swedish school buildings built in the 1960s and 1970s experience indoor air quality problems, where the contaminants are suspected to come from the crawl space underneath the building. The poor indoor air quality causes discomfort among pupils and teachers. Installing an exhaust fan to maintain a negative pressure difference in the crawl space relative to indoors or increasing the ventilation in the classroom are two examples of common measures taken to improve the indoor air quality. However, these measures are not always effective, and sometimes the school building has to be demolished. The relation between pressure distribution, contaminant concentration in the classroom, outdoor temperature, wind, mechanical ventilation, and air leakage distribution is complex. A better understanding of these relations is crucial for making decisions on the most efficient measure to improve the indoor air quality. In this paper, a model for contaminant infiltration from the crawl space is used together with the Monte Carlo method to study these relations. Simulations are performed for several cases where different building shapes, building orientations, shielding conditions, and geographical locations are simulated. Results show, for example, that for a building with an imbalanced ventilation system, air is leaking from the crawl space to the classroom for the majority of cases and that concentration levels in the classroom are usually the highest during mild and calm days.

Keywords

airtightness;
air permeability;
Monte Carlo method;
infiltration model;
crawl space;
indoor air quality

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Indoor/Outdoor Airflow and Air Quality

1 Introduction

Indoor air quality problems in school buildings often gain attention. Many of the problematic school buildings in Sweden are built in the 1960s to 1970s when many new materials and construction principles were gaining attention. These school buildings are often one-story wooden frame buildings with flat roofs and crawl space foundations. If the indoor air quality causes discomfort among teachers and pupils, the problem, of course, needs to be resolved. In some cases, the source for the poor indoor air quality is quickly found, and the problem can be solved without any major disruption in the school operation. However, in some cases, the process of solving the problem can take several years, and many different solutions (for example, new ventilation systems) need to be tested. This commonly results in an increase in penetrations through the thermal envelope and increased air leakage. The entire process can be inconvenient for pupils and teachers and lead to disruptions in the operation of the school. In the worst case, the school building is taken out of operation and later demolished (personal communication with Maria Alm, indoor environment expert at Gothenburg Premises Administration). Figure 1 shows an example of a school building in Gothenburg (southwest Sweden) with a crawl space and indoor air quality problems. In this particular building, the problems were never solved, and the school is now about to be deconstructed. Another school, with similar crawl-space problems, in Tygelsjö (southern Sweden), that was demolished is documented in Nordquist (1996).

There are several types of contaminants found in the indoor air in schools. Some examples are VOCs (volatile

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Fig. 1 A typical school building with a crawl space and indoor air quality problems

organic compounds), bacteria, formaldehyde, and radon (Annesi-Maesano et al. 2013). Some of these contaminants may originate from the crawl space or the ground underneath the crawl space. A Finnish study (Airaksinen et al. 2004) concluded that buildings with a crawl space and a positive pressure difference across the floor construction could have an increased risk for indoor air quality problems at the first floor. In an investigation of 220 Swedish school buildings (Hilling 1994) built between 1978 and 1997, damages and problems were documented. It was found that problems were very diversified, although most problems were related to moisture damage. One example describes how unpleasant odors reach the classroom from the attic through air leakages in the construction.

Contaminants are predominantly transported within the building with moving air. Openings, both intentional and unintentional, with a pressure difference across will have air leaking from higher pressure to lower pressure, and contaminants follow the direction of the airflow. This means that the transport of contaminants within a building depends on both the pressure distribution and the location of openings. In addition, the location of the openings will affect the pressure distribution.

SWESIAQ (Swedish Chapter of International Society of Indoor Air Quality and Climate) is a Swedish chapter of the International Society of Indoor Air Quality and Climate (ISIAQ). SWESIAQ has developed a model for how to work with buildings with indoor air quality problems called the SWESIAQ-model (http://www.swesiaq.se). The SWESIAQ-model acknowledges the importance of measuring the pressure distribution in the building to ensure that air and consequently odors does not move in unwanted directions such as from the crawl space to the classroom. However, there is a lack of information about when and where to measure and tools that can be used to assess the results from the measurements.

This paper aims at providing a method for simulating buildings with a crawl space foundation and indoor air quality problems. The Monte Carlo method is used, and the air leakage and contaminant transport are simulated with an infiltration model. The infiltration modeling technique used is similar to the technique used in software such as CONTAM (Dols and Polidoro 2015) and COMIS (Feustel and Raynor-Hoosen 1990). The modeling technique is well established and has been validated by, for example, Haghighat and Megri (1996).

The Monte Carlo method is used to make the following:

- To investigate correlations between parameters important for the concentration levels and pressure difference across the floor construction. Examples of parameters are outdoor temperature, wind, and airtightness.
- To provide a probability distribution for pressure difference across the floor construction and concentration levels in the classroom for buildings in the cities of Gothenburg and Östersund in Sweden.
- To investigate depressurization of the crawl space to −5 Pa using an exhaust fan.
- To investigate if increased mechanical ventilation is a good measure to decrease contaminant concentrations in the classroom, even though there is a risk of increasing the flow of contaminants from the crawl space.

One of the major difficulties when working with airtightness-related problems in buildings is dealing with the uncertainty of air permeability distribution. Unintentional openings in the construction can occur in many places, most often in connections between different building components. However, there can be great variations in air leakage distribution between buildings dependent on workmanship and type of construction. A statistical modeling approach is therefore chosen in this project where the size of unintentional openings are chosen randomly, and simulations are repeated (Monte Carlo simulation) to yield probability distributions of concentration levels in the classroom and of pressure difference across the floor construction. This way, the uncertainty of air permeability distribution is considered in the simulation. Concentration levels, correlations, and efficiency of measures can be studied for a population of buildings with a given probability of air permeability. An increased understanding of how weather (temperature and wind), air permeability distribution and mechanical ventilation affects the transport of contaminants can lead to more efficient measures when dealing with school buildings on crawl space foundation with indoor air quality problems.

The method presented in this paper can also be useful when working with related topics such as transport of mold spores from cold attics or radon from the ground. For example, in current Swedish recommendations concerning radon coming from the ground, radon levels should be measured during heating season, since the stack effect and, consequently, the radon infiltration should be the highest during this period. But results presented in this paper suggest that for contaminants coming from the crawl space and if production is independent of temperature or relative humidity, mild days with little wind is more critical than colder days and results in higher levels of contaminants in the classroom.

2 Numerical model

A numerical infiltration model is written in the computer software MATLAB. The infiltration model calculates airflows and contaminant transport between the classroom and the crawl space of a school building with a crawl space. The model uses a multizone airflow network technique similar to CONTAM (Dols and Polidoro 2015) and COMIS (Feustel and Raynor-Hoosen 1990). There are no temperature or pressure gradients in the modeled zones (classroom and crawl space) except the horizontal pressure gradient caused by the stack effect. The power-law equation describes the air leakage through cracks and openings between classroom and crawl space as well as to and from the outdoor environment:

$$Q = C(\Delta P)^n \tag{1}$$

Here Q [m^3/s] is the volume airflow through the crack, ΔP [Pa] is the pressure difference across the opening or crack, C [m^3/(s·Pa^n)] and n [—] are airflow coefficients that depend on the leakage type.

Values for C are calculated from the assumed q_{50} (the total air leakage in liters per second across 1 m^2 of thermal envelope at 50 Pa pressure difference) of each wall, floor, or roof. The coefficient n is given the value 0.65, which is considered a good estimate for most cracks and opening in the thermal envelope (Chan et al. 2012).

The driving forces accounted for are pressure caused by the stack effect and wind. The pressure difference caused by the stack effect ΔP_{st} [Pa] is calculated with the following expression:

$$\Delta P_{\text{st}}(z) = (\rho_2 - \rho_1) g z \tag{2}$$

where z [m] is the distance from the neutral pressure plane, ρ [kg/m^3] is the density of air on either side of the leakage, and g is the gravitational acceleration. The wind pressure P_{w} [Pa] acting on the surface of the building is calculated with the following expression:

$$P_{\text{w}} = C_{\text{p}} \frac{\rho u^2}{2} \tag{3}$$

where C_{p} [—] is a wind pressure coefficient, ρ [kg/m^3] is the air density, and u [m/s] is the wind velocity. Values for C_{p} are empirically determined and depend on wind angle relative to the surface and building shape (Orme et al. 1994). Wind pressure coefficients are given for three shielding conditions: (1) exposed, (2) height of surrounding buildings equal to half the height of the school building, and (3) height of the surrounding buildings equal to the height of the school building.

To account for the difference between the height of the weather station, and the building height as well as the roughness of surrounding terrain the wind velocity is corrected with the following equation (Orme et al. 1994):

$$u = u_{\text{m}} K r^a \tag{4}$$

where u_{m} is the wind velocity measured by the weather station and r is the height of the building. K and a are constants dependent on the type of terrain.

The total pressure difference across an opening between the classroom (cr) and the crawl space (cs):

$$\Delta P = P_{\text{cr}} - P_{\text{cs}} + \Delta P_{\text{st}} \tag{5}$$

The total pressure difference across an opening in the thermal envelope:

$$\Delta P_{\text{cr/cs}} = P_{\text{cr/cs}} - P_{\text{w}} + \Delta P_{\text{st}} \tag{6}$$

where $P_{\text{cr/cs}}$ is the zone pressure in the classroom (cr) or the crawl space (cs).

The model solves the airflows at a steady state (when there is a mass balance in each zone). This results in two non-linear equations, one for each zone, and two unknown variables P_{cr} and P_{cs}. The model accounts for mechanical ventilation by adding the mass flow for the fan to the mass balance of each zone, see Eqs. (7) and (8).

Mass balance for the airflows in the building:

$$\sum \dot{m}_{\text{cs}\to\text{cr}} + \sum \dot{m}_{\text{ex}\to\text{cr}} + \sum \dot{m}_{\text{fan1}} = 0 \tag{7}$$

$$\sum \dot{m}_{\text{cr}\to\text{cs}} + \sum \dot{m}_{\text{ex}\to\text{cs}} + \sum \dot{m}_{\text{fan2}} = 0 \tag{8}$$

Equations (7) and (8) form a system of equations with two unknowns: the pressure in the classroom and the pressure in the crawl space. The non-linear system of equations is solved numerically using the Newton–Raphson method (Feustel and Raynor-Hoosen 1990; Dols and Polidoro 2015).

Contaminant transport is determined at a steady state, the total mass flow of contaminants into a zone equals the total mass flow of contaminants out from the zone:

$$c_{\text{cs}} \cdot \sum Q_{\text{cs}\to\text{cr}} - c_{\text{cr}} \cdot \sum Q_{\text{cr}\to\text{cs}} - c_{\text{cr}} \cdot \left(Q_{\text{exh.cr}} + \sum Q_{\text{cr}\to\text{ex}}\right) = 0 \tag{9}$$

$$c_{\text{cr}} \cdot \sum Q_{\text{cr}\to\text{cs}} - c_{\text{cs}} \cdot \sum Q_{\text{cs}\to\text{cr}} - c_{\text{cs}} \cdot \left(Q_{\text{exh.cs}} + \sum Q_{\text{cs}\to\text{ex}}\right) + G = 0 \tag{10}$$

Here G [kg/s] is the contaminant source in the crawl space, c_{cr} and c_{cs} [kg/m^3] are concentrations in the classroom and crawl space, respectively, and Q [m^3/s] is the airflows.

2.1 Temperature in the crawl space

The temperature in the crawl space depends on several factors such as the thermal inertia of the ground and the *U*-values of the walls and the floor construction. The computer software Crawl (Hagentoft 1986) is used to produce a function that calculates the temperature in the crawl space based on outdoor temperature and time of the year.

The function accounts for the thermal storage in the ground beneath the crawl space, the thermal resistance of the crawl space, ventilation rate in the crawl space, outdoor temperature, and temperature in the classroom.

The ventilation rate for the crawl space used in the crawl-function is included as an average ventilation rate calculated with the infiltration model, prior to determination of the crawl-function. This means that there is no direct coupling between the ventilation rate calculated in each simulation and the temperature in the crawl space. However, in the infiltration simulation, there is some variation in ventilation rates caused by wind and stack effect. The temperature in the crawl space is, in any case, not sensitive to changes in ventilation rates. Even when doubling the air change rate, the effect on the temperature is less than half a degree in temperature. The assumption of using a fixed ventilation rate in the crawl space simplifies the calculations significantly and the effect of the assumption on the results is negligible.

2.2 Comparison with CONTAM

CONTAM is a common software for doing air infiltration simulations, and the modeling technique used in CONTAM has been validated by several researches, for example, Haghighat and Megri (1996). CONTAM is therefore used to validate the numerical model described in this paper by running several validation cases. Figure 2 shows the principle drawings of three such cases (A, B, and C), and Table 1 shows the results from the simulations by using both the numerical model and CONTAM. In simulation case A there is one room with two openings and wind as the only driver for air leakage. In case B there is one room, one opening, and one fan that blows air into the room. There is no influence from wind or stack effect. In case C there are two rooms (classroom and crawl space), three openings, fans, and a temperature difference between the classroom and the crawl space.

The results from the simulation in Table 1 show that there is good agreement between CONTAM and the numerical model.

2.3 Climate data

Ten years of weather data from one weather station in Gothenburg (in the vicinity of the Central station) and one weather station in Östersund is collected from SMHI (n.d.) and stored in a weather file. The data has hourly values of outdoor temperature, wind speed, and wind direction.

The two building locations are chosen since they differ in both temperature and wind speeds. Gothenburg has prevailing winds in southwest and southeast directions, where wind from southwest is stronger. Gothenburg has a milder climate than Östersund. Östersund has prevailing winds from northwest and south to southeast direction and colder climate compared to Gothenburg. Figure 3 shows temperature histograms and wind distributions for Gothenburg and Östersund.

2.4 Building description

The simulated school is a one-story building with a flat roof. Two building shapes with similar total floor area are simulated,

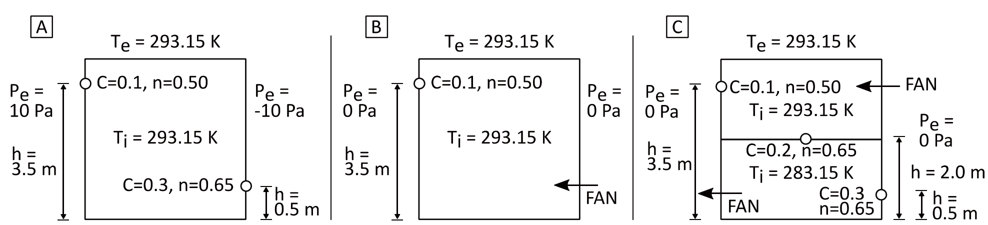

Fig. 2 Illustrations of three validation cases A, B, and C

Table 1 Results from simulations of validation cases A, B, and C using CONTAM and the numerical model described in this paper

	CONTAM [kg/s]	Numerical model [kg/s]
A (air leakage out from the building)	0.4275	0.4275
B (air leakage out from the building)	0.6256	0.6256
C (leakage between classroom and crawl space)	0.5177	0.5178

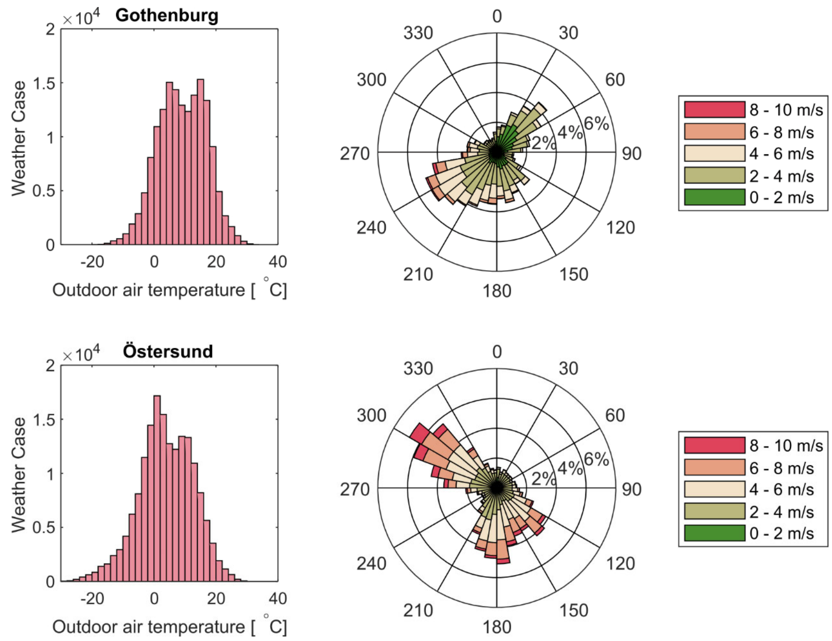

Fig. 3 Climate data for Gothenburg and Östersund: to the left is a histogram of the hourly temperature measurements and to the right is a wind rose showing hourly wind speeds and wind directions

one square-shaped building and one long-shaped building, see Figure 4. The long-shaped building is simulated with four different building orientations and the square-shaped building is simulated with two building orientations.

Both buildings have an imbalanced ventilation system in the classroom where the supply volume airflow is 90% of the exhaust volume airflow which causes a slight underpressure in the classroom. The purpose of the imbalance is to prevent air from leaking through the construction from the inside to the outside since this could lead to condensation and moisture problems inside the thermal envelope if the condensation point is inside the construction. In particular, ventilated attics are prone to these kinds of moisture problems and imbalanced ventilation is, for this reason, common in Swedish buildings and climate. However, depressurizing the classroom also means decreasing the pressure in the classroom in relation to the crawl space which can lead to increased air leakage from the crawl space to classroom. Ventilation airflow rates in both buildings are set according to the SVEBY industry standard for schools (Levin 2016). It is assumed that the supply airflow is preheated to 10 °C and that the indoor air temperature is always kept at 21 °C.

2.5 Monte Carlo simulation

The air permeability distribution in buildings varies and depends on the type of construction, detail design, and craftmanship. Many of the Swedish school buildings with indoor air quality problems have undergone several renovations, for example, the installation of new ventilation systems or air-cleaning devices. Such renovations are likely to affect the airtightness of the building and cause an increased variation in air permeability between buildings.

Monte Carlo simulations are used as a tool for uncertainty analysis in many engineering fields such as electronics and building design (Janssen 2013). With the Monte Carlo method, the input data is described using probability density functions (PDFs) (see Figure 5). The output from Monte Carlo simulations can be interpreted as the likelihood of finding a certain concentration (or pressure difference

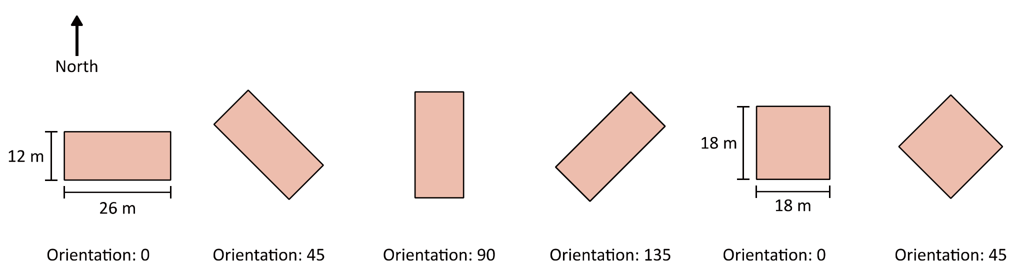

Fig. 4 Two building shapes with building orientations that are simulated

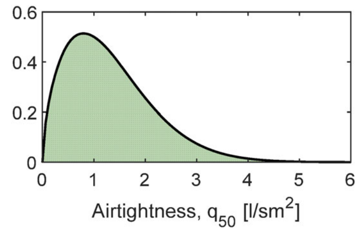

Fig. 5 Weibull probability density function used for randomly choosing airflow coefficient *C* in Eq. (1)

across the floor) or how the concentrations are distributed in a building stock where the airtightness and weather cases are found with a certain probability, described by the PDF in the input data.

The data produced in the simulations can also be used to look for correlations between variables. For example, how the airtightness of the floor construction correlates to changes in concentration levels in the classroom.

There is only limited information available on how the air permeability is distributed within a building, and there is even less information on how the leakage distribution varies between buildings. However, there are some databases on overall air permeability, q_{50} [L/(s·m^2)]. One database with air leakage data from 147000 homes in the United States where the majority of the building are detached single-family houses (Chan et al. 2012) and a French database with 215000 air leakage measurements of both multi-family houses and single dwellings (Moujalled et al. 2018). The distribution of the airtightness in both these databases resembles a Weibull distribution, and consequently the Weibull distribution is chosen to represent the spread in air permeability, see Figure 5. However, since the construction techniques are different in France and USA compared to Sweden, the average value for airtightness is not taken from any of the two databases. The average value for the airtightness is instead chosen based on interviews with consultants having made measurements in Swedish school buildings with indoor air problems.

The probability density function PDF in Figure 5 is used to calculate the airflow coefficient *C* in Eq. (1) by multiplying the area of the building component with the q_{50} provided by the PDF and then determining *C* using Eq. (1) at a pressure difference of 50 Pa. Coefficient *n* in Eq. (1) is set to 0.65 in all cases.

Figure 6 shows a flowchart of the steps in the Monte Carlo simulation. Each iteration starts with randomly choosing an airtightness value from the Weibull distribution for each wall section, roof, and floor construction for a certain building at a certain geographical location. Then, a random weather case is chosen from the climate data. The iteration step is repeated until the convergence criteria for concentrations and pressure difference (see Section 2.6) is fulfilled. Results from the simulations can, for example, be used to plot the probability density function for concentration in the classroom and pressure difference across the floor construction, see Figures 12 and 13 below.

Several combinations of building orientations, shielding conditions (since school buildings are built both in open areas and more shielded areas), and climates are investigated. In the work by Orme et al. (1994), wind pressure coefficients are given for three shielding conditions: (1) exposed, (2) height of surrounding buildings equal to half the height of the school building, and (3) height of the surrounding buildings equal to the height of the school building.

Figure 7 illustrates all the simulated combinations for both the long-shaped building and the square-shaped building.

2.6 Convergence analysis

One of the challenges with the Monte Carlo method is to determine the required number of iterations. Too few iterations will not give a true PDF, while too many iterations can be costly in terms of computational time. However, by continuously determining the variance and mean values of

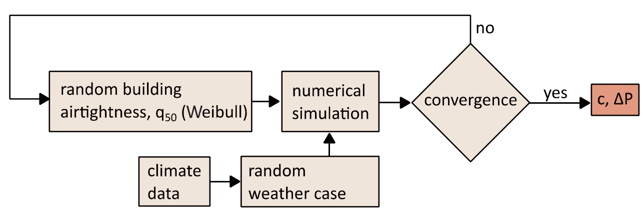

Fig. 6 A flowchart showing the steps in the Monte Carlo simulation used to obtain contaminant concentration in the classroom *c* and pressure difference across the floor construction Δ*P*

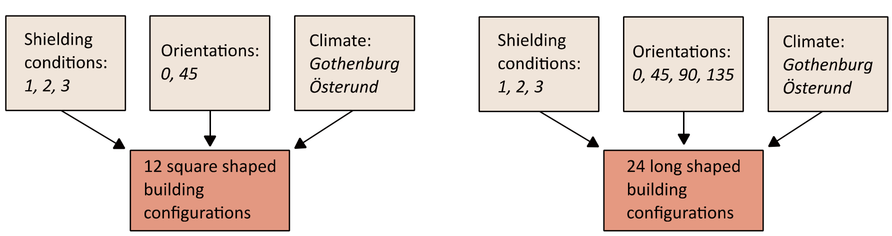

Fig. 7 Combinations of simulated cases: for the long-shaped building (Figure 4), there is a total of 24 simulation cases; for the square-shaped building (Figure 4), there is a total of 12 simulation cases

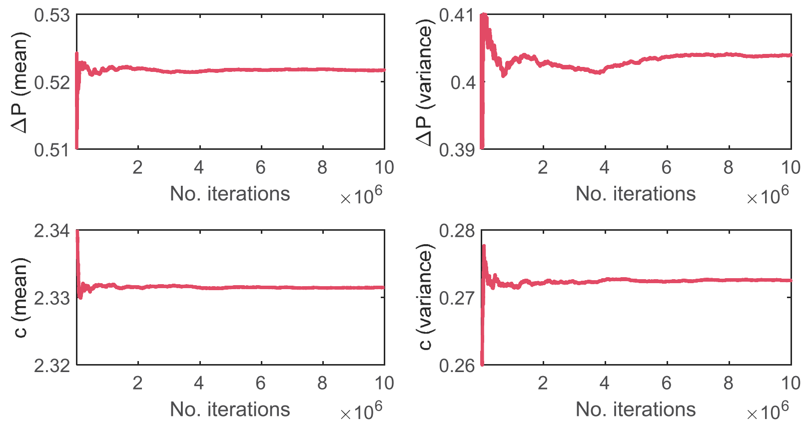

Fig. 8 Convergence plots for Monte Carlo simulations with the long-shaped buildings, building orientation 0°, exposed conditions, and Gothenburg climate

the output variables as the number of iterations increases, the dependency on the number of iterations can be determined. When the mean values and variance are no longer changing significantly, no more iterations are needed. Figure 8 shows the variance and mean values plotted for each iteration.

The convergence is judged by calculating the average values for every 10^6 iterations. If the relative change between two average values is less than 10^{-4}, the PDF is considered to be converged and any additional iterations will have no significant effect on the PDF. The number of iterations required for the simulations in this paper was 10^7 or lower.

3 Results

For results on the pressure difference across the floor construction, a positive sign means that the pressure is higher in the crawl space compared to the classroom. This means that if the pressure difference has a positive sign, air is leaking from the crawl space to the classroom.

3.1 Maximum concentration in the classroom

With a contaminant source in the crawl space that emits contaminants at a constant rate (as in the model), the maximum concentration level in the classroom occurs when all of the air leaving the crawl space passes through the classroom (and not through openings in the walls of the crawl space) and when, at the same time, the only ventilation in the classroom is caused by mechanical ventilation (independent of temperature and wind). For such a scenario the dilution of contaminants in the crawl space and the classroom is minimal and all contaminants produced in the crawl space enters the classroom. This situation results in the highest possible concentration in the classroom and is independent of the airtightness of the building.

It is useful to normalize the concentration in the classroom by dividing the concentration by the maximum concentration in the classroom. The normalized concentration relates the concentration in the classroom to the strength of the contaminant source in the crawl space and the mechanical ventilation. The concentration in absolute terms can be calculated with the following equations:

$$c_{\mathrm{cr,max}} = \frac{G}{Q_{\mathrm{exh}}} \tag{11}$$

$$c_{\mathrm{cr,N}} = \frac{c_{\mathrm{cr}}}{c_{\mathrm{cr,max}}} \tag{12}$$

where c_{cr} is the concentration in the classroom, $c_{\mathrm{cr,\,N}}$ is the normalized concentration in the classroom, $c_{\mathrm{cr,\,max}}$ is the maximum concentration in the classroom, Q_{exh} is the exhaust airflow, and G is the source strength.

An illustration of how the normalized concentration changes as the airflows in the building change is shown in Figure 9. Note that the flow of contaminants is also normalized by dividing the contaminant flow with the strength of the contaminant source, and that the airflows caused by the mechanical ventilation is the same for all cases A to D. In Figure 9 A, all air leaking into the crawl space also leaks into the classroom. In Figure 9 B, some of the air that leaks into the crawl space leaks up to the classroom and some of the air leaks to the exterior, which results in a lower concentration in the crawl space. In Figure 9 C, all air leaking into the crawl space also leaks into the classroom but there is also air leakage in the classroom which reduces the concentration in the classroom. In Figure 9 D, concentrations both in the classroom and the crawl space are reduced.

3.2 Correlations

Pearson's linear correlation coefficient r is a measure of how linear a relationship between two variables are. A value

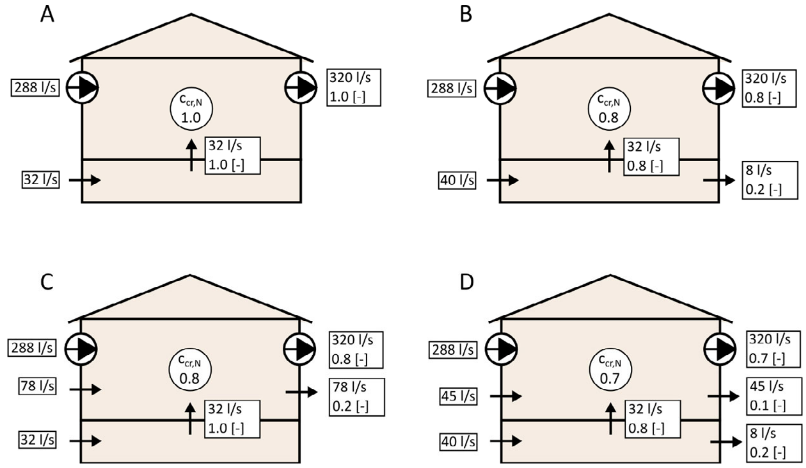

Fig. 9 Illustration of how concentration levels in the classroom are affected by changes in air leakage paths. The value inside the circle in the middle of the classroom is the normalized concentration calculated as the concentration divided by maximum concentration (case A) by Eqs. (11) and (12)

of r = 0 means no correlation, and r = 1 means a perfect correlation. In this paper, Pearson's correlation coefficient is used to study correlations between simulated parameters in the Monte Carlo simulations. Figure 10 shows an example from simulations on a long-shaped building in Gothenburg climate, building orientation 90°, and exposed shielding condition. The figure shows that the concentration in the classroom increases as the air change rate or outdoor temperature decreases.

Table 2 shows correlation coefficients for simulations on the long-shaped building and all three building orientations in Gothenburg climate and Östersund climate. The values marked with red corresponds to the values in Figure 10. However, values in Figure 10 are only for building orientation 90° and exposed shielding condition.

Results in Table 2 show that for the pressure difference across the floor, the outdoor temperature and airtightness of the floor construction are important. Also, wind speed and airtightness of the crawl space walls are of some importance. However, the correlation between wind speed and the pressure difference across the floor depends on both how well shielded the building is and the directions of the wind in relation to the building shape and orientation. This is shown for example if looking only at wind directions between 225° and 270° (Gothenburg climate) and building orientation 135°, see Table 3 and Figure 11. With wind blowing along the long facades of the building, the correlation coefficient becomes 0.37. Similarly, wind directions perpendicular to the long facades gives a lower correlation coefficient 0.14. Independent on wind direction, shielding condition and building orientation, the sign of the correlation coefficient is positive for most wind directions. This means that increased wind speed results in higher positive pressure difference across the floor construction (increased upward airflow) for most cases.

Östersund (Table 2) shows a higher correlation between wind speed and pressure difference across the floor compared to Gothenburg (Table 2). The reason for this is that Östersund, in general, has higher wind speeds than Gothenburg. Since

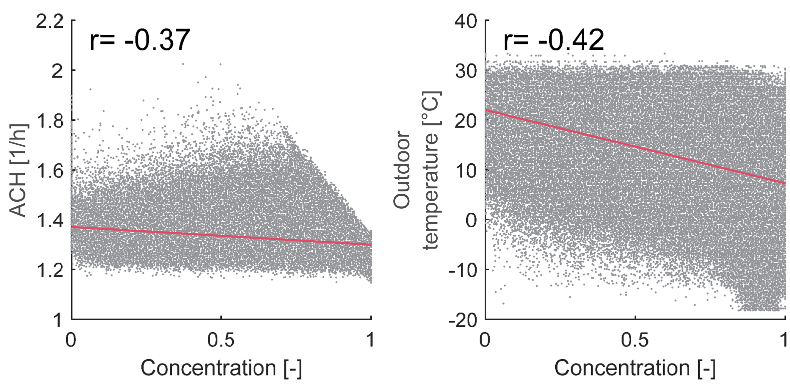

Fig. 10 Outdoor temperature and air change rate (ACH) in the classroom are plotted against concentration level in the classroom for Monte Carlo simulations on a long-shaped building in Gothenburg climate with building orientation 90° and exposed shielding condition. Figures also show the Pearson's correlation coefficient and a least- squares line for the data points

Table 2 Correlation coefficients for simulations on a long shaped building with Gothenburg climate and Östersund climate.

	Gothenburg		Östersund	
	Concentration	Δ*P* (floor)	Concentration	Δ*P* (floor)
Concentration	1		1	
Δ*P* (floor)	0.05	1	−0.19	1
Outdoor temperature	−0.37	−0.43	−0.16	−0.35
Wind speed	−0.18	0.11	−0.33	0.19
ACH (classroom)	−0.34	−0.08	−0.36	0.08
q_{50}	−0.07	−0.01	−0.06	0.03
q_{50} (floor)	0.07	−0.54	0.11	−0.56
q_{50} (roof)	−0.07	0.04	−0.05	0.08
q_{50} (crawl)	−0.06	0.16	−0.10	0.16
q_{50} (classroom)	−0.07	−0.04	−0.10	−0.04

Table 3 Correlation coefficients divided into groups dependent on wind direction. Building orientation 135°, long-shaped building, Gothenburg climate, exposed shielding condition

	90°		135°	
Building orientation: Wind direction	Δ*P* and wind speed	Concentration and wind speed	Δ*P* and wind speed	Concentration and wind speed
0–45	0.14	−0.22	0.16	−0.19
45–90	0.05	−0.23	0.15	−0.16
90–135	0.04	−0.19	−0.01	−0.21
135–180	0.28	−0.20	0.13	−0.25
180–225	0.30	−0.19	0.28	−0.22
225–270	0.14	−0.31	0.37	−0.24
270–315	−0.1	−0.29	0.12	−0.21
315–360	0.21	−0.10	0.06	−0.15

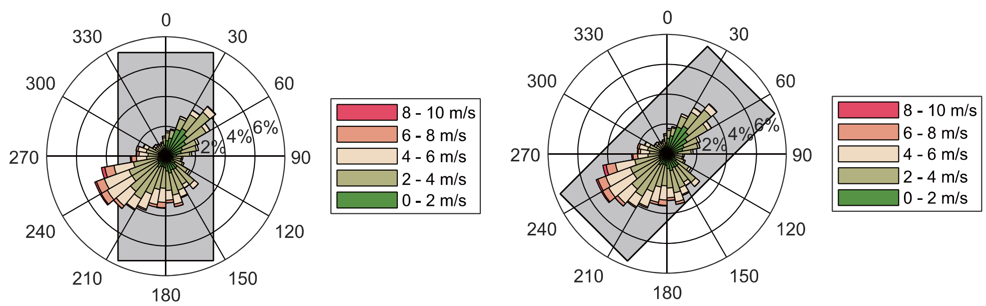

Fig. 11 Wind speed and wind direction for Gothenburg together with building orientation. In the left figure building orientation is 90° and in the right figure the building orientation is 135°

wind pressure increases exponentially with wind speed a stronger correlation between wind speed and pressure difference across the floor construction can be expected at locations with much wind.

The stack effect depends on the indoor temperature, outdoor temperature, and the temperature in the crawl space. The temperature in the crawl space depends on the outdoor temperature, indoor temperature, thermal properties of the ground and the thermal resistance of the building construction. The higher the temperature difference between outdoor and indoor environment, the higher is the stack effect across the floor construction. This means that the pressure difference across the floor construction, which is caused by stack effect, will always have a positive sign if the outdoor temperature is lower than the indoor temperature. This is most often also the case in Swedish school buildings. The correlation coefficient between outdoor temperature and pressure difference across the floor is −0.43 and −0.35 for Gothenburg and Östersund, respectively.

Although the pressure difference across the floor construction is important for the transport of contaminants from the crawl space to the classroom, concentration levels are also determined by the ventilation rates of both the crawl space and the classroom.

As the pressure difference across the floor increases with lower outdoor temperature, both air change rates and air leakage from the crawl space to the classroom increase. However, in most cases, the upward flow of contaminants increases more than the outflow of contaminants. Consequently, the concentration in the classroom is, therefore, higher at lower outdoor temperatures. The correlation coefficient for outdoor temperature and air change rate for the long-shaped building is −0.33 and −0.35 for Gothenburg and Östersund, respectively.

A leakier building means a higher air change rate as the outdoor temperature decreases or as the wind increases. This can be seen if splitting the data in two sets, one with leaky buildings and one with less leaky buildings. Higher air change rates are found in the dataset with leaky buildings and air change rates are higher when there is more wind or lower outdoor temperatures.

However, the correlation between overall building airtightness and concentration levels is not significantly high. The reason for this is that both increased wind speed and decreased outdoor temperature cause a higher pressure difference across the floor construction which in turn leads to a higher transport of contaminants into the classroom. These two effects counteract each other, cancelling out the effect on concentration levels in the classroom. The correlation coefficient between building airtightness and concentration levels in the classroom is −0.07 for Gothenburg and −0.06 for Östersund (Table 2), meaning a slight increase in concentration as the building gets more airtight.

As can be seen in Table 2, there is not necessarily a strong correlation between pressure difference across the floor construction and concentration levels in the classroom. As discussed previously, more windy locations have a stronger correlation between pressure difference across the floor construction and wind speed. But higher wind speeds also mean higher air change rates which reduce the contaminant concentrations. This is the reason Östersund (Table 2) has a stronger correlation between concentration and pressure difference across the floor construction and a stronger correlation between concentration and wind speed compared to Gothenburg (Table 2).

Buildings with a squared shape rather than a long shaped shape (two longer sides and two shorter sides) show similar behavior as the long shaped buildings. The only major difference is that the squared building is less affected by building orientation and wind angle.

3.3 Distribution of pressure difference and concentration

In the majority of the simulations, the pressure difference across the floor is positive (air leaks from the crawl space to the classroom), which is caused by the imbalanced ventilation and stack effect. However, the pressure difference is reversed (so that air leaks from the classroom to the crawl space) in, on average, 2.8% of the cases for the Gothenburg climate and 1.0% of the cases with the Östersund climate.

This means that if using an imbalanced ventilation system, with higher exhaust airflow than supply airflow, and if there is no exhaust fan in the crawl space, air will leak from the crawl space to the classroom during a majority of the time, given that there are openings or cracks in the floor construction.

The likelihood of a certain concentration level in the classroom or pressure difference across the floor construction can be expressed using probability density functions and cumulative distribution functions. In Figures 12 and 13 simulation results for a long-shaped building with a building orientation of 0° and exposed shielding condition placed in Gothenburg is shown in terms of probability density functions and cumulative density functions.

For each case with negative pressure difference across the floor construction the concentration in the classroom will be zero and for cases with high contaminant transport to the classroom in combination with low air change rate

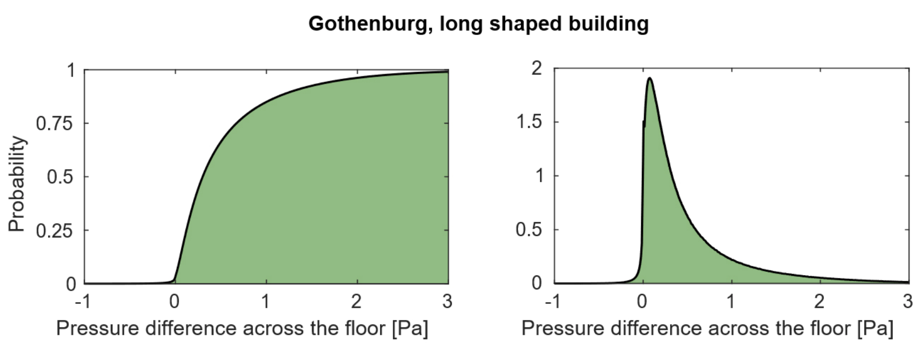

Fig. 12 Pressure difference across the floor construction plotted as a cumulative distribution function (left) and probability density function (right). Res ults from simulations with the long shaped building, orientation 0°, and exposed shielding condition

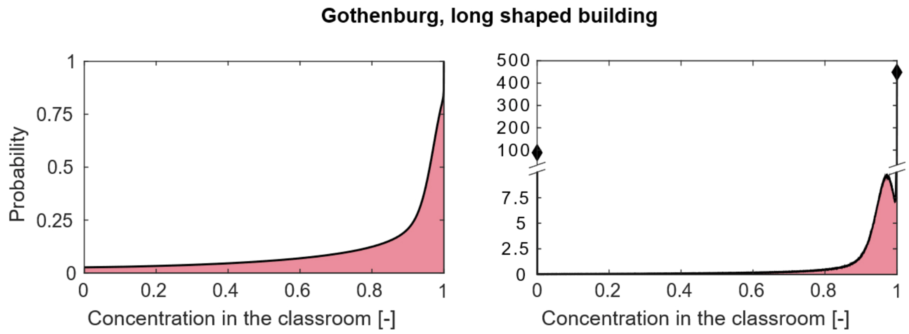

Fig. 13 Normalized contaminant concentration in the classroom plotted as a cumulative distribution function (left) and probability density function (right). Results from simulations with the long shaped building, orientation 0°, and exposed shielding condition

the concentration will be 1 (see examples in Figure 9). Both the concentration at exactly 0 and exactly 1 have a high probability. These values are marked with diamonds and can be seen in Figure 13.

3.4 Crawl space

An exhaust fan is sometimes installed in the crawl space in order to ensure a negative sign of the pressure difference across the floor construction to prevent air from leaking up to the classroom. Simulations show that if the fan is adjusted to achieve a pressure difference across the floor of −5 Pa this is enough to maintain a negative pressure difference when weather conditions change. A pressure difference of −5 Pa is chosen since this the common praxis in Sweden when installing an exhaust fan in crawl spaces in older buildings.

In the work by Domhagen et al. (2020), a situation was presented where the negative pressure of 5 Pa achieved by the exhaust fan in the crawl space was changed to positive pressure. Although such a situation is not found in the simulations presented in this work there is still a possibility for this to happen. It can therefore be advisable to consider the weather during the day when the fan is installed, since some wind speeds, wind directions together with mild temperature might result in achieving a negative pressure difference more easily at lower exhaust airflows. In some cases, this might lead to a too low airflow of the exhaust fan to maintain a negative pressure difference when weather conditions change.

The pressure difference across the floor construction also depends on the airtightness of the crawl space and the floor construction. An airtight crawl space is easier to depressurize, and lower exhaust airflow is needed to achieve the desired depressurization. Crawl spaces sometimes have ventilation openings that needs to be sealed before installing the fan. However, the pressure difference in an airtight crawl space is also more sensitive to changes in airtightness. To investigate how sensitive the pressure difference across the floor construction is to changes in airtightness of the crawl space, one and two openings with a diameter of 0.1 m are made in the wall of the crawl space. The openings represent any of the sealed ventilation openings breaking. Such an event has been noted in field measurements on a school building with a crawl space (Domhagen et al. 2019).

The results in Figure 14 show the distribution of pressure difference across the floor construction with one and two added ventilation openings. Results are produced by first adjusting the exhaust airflow for a fan in the crawl space, for a randomly chosen weather case, so that a pressure difference of −5 Pa is achieved across the floor construction. In the next step a new weather case is randomly chosen and either one or two openings are added to one of the walls in the crawl space. The building is then simulated with the new weather case and additional openings.

The bottom histogram in Figure 14 shows the distribution of pressure difference across the floor construction for the crawl spaces with an airtightness between 0 and 0.5 L/(s·m^2) at 50 Pa.

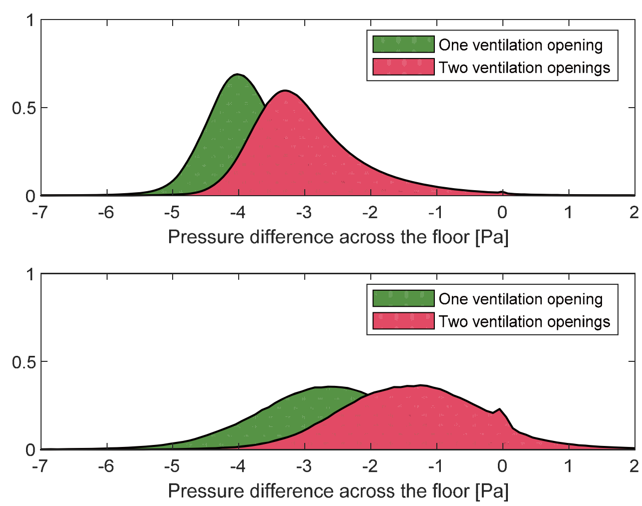

Fig. 14 Distribution of pressure difference if one or two circular openings are made in the wall of the crawl space. In the bottom figure, only the distribution for buildings with a crawl space that has an airtightness lower or equal to 0.5 L/(s·m^2) is shown

The results in Figure 14 shows that the average pressure difference is reduced by about 1 Pa for each opening and that the variation in pressure difference increases as more openings are added. Also, when comparing the more airtight crawl spaces with the less airtight crawl spaces it becomes clear that the pressure difference in the more airtight crawl spaces is more sensitive to changes in crawl space airtightness. Adding two openings can, in some cases, completely change the sign of the pressure difference across the floor construction from negative to positive.

In Figure 15 a reduction in exhaust airflow from the fan in the crawl space is investigated. This could for example happen due to mechanical failures in the exhaust fan or control system. This has been seen in one of the inspected schools where one out of two fans had stopped working. The results in Figure 15 are produced in a similar way as the results in Figure 14. Figure 16 shows a flowchart of the simulation steps taken to produce the results in Figures 14 and 15.

First, the airflow of an exhaust fan in the crawl space is adjusted to achieve a pressure difference across the floor construction of −5 Pa. Then, a new weather case is chosen randomly, and the building is simulated with a 10% and 20% reduction of the airflow in the exhaust fan.

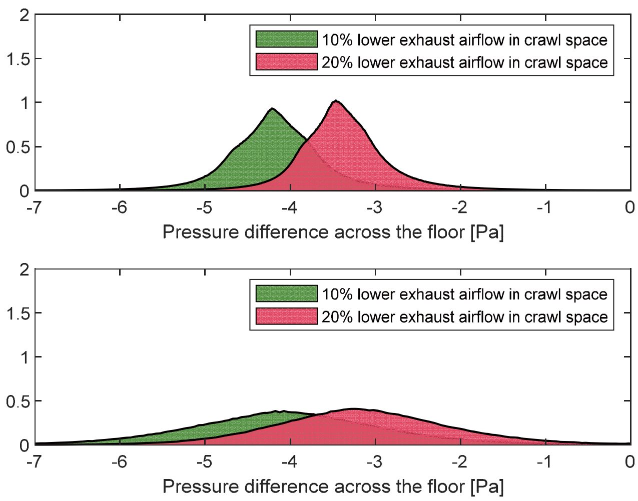

Fig. 15 Distribution of pressure difference if the exhaust airflow in the crawl space is reduced by 10% and 20%. In the bottom figure only the distribution for buildings with a crawl space that has an airtightness lower or equal to 0.5 L/(s·m^2) is shown

Results in Figure 15 shows that a reduction in exhaust airflow, 10% reduction in airflow reduced the average pressure difference by 0.8 Pa and a 20% reduction in airflow reduces the average pressure by 1.6 Pa. The results are similar for more airtight crawl spaces. However, the variation in pressure difference is greater. A reduction in airflow of 20% is not enough to change the sign of the pressure difference in either case.

3.5 Ventilation in the classroom

Increased ventilation is a common measure to take when the indoor air quality is poor. Increasing the air change rate in the classroom can have a significant effect on the concentration levels which can be seen in Table 2. However, if the school has an imbalanced ventilation system and the ventilation rate is increased by increasing only the exhaust airflow this results in a higher positive pressure difference across the floor construction. A higher positive pressure might result in an increased inflow of contaminants to the classroom from the crawl space.

Simulations show that if the exhaust ventilation in the long-shaped building is increased by 10 L/s (from 320 L/s) this will increase the concentration levels in the classroom in 17% of the cases for Gothenburg climate and 24% of the cases in Östersund climate.

Figure 17 shows how the contaminant concentration and flow of contaminants from the crawl space to the classroom change with increased exhaust ventilation. The flow of contaminants is normalized by dividing the contaminant flow with the strength of the contaminant source, as in Figure 9.

By comparing cases where the concentration increases with cases where the concentration decreases it becomes clear that for the cases where the concentration increases, the normalized flow of contaminants is below 1, and for the cases where the concentration decreases the normalized flow of contaminants is equal to 1. Increasing the exhaust ventilation rate increases the pressure difference across the floor construction and leads to a higher flow of contaminants from the crawl space to the classroom. However, increasing

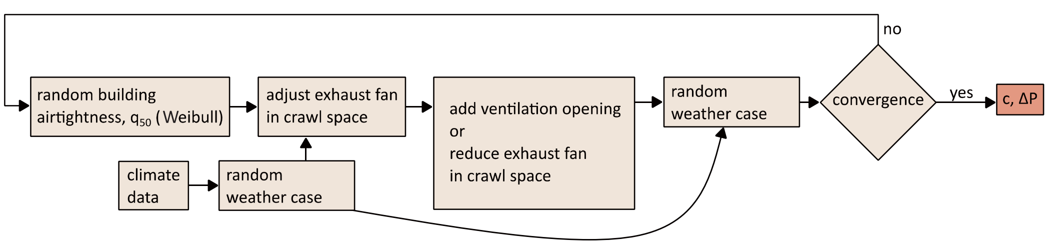

Fig. 16 Flow chart showing the simulation steps when adding ventilation openings in the crawl space or reducing the airflow of the exhaust fan in the crawl space

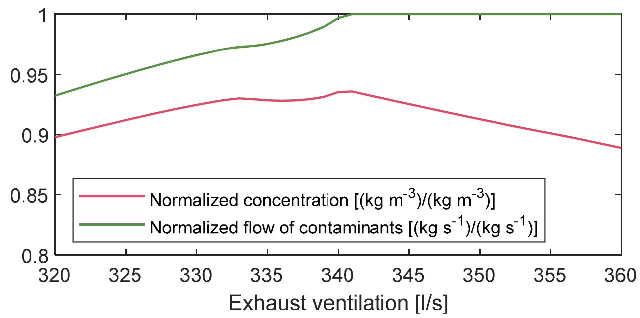

Fig. 17 Contaminant concentration in the classroom and flow of contaminants from the crawl space to the classroom plotted against increased exhaust ventilation. Concentration and flow of contaminants are normalized by dividing by the maximum concentration and flow respectively

the ventilation rate of the classroom also increases the flow of contaminants out from the classroom. With a constant contaminant source in the crawl space, the flow of contaminants into the classroom can never be higher than the source itself. Therefore, when the normalized flow of contaminants is equal to 1, increased exhaust ventilation will only lead to a higher flow of contaminants out from the classroom since the flow of contaminants from the crawl space is already at maximum, the concentration in classroom will start to decrease.

The point at which the concentration starts to decrease depends both on the distribution of permeability and wind as well as outdoor temperature, since these factors influence the pressure difference across the floor construction. For example, the average ratio of permeability of classroom over permeability of the crawl space is about twice as high for the cases when the contaminant concentration increases. A higher ratio means a higher pressure difference across the floor construction.

The increase in contaminant concentrations can be worse if it is windy and if the wind angle combined with the distribution of air permeability results in an underpressure in the classroom and an overpressure in the crawl space. This can happen if for example the wind blows along the longer, leaky, facades of the long-shaped building while the wall of the crawl space facing the wind direction is leaky.

3 Conclusions

The uncertainty of air permeability distribution is a major challenge when working with airtightness-related problems in buildings. Unintentional openings in the construction can occur in many places and there can be great variations in air leakage distribution between buildings. A statistical modeling approach (Monte Carlo simulation) is therefore chosen in this project.

In all the simulated cases, the school buildings have a combined supply and exhaust ventilation system where the exhaust airflow is higher than the supply airflow which causes a small underpressure in the classroom. The pressure difference across the floor construction is positive upwards in most of the simulation cases. The air leakage direction is, however, reversed for 2.8% of the cases for simulations with the long-shaped building in Gothenburg and 1.0% of the cases for simulations with the long-shaped building in Östersund.

In most cases, most of the airflow that enters the crawl space also passes on to the classroom. This means that, for a constant contaminant source in the crawl space, concentration levels in the classroom will reach high levels even though the air leakage from the crawl space to the classroom is small.

It is possible to improve the indoor air quality by increasing ventilation rates. However, if increasing the ventilation rate results in an increase in pressure difference across the floor construction it is not certain that increasing the ventilation leads to reduced concentration levels. Increasing the ventilation rates could be an efficient measure if both the supply airflow and the exhaust airflow are increased simultaneously (so that the pressure difference across the floor construction does not increase).

In the simulations, the ventilation rates in the classroom are increased by increasing the exhaust airflow by 10 L/s which results in increased concentration levels in 17% of the cases for simulations with the longs shaped building in Gothenburg and increased concentration levels in 24% of the cases for simulations with long shaped buildings in Östersund. Both examples were simulated with exposed conditions and 0° building orientation.

Simulations show that installing and adjusting an exhaust fan in the crawl space to achieve a pressure difference across the floor construction of −5 Pa can be enough to prevent air leakage from the crawl space to the classroom. However, the pressure difference across the floor construction in such a case can be sensitive to changes in the airtightness of the crawl space. Simulations show that if the airtightness of the crawl space changes, for example with one or two additional ventilation openings, this can be enough to change the pressure distribution in the crawl space so that the pressure difference across the floor is positive upwards for some weather cases. Also, prior to installing an exhaust fan in the crawl space, the crawl space itself is made more airtight. However, the pressure distribution in a more airtight crawl space with an exhaust fan is more sensitive to changes in airtightness.

Wind speed and outdoor temperature are in general more important for the concentration levels than the airtightness of various parts of the building. However, increased wind speed leads to increased air change rate in the classroom which in most cases reduces the concentration levels. Nevertheless, increased wind speed can also cause a higher pressure difference across the floor construction, for example when the wind direction is parallel to the longer sides of the building, which increases the flow of contaminants to the classroom. However, the highest concentration levels in the classroom are found during days with little wind and mild outdoor temperature.

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