EDUCATION AND INDOOR CLIMATE

Research paper

Air quality and ventilation in schools

Swegon

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Abstract

Several thousand years ago, the first so-called schools were founded, and the school education of people started. Today, education can take up to ¼ of human life, and most of the time is spent indoors – in school buildings. Environment – inside (indoor) and around (outside) – school buildings affect students' health, thinking and performance. Decades of scientific and research findings show that there already exists substantial and robust evidence of how a healthy indoor climate and good ventilation affect children and their performance in schools.

The school building represents an excellent opportunity to intervene and protect the students' health. The school or building owner must ensure a healthy environment while being sustainable, energy-efficient and cost-effective. The school environment needs to be liveable and conducive to learning: full of fresh air and good (day)light, emphasising a comfortable atmosphere and providing good acoustic conditions. Today's actual trends in school buildings focus on the systems that are variable and demand-based in delivering an essential indoor climate, flexible and controllable in use, integrated yet intelligent and adaptable to potential and future requirements.

Students deserve to develop, learn and thrive in a healthy environment that optimises their potential to succeed and safeguards children's well-being. The future needs healthy and smart school buildings with an excellent indoor environment for healthy air in schools.

KEYWORDS: school, ventilation, students, education, knowledge, indoor climate, well-being, health, heating, ventilation, air conditioning and refrigeration (HVACR)

Background

Facts about the building stock

A large part of the European building stock (residential and non-residential buildings) is in need of renovation, as 2/3 of the building stock was built before the 1970s. It can be safely assumed that most of these buildings will still stand in the 2050s.

Every year, new building constructions in Europe make up only about 1% of the existing building stock (Artola, 2016).

In Europe, about 75% of buildings are residential, and the rest – 25% – are non-residential (commercial) buildings with various activities. The educational building stock represents 17% of the non-residential building stock (or respectively 4.25% of the total building stock, see Figure 1).

Note that in America (the USA and Canada), the building stock is middle-aged, and the largest share of buildings was built before the 1980s. In the USA, education, mercantile, office, and warehouse/storage buildings account for 60% of total commercial floor space and 50% of buildings (EIA, 2018).

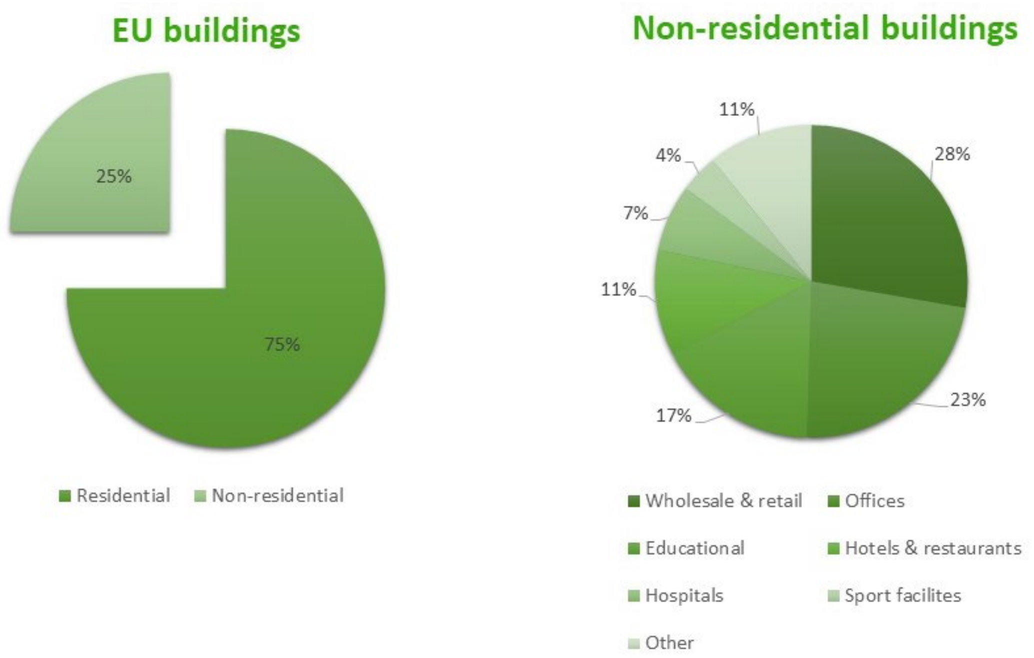

Figure 1: Overview of the non-residential and residential building stock in Europe (BPIE Report, 2011) on-residential and residential building stock in Europe (BPIE Report, 2011)

Facts about the educational building stock in the European Union and North America

- The European educational building stock is relatively old, often dilapidated and has poor energy performance.
- Most European school buildings have been built for traditional front-of-class teaching.
- A large part of the operational costs of schools in Central Europe and in the Scandinavian countries are taken up by heating the premises and the maintenance and upkeep of the buildings.
- The current building stock is already old, but it will still stand in the 2050s. However, the average lifespan of a building varies considerably based on building technology and building service equipment. Also, the lifespan of a building is very much dependent on the quality of built and the level of maintenance (among many other factors).
- There is no predefined model of a school building in Europe and America. Some schools have a very large footprint and are very spread out, with one or two-storey buildings or multi-storey buildings.
- The overall age of school buildings in the USA is 44 years (and 12 years since the major renovation), and also the lifespan of education buildings is estimated at about 40 years in Canada.
- In America, when a school building is 20 to 30 years old, frequent replacement of equipment is needed. After 30 years, the original equipment should have been replaced, including the roof and electrical equipment. And after 40 years, the school building begins to fall into disrepair, and after 60 years, most schools are abandoned.
- In the USA, newer school buildings tend to be larger than older buildings. The average size of the school building is 31,000 ft2 (or respectively 2,880 m2).

Time spent in schools

A school is an educational institution that provides a learning environment for the education (schooling, school attendance) of students (or pupils) under the guidance of educators (or teachers, academic people). The school offers an educational space for many different activities based on the numerous needs and requirements of students and teachers. Children as students will spend most of their early lives in schools, which is why the indoor environment in schools is so important.

Educational stages

Most countries have formal educational stages (subsequently the series of schools), some compulsory and some voluntary. The educational stages vary country to country but usually includes before school (kindergarten, preschool), primary education for young children (primary or elementary school), secondary education for teenagers (secondary, middle or high school) and tertiary or higher education (college, university), see Figure 2.

There are also many alternative educational facilities (for specific educational needs, religious, private, etc.) and schools for adults (for example, training academy, business school, etc.). Independent education is home-schooling or distance learning.

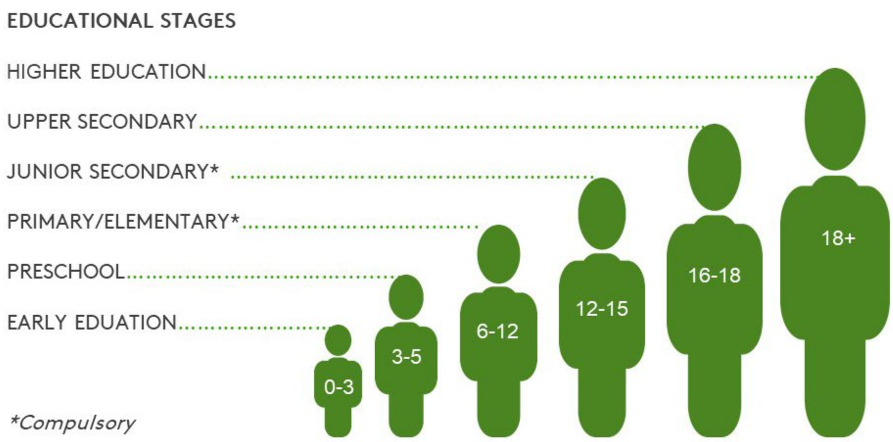

Figure 2: Educational stages applicable for most of the developed countries

Years, weeks and hours in schools

Children spend many years in schools. Educational stages and schools vary by country, but in general, children start education at the age of 6-7, followed by the primary school at the age of 7-10, secondary school from the age of 10-14 and high school from the age of 14-18 (in some countries until 16 years of age). Usually, the children reach the age of 18+ and continue their third-level education at a college or university for another 3-5 years, see Figure 3.

Keep in mind that children may also have a voluntary education before the age of 6. After graduating from university, they also often continue in further academic education or self-education through various educational programs/training or lifelong education.

The best education systems in the world require students to go to school between 175 and 220 days a year (or between 35 and 45 weeks). The average school day lasts from 5 to 8.5 hours per day, see Figure 4. This variation suggests that the total number of school days (or hours) per year is not a determining factor in student performance. (NCEE, 2018)

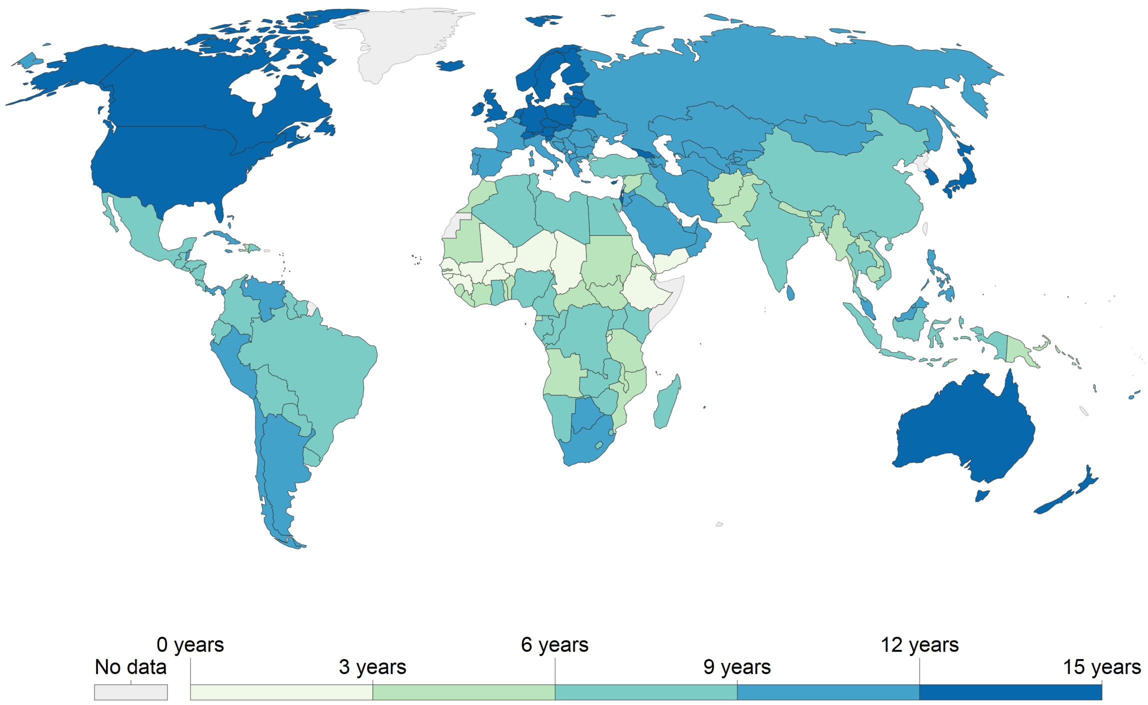

Figure 3: Mean years of schooling in the world in 2017. Average numbers of years of total schooling across all education levels for the population aged 25+ (Our World in Data, 2016)

Note that total holidays can range from 8 to 16 weeks (including summer breaks from 5 to 11.5 weeks per year + additional breaks throughout the year).

Based on this information, formal education can be estimated, generally, at 10-12 years (minimum), 17-20 years (standard with university education), and it can also take up to 20+ years (with postgraduate education).

* Note that this mainly applies to developed countries.

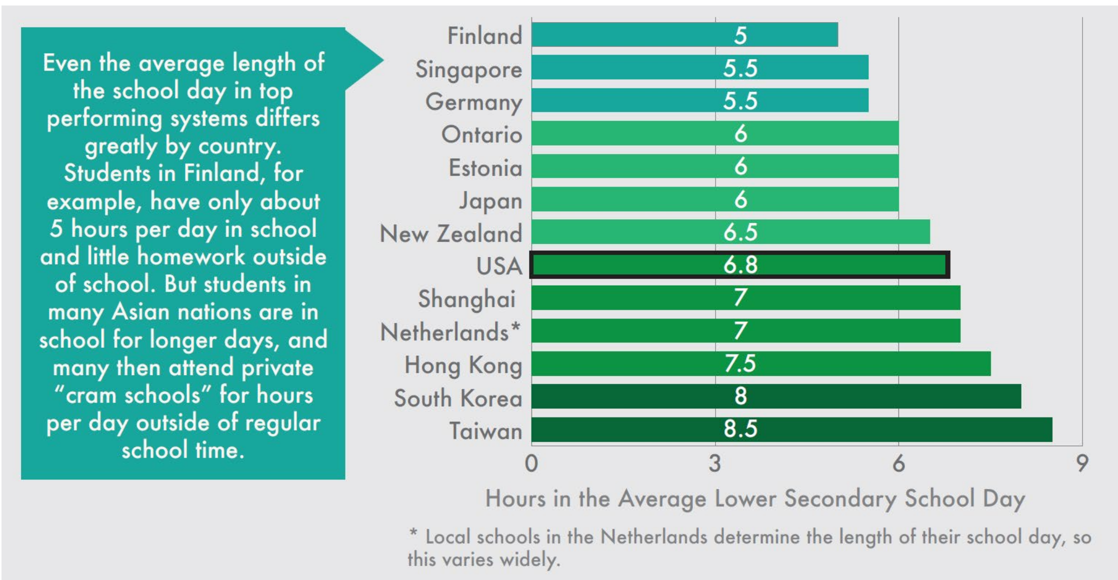

Figure 4: How long is the average school day (NCEE, 2018)

When it comes to student performance, more important than the amount of time students spend in class, is how that time is spent (NCEE).

Education of the world's population

In 2021, the current world population is approximately 7.8 billion. The school-age population (aged 6-25) is approximately 33% of the world's population (Worldometers, 2021).

However, it should be noted that not all children have access to proper education, especially in underdeveloped countries.

For comparison:

- The current population in Europe is 9.8% of the world's population (that is approximately 747 million), and the European statistics show that in 2018 approximately 76.2 million students were enrolled in schools (of which 15.7 million in preschools) and another 17.5 million students in tertiary education. It equates to a total of 76.2 million students (Eurostat, 2020).
- The population of North America is 4.7% of the world's population (approximately 370 million), and the statistics from the USA and Canada show that in 2020 there were 56.4 million students (in elementary, middle and high schools) + 19.7 million students (in college and universities) + 2.1 million students in Canada. It equals a total of 78.2 million students.

However, the length of education in schools is steadily increasing. If the current age-specific enrolment rates persist throughout the child's schooling, Figure 5 shows the number of years a child of school entrance age can expect to receive.

In Europe and Northern America, from the average life expectancy of 79 years (82 for females and 76 for males) and education length between 10-20 years, it can be estimated that a person spends about 1/7 or even a quarter of their life at school (education before/after school is not taken into account).

This corresponds to 8,765 hours and up to 175,300 hours of education, and consequently, the time spent in schools.

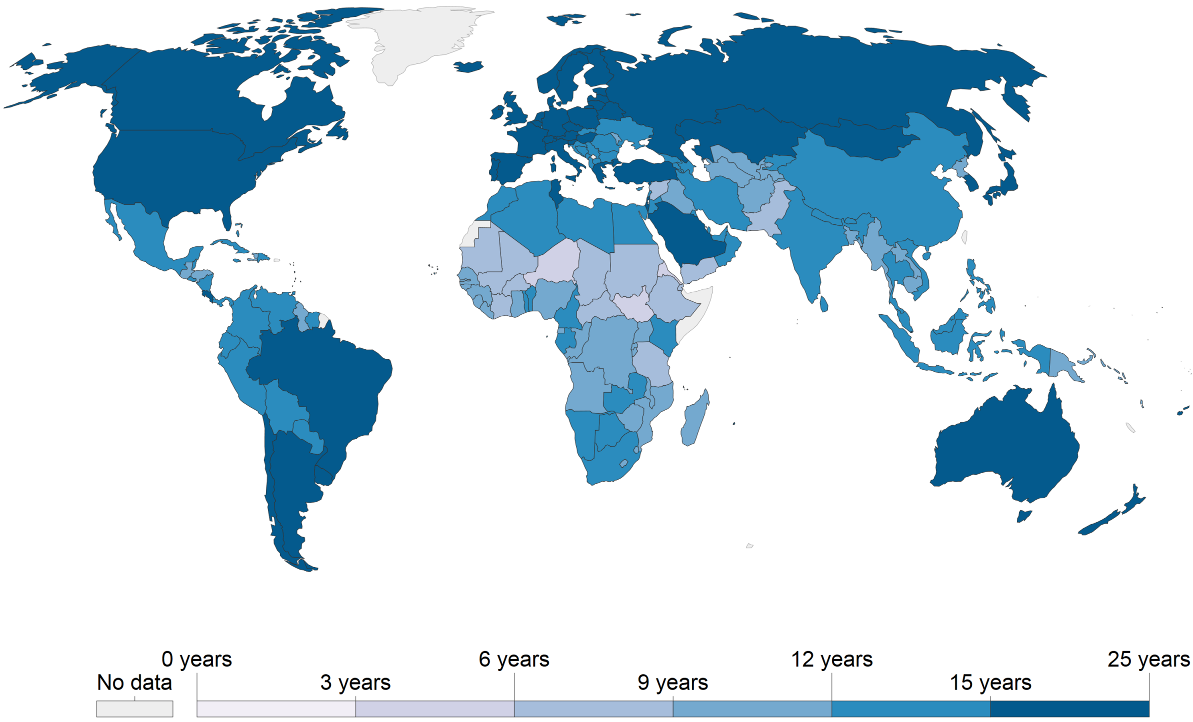

Figure 5: Expected years of schooling in 2017 if the current enrolment rate persists (Our World in Data, 2016)

Standards and regulations for comfort and ventilation in schools

Ventilation in schools affects indoor air quality (IAQ), which is generally evaluated by temperature, relative humidity, carbon dioxide (CO2) concentration and ventilation rates. Keep in mind that IAQ is part of the indoor environmental quality (IEQ), which also includes other parameters (based on PMV and PPD), such as thermal comfort, daylight/light and sound conditions, etc.

The predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) are indexes that express building occupants´ satisfaction with the thermal environment (based on occupants´ subjective evaluation).

Building standards recommend design values for different types of buildings. These general values are usually accepted at international and national levels. See Table 1 of the European building standards (REHVA) and Table 2 of the American building standards (ASHRAE). There are also some specific building guidelines for schools – ventilation, comfort and IAQ (Building Bulletin and Passive house requirements).

Standards for schools (classrooms, lecture hall and other spaces) often specify the temperatures for summer and winter (min, max in °C), R.H. (%), CO2 (ppm), ventilation rate (in cfm, i.e. ft3/min/p; m3/h, l/s/p, l/s m2 or air exchange rate h-1), among others. And there are also guidelines for the visual and acoustic levels.

EN 16798-1:2019

The light levels needed for a particular visual task and the recommended values for schools are 100 lux for movement in corridors, 300 lux for simple tasks in classrooms, 500 lux for moderately complex tasks in auditoriums and laboratories, and 750-1,000 lux for complicated tasks. However, the recommended levels for artificial lighting in schools are 300 lux.

Recommended noise level (indoors) is 35 dB(A) for classrooms and 40 dB(A) for other areas.

EN 16798-1:2019 Energy performance of buildings. Ventilation for buildings. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.				
	IEQ I (high)	**IEQ II (medium)**	IEQ III (mod-erate)	IEQ IV (low)
Temperature [°C] range for winter with clo 1.0 (*with activity level of 1.2 met)	21–23 [°C]	**20–24 [°C]**	19–25 [°C]	17–25 [°C]
Temperature [°C] range for summer with clo 0.5 (*adaptive - less strict temperature limits)	23.5–25.5 [°C]	**23–26 [°C]**	22–27 [°C]	21–28 [°C]
Relative humidity – with optimum levels of 40–60%	30–50%	**25–60 [%]**	20–70 [%]	<20, >70 [%]
CO2 concentration – maximum levels (*levels above outdoor concentration of 480 ppm + maximum permitted concentration above)	1,030 [ppm] (480+550)	**1,280 [ppm] (480+800)**	1,830 [ppm] (480+1,350)	>1,830 [ppm] (480+>1,350)
Ventilation rate (*fresh air supply of minimum 3–5–8 l/s/p)	1.0–6.0 [l/s, m2]	**0.7–4.2 [l/s, m2]**	0.4–2.4 [l/s, m2]	0.3–2.0 [l/s, m2]

Table 1: Parameters for buildings from the European building standards

This standard focuses on setting new rules and requirements for indoor environmental parameters for the thermal environment, indoor air quality, lighting and acoustics, and explains how to use these parameters for building system design and energy performance calculations. (CEN, 2021)

ASHRAE 62.1:2019

ASHRAE recommends 300-500 lux and 30-45 dB(A) for the classroom.

ASHRAE 62.1:2019 Ventilation for Acceptable Indoor Air Quality ASHRAE 55:2020 Thermal Environmental Conditions for Human Occupancy		
Temperature [°C] range for winter (*assuming activity sedentary and slightly active)		20–24 [°C] (68–75°F)
Temperature [°C] range for summer		23–26 [°C] (73–79°F)
Relative humidity – optimum levels		30–60 [%]
CO_2 concentration (*outdoor concentration of 400 ppm)		1,000 [ppm] for teaching facilities (*1,500 [ppm] maximum level)
Ventilation rate	Classroom, art room, computer lab (*occupant density 20-35 people per 100 m2)	10 [ft3/min/p (or cfm/p)] or 5 [l/s/p] or 0.6 [l/s, m2]
	Lecture classroom, lecture hall (*occupant density 65-150 people per 100 m2)	7.5 [ft3/min/p (or cfm/p)] or 3.8 [l/s/p] or 0.3 [l/s, m2]

Table 2: Parameters from the American building standards

By the time the student graduates from high school, the student will spend more than 15,000 hours at the school, which is the second-longest period of indoor exposure after his/her time at home (Schools for Health).

Building Bulletin 101:2018

Another interesting document is B.B. 101:2018 Guidelines on ventilation, thermal comfort and indoor air quality in schools (issued by the Education and Skills Funding Agency, U.K.) with stricter air quality objectives and CO2 as a key indicator for ventilation and IAQ. (BB 101, 2018)

- If natural ventilation is used, sufficient outdoor air should be provided to achieve an average daily CO2 concentration <1,500 ppm. The maximum concentration should also not exceed 2,000ppm for more than 20 consecutive minutes each day.
- If mechanical ventilation is used, sufficient outdoor air should be provided during the occupied period to achieve a daily average CO2 concentration <1,000ppm (max concentration should not exceed 1,500ppm for more than 20 minutes each day).

Recommended ventilation should be provided to limit the concentration of carbon dioxide in all teaching and learning spaces (Building Bulletin 101:2018).

- In a new building, the ventilation solution should be designed to achieve a CO2 concentration <1,200ppm for the majority of the time (equivalent to an outdoor concentration of 400 ppm + 800 ppm indoors) for the majority of the occupied time during the year. In a renovated building, the CO2 concentration can increase up to 1,750ppm.
- Continuous monitoring should be used to monitor and control the indoor environment, with parameters such as temperature, CO2, energy consumption, etc.
- There are also growing concerns about the indoor environmental quality (IEQ) in school buildings, as well as the need to control indoor pollutants, such as CO2.
- A significant part of outdoor air pollution caused in high-density places (cities and town centres) is supplied to the building and therefore increases pollutants indoors. This means that the incoming air must be filtered to higher levels than usual.
- A draught (high air velocity) is sometimes caused by the outdoor air supplied to the room by a mechanical ventilation system, so the acceptable supply air temperature for any room type is usually 16°C (assuming a room temperature of 21°C). The air velocity should be maintained in the range of approximately 0.12-0.25 m/s and within the temperature range of 19-27°C.

- The concept of adaptive thermal comfort is also introduced to avoid overheating in buildings so that the temperature threshold can change daily, depending on external conditions. With the main criterion that the number of hours of the predicted operative temperature exceeds the maximum acceptable operative temperature by 1K or more, it must not exceed 40 occupied hours in the period from 1st May to 30th September.
- The noise levels in a standard classroom should not exceed 35 dB(A), including outside noise. Areas for students with special educational needs (SEN) should not exceed 30 dB(A). This usually requires a combination of quiet operation of the ventilation system itself and attenuation of external noise by either extra attenuation of the ductwork in the centralised system or standalone units that incorporate high levels of acoustic insulation in the airways.

Keep in mind that there are also other interesting building bulletins for schools B.B. 87 (Guide for environmental design in schools) and B.B. 93 (Acoustics design of schools).

Passive house requirements for schools

Today, the passive house standard is often used for all types of buildings, and the research group has also developed a set of criteria for building passive house schools. (Passipedia, 2020)

Remember that there are some general requirements for a passive house: annual heating demand of 15 kWh/(m².a) (based on the total net useable area), required airtightness of n50 < 0.6 h-1 (< 0.3 is recommended), window U–value ≤ 0.85 W/(m².K) (including installation thermal bridges), annual primary energy demand ≤ for 120 kWh/(m².a) for all non-renewable energy supplied to the building, etc.

There are also requirements for passive house schools:

- A modern school should have mechanically controlled ventilation to supply fresh air to meet the criteria of acceptable indoor air quality.
- The airflow rates of the school's ventilation system should be based on health and education objectives and not on the upper limits of comfort criteria (CO2 levels of 1,200-1,500 ppm).
- The designed airflow rates should be between 15-20 m³/h/person (possibly more for the higher average age of students).
- Keeping the indoor relative humidity above ~30%.
- If the outdoor temperatures are low (lower than ~14°C), an air humidifier will have to be used and kept clean at all times.
- Fresh air requirements in a classroom are about 3 h-1 or even more if supplied by a mechanical fresh air supply.
- Ventilation systems in schools must be operated periodically or according to demand.
- Regulation of air volume is according to demand and based on the occupancy (CO2 is used as an air quality indicator).
- Passive house schools must be designed with a building envelope with a high level of thermal protection. This is the decisive and crucial criterion for schools.
- To ensure summer comfort in a passive house school, the frequency of temperatures above 25°C should be limited to less than 10% of the hours of use.
- Due to the extremely high temporary internal loads in school buildings, special attention must be paid to the comfort in summer (during hot spells using sufficient night-time ventilation – mechanical and/or free cooling – and also effective shading of the glazing).

Swegon in schools:
Jean Giono High School
Marseilles, France
Surface: 6,000 m2

Essential requirements for educational facilities

Design and planning

Schools consist of organised areas based on the purpose of teaching and learning located in one or more buildings. The basic areas are classrooms for main subjects (general subjects, computer, language, etc.), workshops (arts, science, labs, etc.) and other educational spaces (media centre, library).

The school building usually also has large educational/event spaces (auditorium and lecture hall), administration premises (for teachers, administrative staff, visitors and parents) and physical education (sports hall, gym, etc.), including facilities. There are also other places such as a cafeteria/dining and outdoor spaces to relax, among others (Hanover Research, 2011).

All school buildings result from the social actions by various relevant actors (architects, government officials, planners, departments, school boards, students, teachers, etc.), who may influence the planning and design of a building and (re)interpret the building during occupancy.

Light, temperature and air quality. Together, these elements account for half the learning impact of school design (Building better schools, Velux).

Swegon in schools:
General and Technilogical Highschool
Carquefou, France
Surface: 11,500 m2

Design needs

- Accessible and adaptable – designed to be flexible to increase potential, such as modification of the areas, easy to change layout of furniture and usage.
- Aesthetics – balanced and reflecting the values of education.
- Effective and efficient – in cost and energy, balancing design and construction costs with maintenance and operational costs.
- Environmentally and friendly – concerning building materials, equipment and products.
- Comfortable and functional – a productive school environment to provide a comfortable, safe and healthy environment for students and staff. Especially concerning indoor air quality and thermal comfort of occupants.
- Safe and sustainable – in relation to all safety issues and secure school property (human and material assets for occupants and visitors) and resilient to the environmental and climate changes.

Spacial patterns and requirements for school

School design/spatial patterns, specific characteristics for education, and outdoor conditions greatly impact school buildings. From traditional school buildings (such as one-classroom schools in the 1900s) to the educational requirements of the 21st century (open plan classrooms with spaces for collaborative tasks) require an effective strategy, and the flexibility of all spaces must still have the highest efficiency and adaptability in the future (Rigolon, 2010).

According to the US EPA, schools have up to four times more occupants than office buildings in the same amount of floor space (EPA).

There are many existing school buildings' settings (such as courtyard, block-type, cluster, town-like type). Learning methods today are based on project-based activities that actively involve students (rather than on the simple transfer of knowledge as in the past), and therefore effective flexibility in the use of spaces has an important consequence on the design of school buildings.

The population of the school is relatively high, ranging from several hundred to several thousand students. The classroom has an average floor area of 40-80 m^2. The number of students per class varies between 17 and 30, but there can be large differences between countries, see Figure 6. This equates to an average floor area per student between 2.27m^2 and 3.63m^2, without considering the floor area taken up by furniture. (Trachte et al., 2015)

Surprisingly, there is a limited building requirement for space requirements specifying classrooms' dimensions and volume (with respect to m2 – or m3 – and per student). Other research findings indicate the guided value of 0.6-3 m2/student for large lecture rooms/auditorium (Engineering Toolbox, 2003).

Also the interesting fact is that, on average, there are approximately 10-13 students per teacher in the classroom (Eurostat, 2020).

*Note that in comparison, data for office occupancy show 7-13 m2/occupant in office buildings.

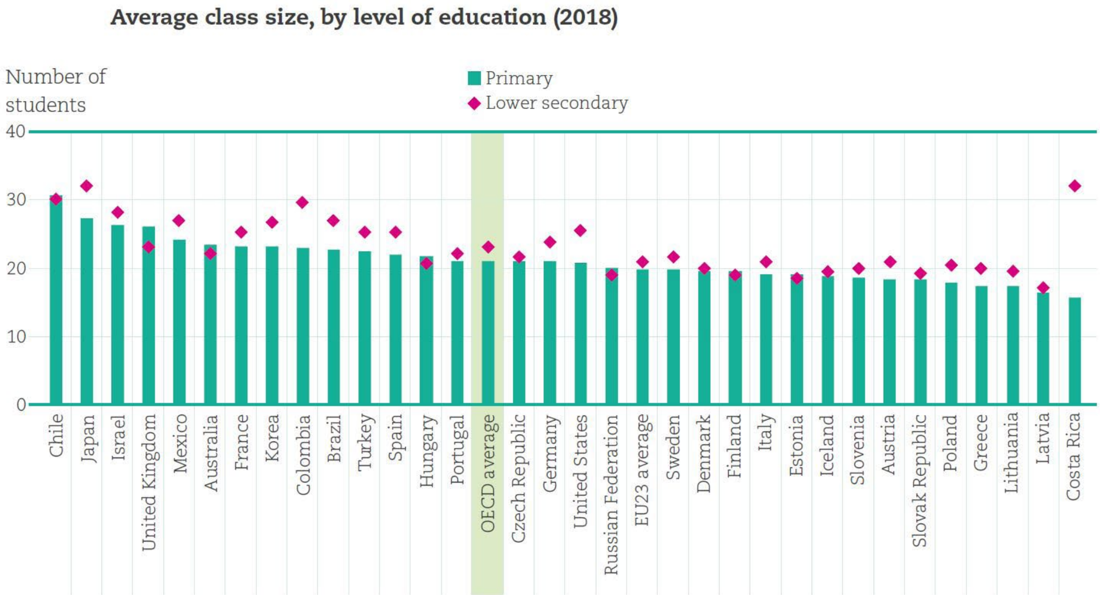

Figure 6: Average number of students in the classroom by the level of education (OECD, 2018).

Design plans versus actual usage

In modern buildings, heating, ventilation, and air-conditioning (HVAC) systems are often initially designed and based on simple occupancy schedules (and other schedules, such as lighting, heating/cooling requirements).

These design values are typically used at the initial design stage, and in the aftermath, the building systems with controls are used for fine-tuning the actual (real) occupancy based on continuous data collection (or monitoring).

However, actual occupancy data shows that, in general, classrooms are typically unoccupied more than occupied and the schools are primarily occupied during school hours and more or less empty on weekends and holidays, see Figure 7.

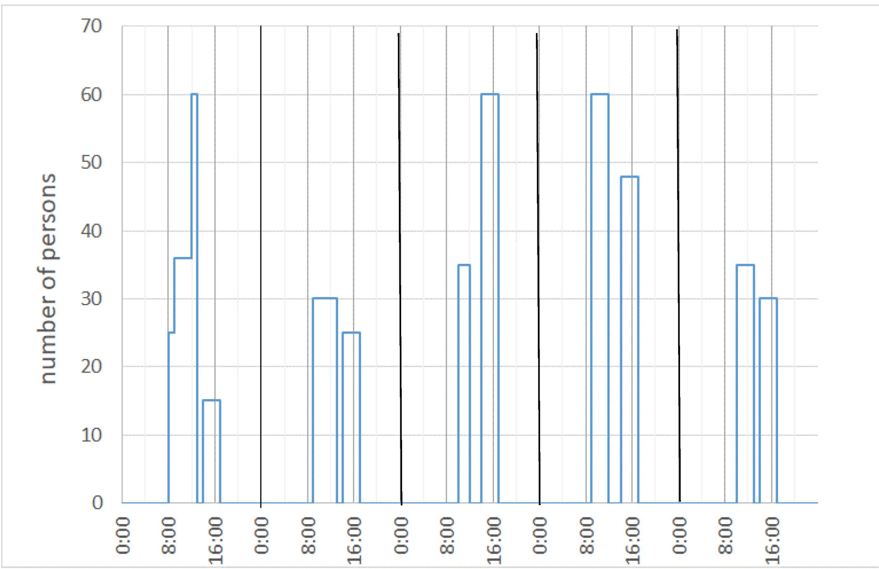

Figure 7: Actual (measured) classroom occupancy during one week (Monday to Friday) at KU Leuven in Belgium. Note that the maximum occupancy is 80 persons or 1.78 m2/person. (Breesch et al., 2019)

The use of areas in schools very much depends on: the type of school/education (typical college compared to a science school), the type of space (use of a typical classroom compared to computer labs) and the number of typical areas (usually many general classrooms compared to just one sports hall), see Figure 8.

School buildings are used approximately 30 weeks, or 200 days a year, with relatively long periods during which they are unoccupied and, in general, few activities take place on weekends and evenings, other than partial occupancy of sports halls, gyms or some cultural spaces.

Another factor that makes educational facilities somewhat unique is also the way in which they are utilised. Studies show that utilisation rates are typically low or very low. This means that at any given time, most rooms are not in use in the school building, and ventilation could be minimised. On the other hand, when in use, the demand for ventilation (and equally for a good indoor climate) is very high.

In short, the research data show that the schools have problems with high occupancy density in classrooms, which leads to overcrowding and higher ventilation requirements due to the high internal gains and significant emissions of pollutants inside (and often outside) buildings.

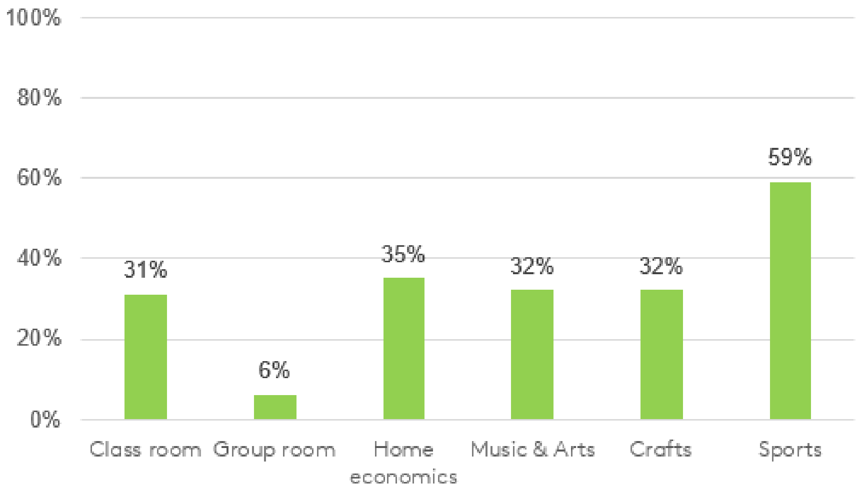

Figure 8: Occupancy rate of different room types in school buildings (Johansson, 2010).

Air replacement in schools

To ensure a good indoor environment, the school building needs to have an air replacement system – adventitious and/or controlled air movement. Air can be exchanged by infiltration (through a not-airtight building envelope), airing (manual operation of openings) and ventilation (natural, mechanical or hybrid). See more in Figure 9.

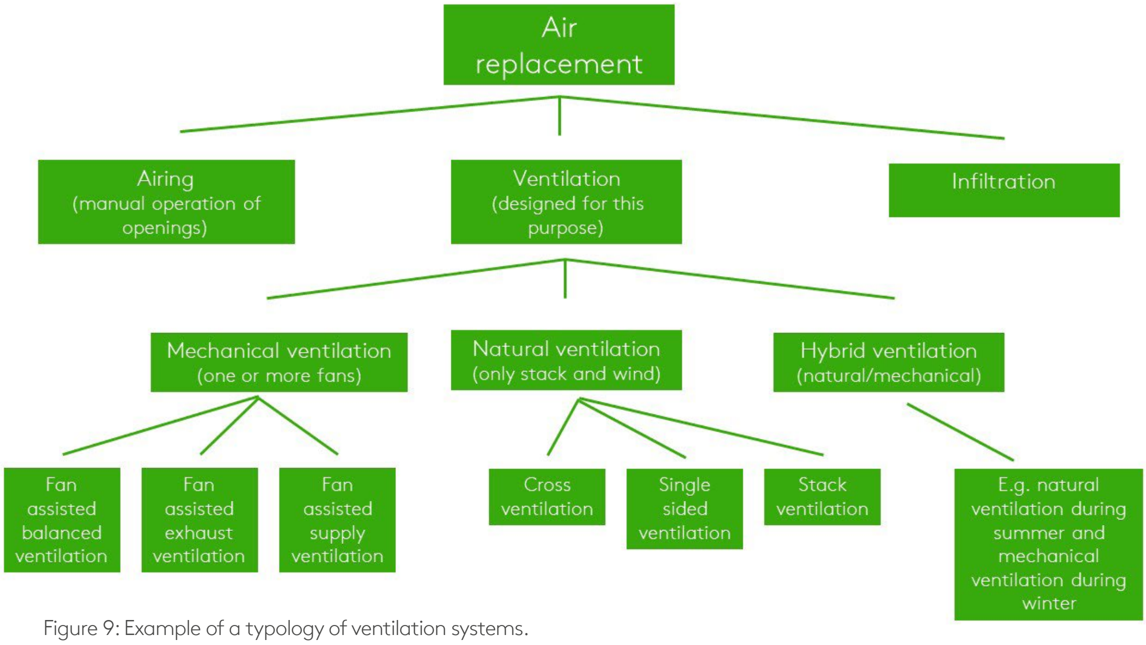

Figure 9: Example of a typology of ventilation systems.

Infiltration

Air leakage, or also known as infiltration, is usually unintentional and can cause several issues such as energy-inefficiency (25–50% of cooling/heating costs), problems with comfort (draught, moisture leakages, radon and mould), and it is almost impossible to maintain and control the required indoor environment (Younes et al., 2011).

Infiltration can be, in fact, measured by a blower-door test. For example, a good level of airtightness is required for passive house certification of n50<0.6 h-1.

The air pressure test, or the n50-value, measures the total leakage through the building envelope (describes the air changes at a differential pressure of 50 Pa). The n50 leakage rates may not be greater than 0.6 h-1 to comply with the passive house certification criteria (according to Passivhaus Institut).

Reducing infiltration effectively requires a continuous air barrier system to create an airtight building envelope, etc.

There are many measurements of average infiltration in classrooms that show a range from below 0.6 h-1 (modern school building), and from 1.1-4.6 h-1 (newer school buildings) and up to 7-9 h-1 (standard school buildings).

Natural ventilation

Airing, also known as natural ventilation, is a traditional technique for replacing indoor (stale) air with outdoor (fresh) air. Natural ventilation is the intentional exchange of air through openings (windows/doors, air vents, roof stacks/chimneys, etc.). The operation of openings can be manual, automated or both. The driving force of natural ventilation is the wind and the stack effect. This includes single-sided ventilation, cross ventilation or stack ventilation systems.

Natural ventilation depends on the architectural design, the building envelope, the role of occupants (how often they open or do not open windows), and the outdoor and indoor environment.

The window opening for airing can pose issues when the outdoor conditions are not good either from air pollution, cold/hot weather, noise from outside, wind, etc. It is also difficult to control the amount of air exchange, i.e. to maintain the indoor environment because airflows are more complex and difficult to predict. Part of the natural ventilation can also be free cooling, usually used at night-time to cool down the school building to reduce overheating in the summer.

For natural ventilation to be effective, the external air supply to all teaching and learning areas should be at least 3 l/s per person, a minimum daily average of 5 l/s per person and the ability to achieve a minimum of 8 l/s per person at any occupied time (BB 101, 2018).

Research shows that windows could be used to provide enough air to meet indoor air quality requirements if the outside temperature was above 8°C – and the wind speed was below 10 m/s (Angelopoulous, 2017).

When using natural ventilation (at least 4 l/s/p), the research shows that the appropriate ventilation is achieved only for about a quarter of the year (24%), (Duarte et al., 2017).

Mechanical ventilation

Air replacement, or mechanical ventilation, is the most effective way to provide fresh, filtered air to classrooms. Ventilation is used to reduce exposure to air pollutants that affects human response, and mechanical ventilation can only be a part of any solution to reduce the exposure, see Figure 10. Exposure can also be reduced in other ways, including source control, i.e., reducing emissions from products used in buildings or capturing pollutants at their source, filtration and air cleaning.

Instead of these solutions, mechanical ventilation can be used together with them, or once other solutions are in place, and mechanical ventilation is the last way to improve indoor air quality, to reduce the risks associated with exposures that could not be reduced by other means. All is based on the assumption that the air supplied to the interior is clean, and this precondition must always be met. (Wargocki, 2021)

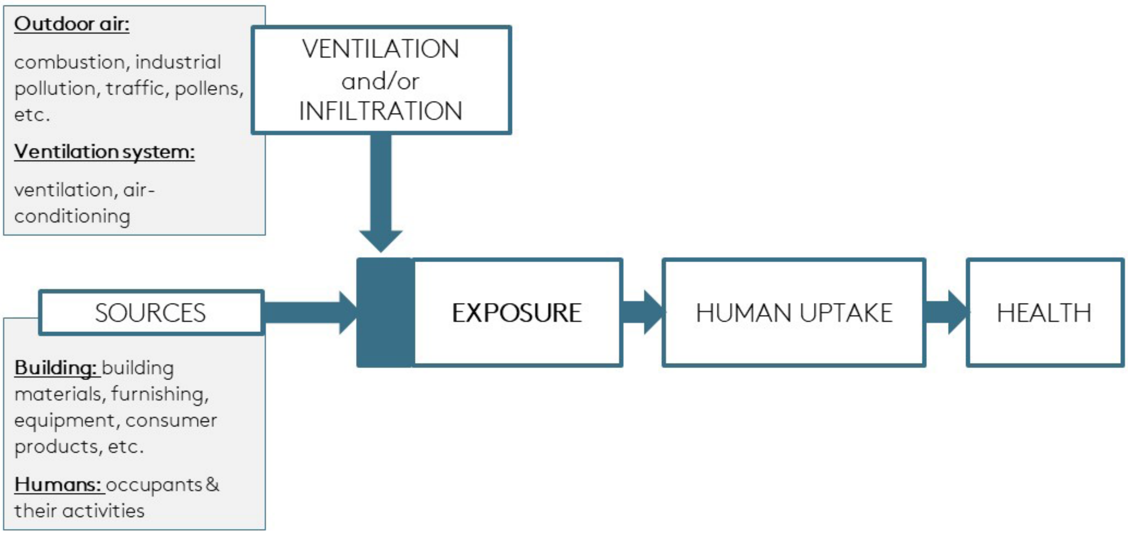

Figure 10: Mechanical ventilation as a mediating factor, not a cause (Wargocki, 2021).

Mechanical ventilation ensures a controlled flow of supply and extract air, enabling an essential control of room temperature, humidity and air quality. Temperature, relative humidity, and CO2 (that could be coupled with VOCs) sensors detect changes in pollution levels and automatically adjust the fan speed to ensure reliable air quality control.

There are many types and systems of mechanical ventilation – centralised or decentralised, displacement or zone-based, and constant or variable or demand-controlled (CAV, VAV, DCV). Mechanical ventilation (HVAC) is a complex system and has many components such as heat recovery, exhaust, air filters, blowers, fans, ducting, sensors, control system, etc.

Mechanical ventilation with heat recovery can recover up to 92% of the energy that would normally be lost through other types of air replacement.

Swegon in schools:
Olympus De Gouges School
Paris, France
Surface: 12,600 m2

Facts and findings from research

There is a unique aspect to children and schools, meaning that children's developing bodies may be more susceptible to environmental exposures than those of adults. Children breathe more air, eat more food and drink more fluids in proportion to their body weight than adults. That is why air quality in schools is particularly of concern. The proper delivery of indoor air is more than a question of 'quality'; it encompasses safety and stewardship of the investment in students, staff and facilities.

Many factors can influence students' academic achievement, but the indoor environment quality (IEQ) in the classrooms can positively impact teaching and learning, which increases the likelihood of better student academic achievement (see Figure 11)

Children are not little adults. They have unique needs, sensitivities and vulnerabilities. And it is becoming increasingly evident that the current school building conditions may not sufficiently protect the students' developing bodies and minds (Schools for Health).

Many schools do not provide students with a good indoor environment; they fail to provide a sufficient outdoor air supply rate and often are too warm in the summer months. Research findings indicate indoor air pollution, excessive levels of CO_2, inadequate daylight levels, elevated noise levels and poor ventilation. In the context of schools – beyond the schools four walls – there are also other factors influencing the students, such as outdoor air pollution, noise and location from outdoor sources. Several other factors affect the school air resulting from ageing infrastructure, inadequate maintenance of equipment, etc. Many problems can be found in old and also brand newly constructed school buildings.

Figure 11: Conceptual framework for the influence of indoor environmental conditions on academic achievement in schools (Brink et al., 2020).

Indoor environment in schools

Indoor environmental problems can be subtle and may not always have easily recognisable effects on health, well-being or performance. The indoor environment in schools is all about the quality of indoor air (temperature, relative humidity, CO_2, VOCs, and other) and other related conditions (thermal comfort, light, noise, etc.). However, in schools, there are also various pollutants from buildings materials (chemicals, cleaning supplies for art and science, etc.) and local problems such as mould, asbestos, radon, etc.

The indoor environment in schools (air quality and thermal comfort) affects schoolwork and is thought to cause discomfort sensations, distract attention, reduce arousal, as well as motivation (see Figure 12).

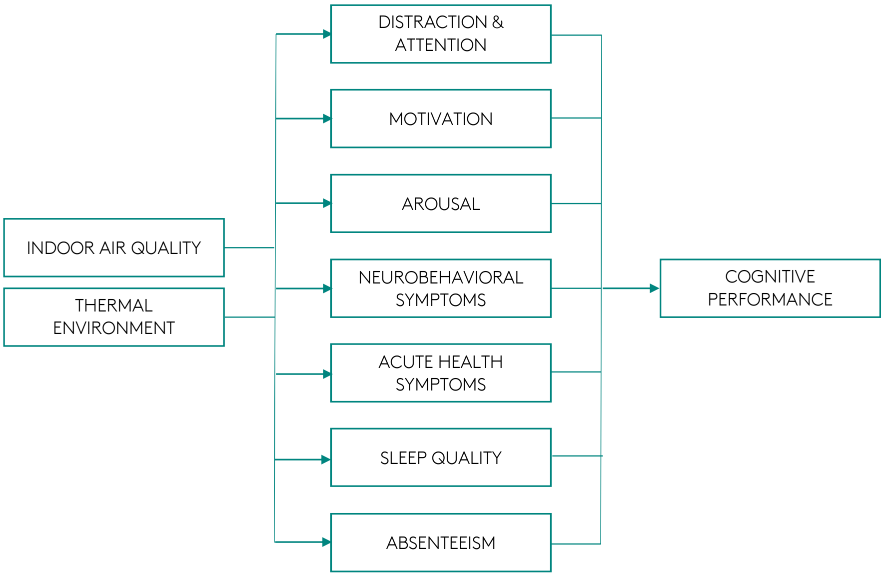

Figure 12: The mechanism by which mental work is affected by indoor air quality and thermal environment (Wargocki et al., 2016).

Temperature and relative humidity (T, RH)

- A survey of more than 4,200 students and 134 principals representing 297 schools in Finland examined the associations between school's building attributes, IEQ, and self-reported upper respiratory symptoms. The researchers noted that students' reports of upper respiratory symptoms were significantly associated with principals' reports of unsatisfactory (too hot or too cold) classroom temperatures during the heating season (Toyinbo et al., 2016).
- Warmer classroom temperatures were also associated with students' perceptions of poor air quality, self-reported symptoms of stuffiness, headache, eye, nose, throat symptoms, fatigue, and difficulty breathing (Turunen et al., 2014; Bidassey-Manilal et al., 2016).
- Another study of 10-12 years old children observed that the lowering classrooms temperatures from 25 to 20°C (77 to 68°F) during warm weather was associated with significant improvements in students' speed on arithmetic and language-based tests. The children reported experiencing the indoor air as much fresher. Based on these findings, the researchers calculated a dose-response relationship indicating that each 1°C (1.8°F) reduction in temperature could translate into a 4% improvement in students' performance speed (Wargocki et al., 2013).
- A study of more than 3,000 schoolchildren in 140 classrooms of fifth-graders in the southwestern United States also reported that each 1°C decrease in temperature within the range of 20–25°C (68–77°F) was associated with an additional increase of 12–13 points in students' average test scores in mathematics. Science and reading test scores showed effects of a similar magnitude but with higher variability. The researchers concluded that students' academic performance could significantly benefit from maintaining adequate thermal comfort in classrooms (Haverinen-Shaughnessy et al., 2015).
- The report reviewed findings from more than 200 scientific studies. Some findings included: a survey of 75,000 high school students in New York City that found students were 12.3% more likely to fail an exam on a 32°C (90°F) day versus a 24°C (75°F) day.

Carbon dioxide concentration (CO_2)

- Normal breathing of a child aged 7-9 years old generates 14 litres of CO2 per hour, which is 50% lower than the amount produced by a teenager (in conditions of moderate physical activity, a 15 years old student can release up to 85 l of CO2 per hour). High CO2 concentration makes classrooms uncomfortable.
- Findings from studies with 20 or more classrooms show CO2 values ranging from 1,400 ppm to 5,200ppm, see Figure 13 (Fisk, 2017).
- CO2 concentration above 1,000ppm could cause lack of concentration, blurred vision, sweating, restlessness, vomiting, flushed skin, and even panic attacks.
- Adverse effects have been reported for elevated CO2 levels in classrooms, including decreased satisfaction with IAQ (Chatzidiakou et al., 2014) and symptoms of wheezing among children in day-care centres (Carreiro-Martins et al., 2014).
- With similarly poor CO2 levels (and ventilation rates) in school buildings, students have been observed to experience greater fatigue and impaired attention span (Chatzidiakou et al., 2012); poorer performance in concentration tests (Dorizas et al., 2015); and lower levels of focus among university students during lectures, see Figure 14 (Uzelac et al., 2015).

Volatile organic compounds (VOC)

- VOCs are not perceptible by smell but can negatively affect health even at concentrations lower than 3 µg/m3.
- Indoor exposure to VOCs, such as formaldehyde (present in many adhesives, glues, polyurethane, foam insulation, particleboard, plywood, pressed wood, fiberboard, carpet backing, and fabrics), is associated with asthma-like symptoms in school children (Annesi-Maesano et al., 2013) And as well as with eye, nose, and throat irritation; headaches; nausea; and more (EPA, 2016).
- Particulate matters (PM2.5 and PM10) represent additional pollutants. High indoor concentrations of PM2.5 and PM10 can cause cardiopulmonary diseases.

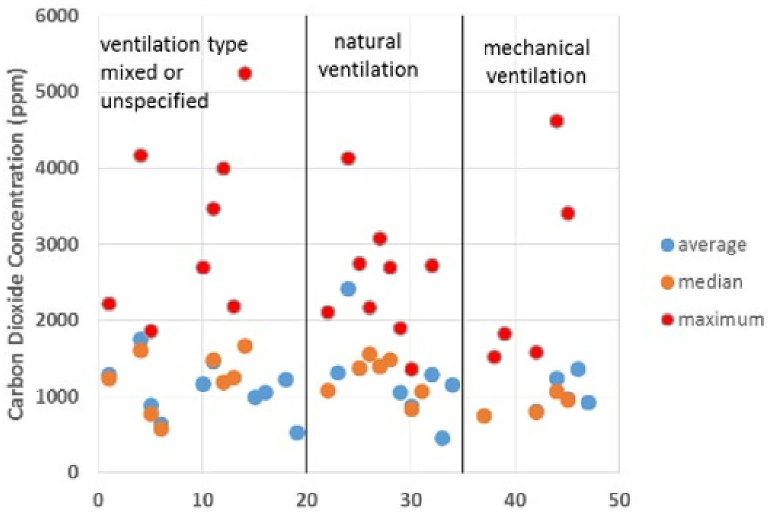

Figure 13: Measured CO2 concentration from studies with 20 or more classrooms – time-average (Fisk, 2017).

Comfort, performance and ventilation

Different types and rates of ventilation

- Classroom ventilation rates are directly associated with students' academic achievements. Measurable progress in maths and reading (assessed through standardised tests) may be observed when improving IAQ in the classrooms.
- However, classroom's internal factors negatively affecting IAQ seem to have a higher impact than pollutants coming from outside.
- Types of ventilation systems (natural, mixed and mechanical) also influence CO2 and ventilation rates, see Figure 13. Consistent with the high reported CO2 concentrations, many studies report average or median ventilation rates in the range of 3 to 5 l/s (6 to 11 cfm) per occupant, with one average as low as 1 l/s (2 cfm) per occupant (Fisk, 2017).
- Lower ventilation rates have been linked to more missed school days caused by respiratory infections (Toyinbo et al., 2016); greater prevalence and incidence of 'sick building syndrome' symptoms (Chatzidiakou et al., 2015).
- Lower ventilation rates may lead to increased asthmatic symptoms, nasal patency, and risk for viral infections (Chatzidiakou et al., 2012); and the transmission of airborne infectious diseases chickenpox, measles, and influenza (Luongo et al., 2015).
- Researchers observed a link between ventilation rates and performance on standardised tests in math and reading, estimating that each 1 l/s/p increase in ventilation rate was associated with an expected increase of 2.9% and 2.7% in math and reading scores, respectively (Haverinen-Shaughnessy et al., 2011).
- The link between ventilation and achievement was substantiated in another study in which students in schools that failed to meet a minimum ventilation rate of at least 6 l/s/p were found to be more likely to perform poorly on mathematics tests (Toyinbo et al., 2016).
- Findings from 11 studies show that performance generally improved a few percent, to as much as 15%, with increased ventilation rate or with lower CO2 concentration. Typically reported improvements in performance with increased ventilation rates range from a few percent up to as high as 15% (Fisk, 2017).

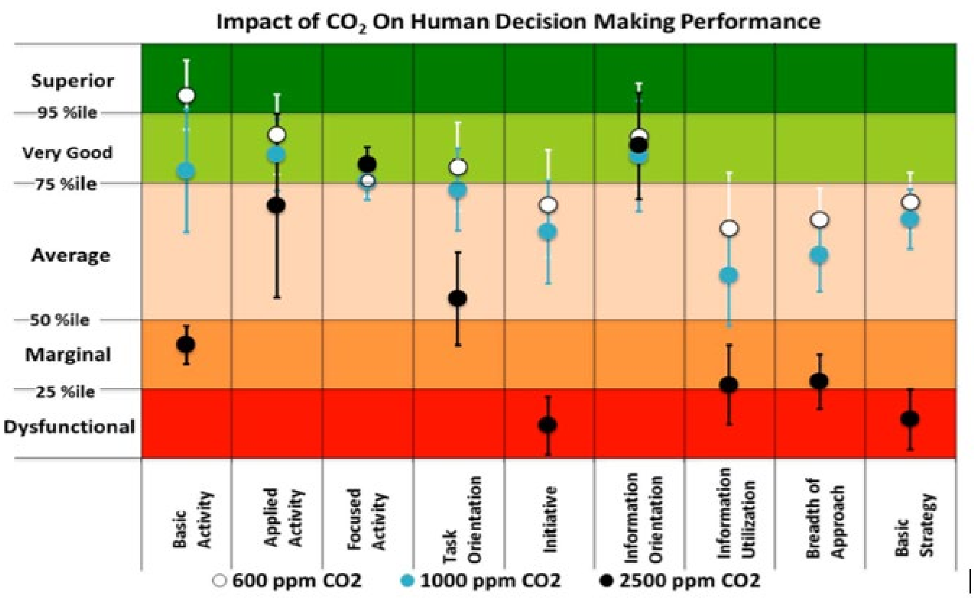

Figure 14: Impact of CO2 on human decision-making performance - for adults (Satish et al, 2012).

- Doubling the outdoor air supply rate (from 3 to 9.6 l/s/p) would improve schoolwork performance in terms of speed by about 8% overall and by 14% for the tasks that were affected significantly, with only a negligible effect on errors, see Figure 15, (Wargocki et al., 2016).
- Measured CO2 levels in fifth-grade classrooms in 100 schools in the USA and showed that poor ventilation reduced the number of students managing to pass language and mathematics tests. A linear relationship was found, suggesting 3% more students passed the tests for every 1 l/s per person increase in ventilation up to 7 l/s per person (Haverinen-Shaughnessy et al., 2011).
- Another study in fifth-grade classrooms in 70 schools in the USA showed that mathematics scores improved by about 0.5% for every 1 l/s per person increase in ventilation rate in the range from 0.9 to 7 l/s per person (Haverinen-Shaughnessy et al., 2015).

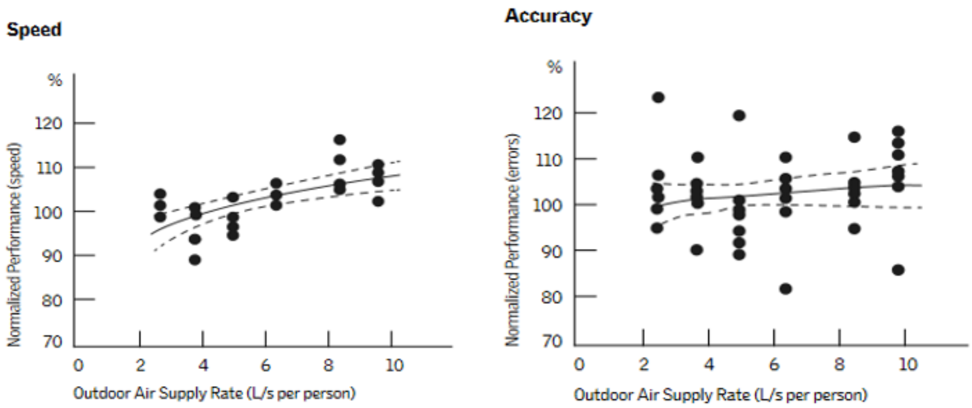

Figure 15 (a,b): Student performance versus ventilation rate based on a study in Denmark. Performance was based on the speed (a) and accuracy (b) of completing various schoolwork tasks (Fisk, 2017).

Daylight, lighting and views outside

- Many studies on the health impacts of daylight have reported evidence for benefits, including improvement of vision, better sleep quality, and reduced symptoms of eyestrain, headache, and depression.
- The Clever Classrooms study conducted by the University of Salford in the U.K., concluded that good daylight helps create a sense of physical and mental comfort: its benefits more far-reaching than merely an aid to sight (Barrett et al., 2015).
- Access to good-quality and task-appropriate lighting at school is important because many classroom activities — like reading and writing — are visually oriented and form student learning. Oral reading fluency (measured as words read correctly per minute) is an important precursor in the development of reading comprehension.

A study of 172 US third-grade students tested the effect of high-intensity (1,000 lux & 6,500 K) glare-free 'focus' lighting on students' oral reading fluency performance for a full academic year.

By mid-semester, students in the 'focus' lighting showed a higher percentage increase in oral reading fluency performance compared with students in 'standard' lighting (500 lux & 3,500K) classrooms (36% versus 17%), (Mott et al., 2014).

- Children are more sensitive to light exposure than adults because they have larger pupils and have significantly greater light-induced melatonin suppression, with young adolescents having greater circadian-system sensitivity to light exposures than older adolescents (O'Hagan et al., 2016).
- Low levels of light indoors combined with less time spent outdoors have been associated with increased risk for near-sightedness (myopia). And studies also show that increasing children's time spent outdoors may reduce the risk of developing myopia or slow its progression (Kocak et al., 2015).
- A study by the Sorbonne University covering 13 European countries with 2,387 children participating concluded that academic performance can increase by up to 15% when students work in classrooms with larger windows – due both to increased daylight and a better view of the outside world (Maesano, 2016).
- In children, higher levels of average daily daylight exposure have been associated with reduced weekday and weekend sedentary time and increased physical activity levels on the weekends (Aggio et al., 2015).

Control of sound and noise

- In school, acquisition of knowledge, skills and social norms are very largely dependent on oral communication. Students must be able to hear, listen to and understand the teacher's voice. Given how important it is for students to learn to manage their own noise, so as not to disturb the group, control of sound and noise in the school enables an acoustic environment of suitable quality for the children's physical and intellectual development. Teaching establishments are, thus, buildings whose acoustic environments are intrinsically linked to their functional quality.
- Chronic exposures to internal and external sources of noise can lead to deficits in test scores. Noise exposures are often determined by location, such as proximity to major roadways or airports, but internal sources of noise can be equally important, see Figure 16.
- An optimal acoustic environment is fundamental for comfortable understanding during prolonged periods of attention. Learning is easier and less tiring and the teacher is more effective and less stressed (Deoux, 2010). Two important aspects of hearing well in a classroom are low background noise (unwanted sounds) and short reverberation time (length of time sound lingers in a room), (Acoustical Society of America, 2010).
- The Acoustical Society of America recommends maximum background noise exposure levels of 35 dB(A) for unoccupied core-learning spaces in permanent school buildings and a maximum reverberation time of 0.6–0.7 seconds, depending on classroom volume(Acoustical Society of America, 2010).

A growing body of evidence shows that noise and reverberation conditions in classrooms vary and often fail to meet [the] recommended standards (Lewis et al., 2014).

- Children under age 15 are more sensitive to difficult listening conditions because they are still developing mature language skills. Compared with adults, children have more difficulty with complex listening tasks (Sullivan et al., 2015).
- Noise interference in the classroom can impair children's speech and listening comprehension as well as their concentration, understanding of verbal information, reading comprehension, and memory (Stansfeld et al., 2015).
- Noise has both auditory effects, such as hearing loss, and non-auditory effects, such as annoyance, sleep disturbance, stress, hypertension, and effects on performance. International studies of the effects of noise show diverse health outcomes in students, including increased fatigue, stress, and irritability (Seabi et al., 2015).
- Noise has also been found to affect reading and writing adversely; research suggests that chronic exposure to noise affects children's cognitive development (Klatte et al., 2013).
- For example, HVAC systems have been identified as a common source of background noise in classrooms. In a study of 73 elementary schools in Florida students in schools cooling with the noisiest types of HVAC systems were found to underperform on student achievement tests compared with students taking tests in schools with quieter systems (Jaramillo, 2013).
- Furthermore, ambient noise annoyance has also been associated with poorer performance on mathematics tests among urban high school students (Zhang et al., 2015).

Decibel (dB)	
160	
150	
140	Jet aircraft
130	
120	Jackhammer
110	
100	Industry noise
90	Loud speaker
80	
70	Open plan office
60	Conversation
50	Home (living room/kitchen)
40	Rain noise
30	Bedroom
20	
10	Leaves in soft wind
0	

Figure 16: Typical sound levels (Building better schools, Velux).

Beyond the four walls - context matters

In addition to the four walls of the school building, many environmental and social contexts can adversely affect students' well-being and influence their academic potential. There are also many other factors influencing students' health and absence, for example: the proximity to heavy and noisy traffic and industrial and chemical facilities, among others, see Figure 17.

Outdoor environmental pollution and nearby sources

- CO2 can also arise from outside the school, being widely produced by the combustion of fossils or road traffic and other anthropogenic activities responsible for the emissions of nitrogen dioxide (NO2).
- The research showed a better trend (up to + 13%) in cognitive development indicators – such as attention and memorisation capacity – in those schools with the lowest levels of traffic-related ultrafine particulate, carbon particles and NO2.
- Emissions of nitrogen dioxide NO2, being widely produced by combustion of fossils or road traffic and other anthropogenic activities, can cause respiratory problems in school children (i.e. asthma exacerbations, increased susceptibility to viral infections etc.).
- The natural emission of gas radon comes from underground cavities, which typically accumulates in poorly ventilated classrooms and can affect lung function in chronic exposures.
- Additionally, exposure to diverse traffic-related fine particles (e.g., motor vehicle exhaust and road dust) were associated with an increased likelihood of wheezing, shortness of breath, inhaler use and asthma symptoms in children with asthma (Gent et al., 2009).
- Schools located near airports are a unique subset of schools because of the impacts of aircraft noise. Aircraft noise is a common source of noise annoyance; it can affect an individual's quality of life and causes irritation, discomfort, distress, or frustration, headache and stomach-aches (Seabi, 2013).
- In schools exposed to large amounts of aircraft noise, 86% of teachers reported keeping the windows closed even in warmer weather and 38% indicated they undertook fewer outdoor activities with their students (Bergstrom et al., 2015).

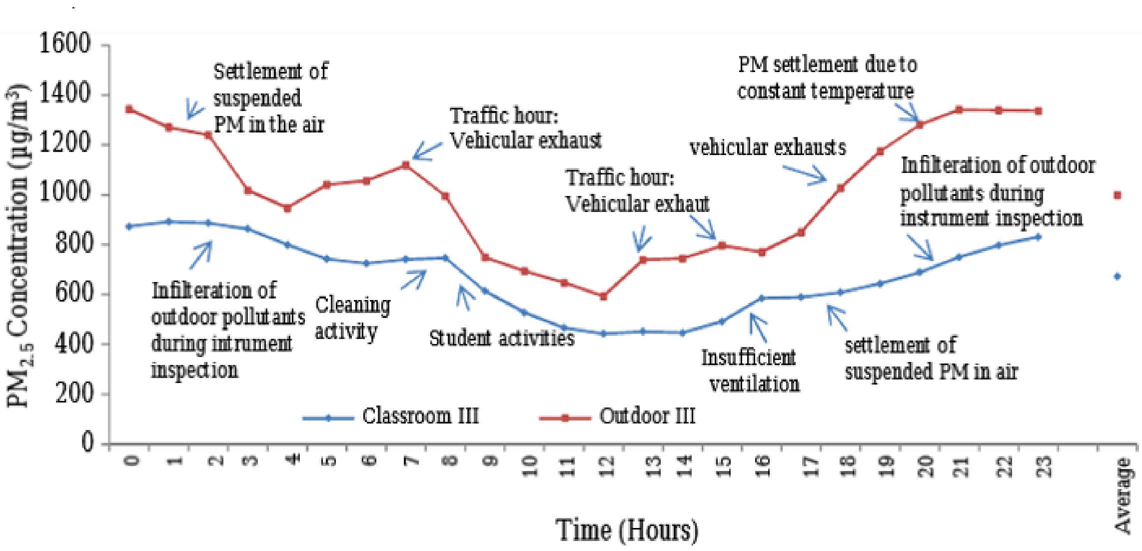

Figure 17: PM2.5 average concentrations for 24 hours in the classroom with occupancy (7:00-17:00). Note that the air change rate was 0.43 h-1 with doors closed and 1.1 h-1 with doors opened (Aziz et al., 2015).

Absenteeism from schools

- Elementary school students are more likely to be absent because of health reasons or circumstances beyond their control (i.e., asthma, transportation, or unstable housing).
- Higher outdoor air pollution levels around schools have been linked to increased rates of chronic absenteeism (MacNaughton et al., 2017).
- Nearly 1 in 13 children of school-age has asthma, the leading cause of school absenteeism due to chronic illness. Asthma accounts for 13.8 million missed schools days each year (Centres for Disease Control and Prevention, 2013).
- There is substantial evidence that indoor environmental exposure to allergens, such as dust mites, pests and moulds, plays a role in triggering asthma symptoms. These allergens are common in schools (Centres for Disease Control and Prevention, 2015).
- The strongest study, which followed 162 classrooms for two years, found a 1.6% decrease in absence for each 1 l/s (2 cfm) per person increase in ventilation rate (Mendell et al., 2013).
- Another study found absence decreasing by 0.4 days per year for each 100 ppm decrease in CO2 concentration (Gaihre et al., 2014).
- A study in 434 American classrooms found student absence decreased by 10-20% when the CO2 concentration decreased by 1,000 ppm (Shendell et al., 2004).

Environmental psychology and other factors

- Researchers in environmental psychology (biophilic design) have become increasingly interested in the restorative effects of visual access to natural environments (Li et al., 2016).
- Students in classrooms with access to green views through their windows have been observed to experience significantly faster recovery from stress and mental fatigue and performed significantly higher on tests of attentional functioning, compared to students in classrooms with no windows or windows looking out onto other buildings facades (Li et al., 2016).
- Social factor – keeping children in school – is essential to their education, and educational attainment has a more significant impact on long-term health than childhood socioeconomic status. Increased educational attainment has been shown to reduce gaps in health and life expectancy associated with disparate socioeconomic status. (Montez et al., 2014).

Conclusion

Health in schools

Many decades of scientific research have led to numerous insights into how the indoor environment affects students' well-being and health. These findings provide robust public health evidence that environmental exposures in school buildings can impact students' thinking and performance. Studies also show that environmental factors in and around the school building can interact in complex ways. The school building itself, where students spend a significant portion of their childhood, therefore represents an excellent opportunity to intervene and protect the health of children – the most vulnerable citizens.

Children's time in schools is critical to their physiological, social and emotional growth and development, as children are more susceptible to many indoor conditions than adults (Schools for Health).

Effects of the indoor environment on learning

Indoor environmental quality (IEQ) inside the building is a key element in making the building suitable for learning and work. Over the last decades, the existing gathered evidence has shown that the vast variety of IEQ´s influence on educational processes and outcomes. Good IEQ in educational buildings increases students´ academic achievement, i.e. their productivity, efficiency and learning. It also affects the student's efficiency, concentration, self-confidence, learning outcomes and absenteeism of students, etc. In addition, IEQ can also affect the quality and effectiveness of teaching, among others. Overall, the effects of IEQ in schools can offer enormous benefits – in terms of increased academic performance, students´ good health and the prospective future of a growing population.

The new paradigm for ventilation in schools

Ventilation is and will continue to be one way to safeguard the right to healthy indoor air in schools. Criteria for schools should consider the different effects on building occupants and ensure that the building systems are designed to fulfil their needs and used effectively. The necessary paradigm change should concern new design requirements, new ventilation solutions and new ways of designing, operating and maintaining energy- and cost-effective methods. Also, the cost of the negative consequences of poor ventilation for health, performance and socioeconomic well-being need to be at the centre of all attention. The new paradigm for ventilation in school buildings should have every single building occupant (students, staff and others) at the centre of all recommendations and actions.

Dynamic relationships

In the past, the world and understanding of education were quite different from today. The school buildings were lit by the sun, heated by massive oil and coal furnaces. The children were to be seen and not heard. The schools were designed for a smaller number of students, the teaching of single subjects and with less emphasis on adaptability. The increased number of students with a greater variety of taught subjects means that effort needs to be made for multi-purpose and flexibility of all spaces.

Building's systems will need to be able to adapt to future building changes – the schools will have to stand the test of time and integrate with future building modifications, taking into account lifetime costs, not just capital cost. All will be based on demand and occupancy – all systems will have to deal with variable occupancy, swiftly adapt to various parameters, and demand spatial requirements. And the operation of all school buildings and building systems will be based on monitoring, manageability and predictability.

Healthy buildings, healthy people and healthy children (Schools for Health).

Sustainability and climate education

Education is also an essential element of the planet's sustainability and the global response to climate change. It helps young people understand and address the impact of global warming, encourages changes in their attitudes and behaviour, and helps them adapt to climate change trends. There must be effective ways for schools to teach climate change education so that children can be better prepared to deal with future environmental challenges. It is all about the knowledge, attitude and behaviour of everyone and for everyone.

Education transforms lives (UNESCO).

The future for education and schools

Education is becoming increasingly important around the world. The global picture shows estimates and projections of the total world population by the level of education. It shows that more and more educated people will inhabit our world. While in the 1970s, there were only around 700 million people in the world with secondary or post-secondary education, by the 2100s this number is predicted to be 10 times larger. As a result of the growing population and the growing urban and globalised world, education will flourish, and more resources would be needed for education worldwide. Therefore, greater attention will also need to be paid to ensure that the indoor environments in schools are adequate for children's health and their ability to learn. The future needs healthy and smart school buildings with a good indoor environment for healthy air in schools.

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