School of the Future

IMPROVED INDOOR ENVIRONMENTAL QUALITY

Retrofit guidelines towards zero emission schools with high performance indoor environment

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Front page illustrations

Top from left:

Tito Maccio Plauto Scuola, Cesena, Italy.

Solitude Gymnasium, Stuttgart, Germany. Photo: Ingenieurbüro Fisch.

Brandengen skole, Drammen, Norway.

Hedegårdsskolen, Ballerup, Denmark.

Bottom from left:

Façade of a meeting room from the inside of Fraunhofer IBP, Germany. Photo: S. Steiger.

Classroom of Maccio Plauto Scuola, Cesena, Italy.

Borgen skole, Asker, Norway. Photo: K. Buvik.

Outside air supply in Tanga School, Sweden. Photo: MEDUCA [5].

Disclaimer

INTRODUCTION

OBJECTIVES

The purpose of this booklet is to provide designers and planners with retrofit guidelines for concepts and technologies regarding energy efficiency and good indoor environment quality in school buildings - from simple, but significant energy reduction and indoor environment improvements up to the final target: Zero emission schools.

The objective of this work is to develop an overview on the available building and system retrofit technology systems for energy efficient school buildings including their impact on the energy performance and indoor environment quality and their economic feasibility. The intended audience for the report are designers and planners of school buildings. The idea is that municipalities all over Europe can use the guidelines and find useful technologies for their specific school buildings. In addition, the work constitutes background knowledge for further work in the "School of the Future" project, especially the extension of the information tool.

The energy efficient building has many benefits with regard to indoor conditions and comfort, besides the obvious benefit of low energy consumption if it is designed carefully. These benefits relate to thermal and acoustic indoor climate as well as indoor air quality.

The indoor climate parameters included and described in this guideline are the following:

1. Thermal indoor climate
2. Indoor air quality
3. Lighting conditions
4. Acoustics and noise protection.

Besides the guideline on Improved Indoor Environmental Quality 3 guidelines on Building Construction Elements, Building Service Systems and Concepts for Zero Emission Schools will be written.

"SCHOOL OF THE FUTURE" PROJECT

"School of the Future" is a collaborative project within the 7th Framework Programme of the European Union in the energy sector. It started in February 2011 and will run for 5 years. The aim of the "School of the Future" project is to design, demonstrate, evaluate and communicate shining examples of how to reach the future high performance building level. School buildings and their primary users: pupils – the next generations – are in the focus of the project. Both, the energy and indoor environment performance of 4 demonstration buildings in 4 European countries and climates will be greatly improved due to holistic retrofit of the building envelope, the service systems, the integration of renewables and building management systems. The results and the accompanying research and dissemination efforts to support other actors dealing with building retrofits can lead to a multiplied impact on other schools and on the residential sector, since the pupils can act as communicators to their families. Tailored training sessions are aimed to improve the user behaviour and the awareness of energy efficiency and indoor environment.

Zero emission buildings are a main goal in various country roadmaps for 2020. The demonstration buildings within the project may not completely reach this level as the aim of the call is cost efficiency and multiplication potential. The retrofit concepts will, however, result in buildings with far lower energy consumption than in regular retrofits with high indoor environment quality - thus leading the way towards zero emission. They can be considered as schools of the future. Results from national examples of zero emission schools will complete the information used for developing the deliverables such as guidelines, information tools, publications and a community at the EU BUILD UP portal.

The project is based on close connection between demonstration, research and industry represented by the "design advice and evaluation group". The proposal idea was introduced at the E2B association brokerage event with high interest which results in a consortium including well-known partners from the building industry.

PARTNERS WITHIN THE "SCHOOL OF THE FUTURE" PROJECT

Country	Partner
Germany	Fraunhofer Institute for Building Physics (Fraunhofer IBP, Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung), Coordinator
	Landeshauptstadt Stuttgart
Italy	ENEA (Agenzia Nazionale Per Le Nuove Tecnologie, L'Energia E Lo Sviluppo Economico Sostenibile)
	Comune di Cesena
	Aldes Spa
Denmark	Cenergia Energy Consultants ApS
	Aalborg Universitet - SBi
	Ballerup Kommune
	Saint-Gobain Isover a/s
	Schneider Electric Building Denmark AS
Norway	Stiftelsen SINTEF
	Drammen Eiendom KF
	Glass og Fasadeforeningen

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THERMAL INDOOR CLIMATE

The overall thermal sensation relates to the air temperature, the mean radiant temperature, the air velocity, the humidity and the activity and clothing of the persons in the room. Besides these overall thermal conditions, the local thermal conditions like draught and radiation asymmetry influence the overall thermal comfort.

Draught is defined as an unpleasant air movement, which leads to a local cooling of especially unclothed body surfaces. The draught risk is determined by air temperature, air velocity and its turbulence. Radiation asymmetry comes from single-sided cold or hot surfaces like windows or heating/cooling elements. They can cool or warm parts of the human body and therefore cause persons feeling uncomfortable. The same effect can be seen with cold or hot floors, not through radiation, but through direct contact with the surface.

Requirements for thermal comfort in winter conditions

Required operative temperature in winter

The operative temperature is a quite simple, but good indicator for overall thermal comfort, which takes into account the two main heat exchange mechanism between persons and surrounding, convection and radiation. It is calculated in typical indoor climate as the average of the air temperature and the mean radiant temperature from surrounding surfaces. With a typical winter clothing (1.0 clo) and activity of persons in school (1.2 met) the operative temperature in school should be between 20 °C and 24 °C for new and modernised buildings and a normal level of expectancy for thermal comfort [1]. For high energy efficiency it will be better to preheat the room to the lowest comfort temperature: 20 °C, especially because of quite high heat emissions from up to 30 persons in a room, who are heating up the room further during occupancy.

The achievement of thermal comfort in existing buildings is often determined in winter based on local discomfort parameters: radiation asymmetry and draft risk caused by untighten envelopes, low surface temperatures and mechanical or window ventilation.

Avoid radiation asymmetry caused by cold surfaces

A low mean radiant temperature requires a high air temperature to get the same operative temperature i.e. the same overall thermal comfort. Because the mean radiant temperature is primarily based on the surface temperature of the room and the position of the person in the room, a building with a low level of insulation requires a high air temperature due to its low surface temperature, especially for places next to the building envelope.

The following figure shows the required air temperature at 1 m distance from the external envelope, depending on the window's surface temperature, calculated for an operative temperature of 20 °C.

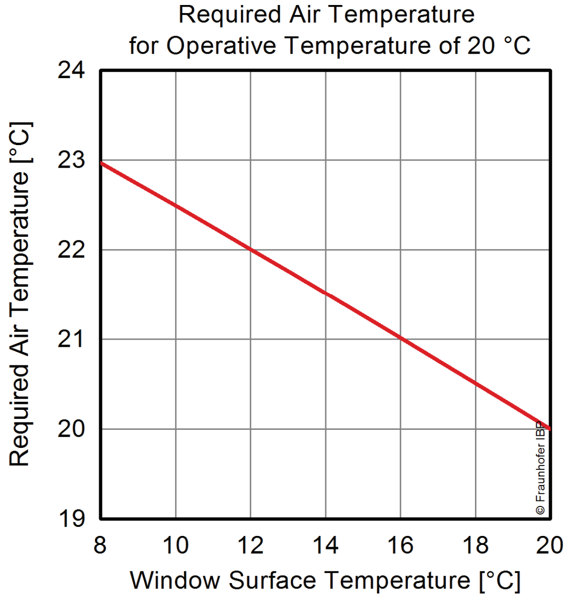

Figure 1: Required air temperature for an operative temperature of 20 °C, depending on the window's surface temperature. The room used for the calculation is a standard school room of 7.5 m length, 7 m width, and 3.2 m heights. It has five internal surfaces and one external wall including a window area of 9.36 m². Position: 1 m distance from the external envelope.

As seen in Figure 1, if the window's surface temperature is 10 °C, the air temperature should be 2.5 K higher than the required operative temperature of 20 °C. However, this low surface temperature and high air temperature cannot provide thermal comfort due to the local discomfort. The radiation asymmetries caused by the difference of the left and right plane radiant temperatures result in a high discomfort. Additionally, the cold surfaces cause local draught.

Therefore, the high performance envelope, especially windows, will contribute not only to the reduction of the transmission heat loss, but will also enable to lower the necessary indoor air temperature (Figure 2). It should be mentioned, that only improving windows (U-value and air tightness) can cause mould problems on surfaces with lower surface temperatures and esp. on thermal bridges if the rooms are not ventilated properly.

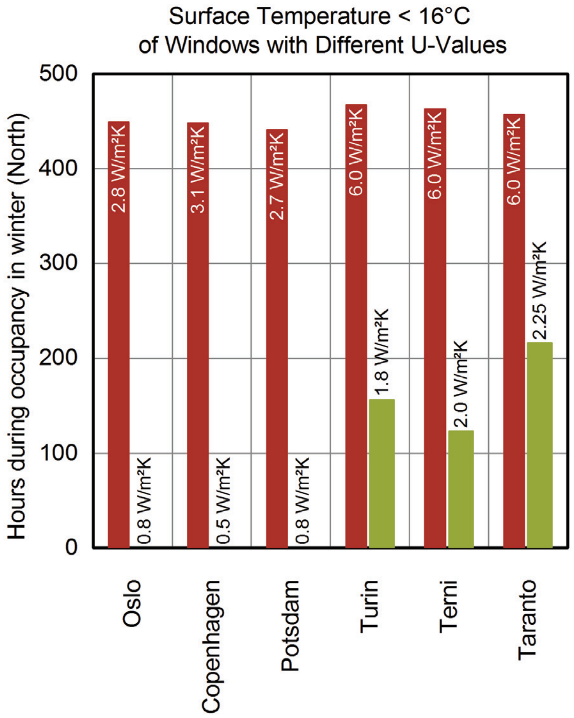

Figure 2: Hours with surface temperatures below 16°C for windows with different U-values (windows in existing buildings and high insulation standard for windows) simulated for the heating period (December to February). The heating set-point is 20°C for Oslo, 22°C for Copenhagen und 21°C for the rest of the places [2].

Additionally, the total overall thermal comfort will be increased in winter, thanks to the reduction of local thermal discomfort. For the same reason floors against earth or unheated cellars should be insulated.

In winter, the thermal comfort in high energy efficient schools will be clearly better than standard reference schools, based on the high level of insulation, air tightness in the constructions and reduced thermal bridges.

Avoid draught risk

While draught risk based on the untight envelope and cold windows will not be a problem in energy efficient schools, the high ventilation air exchange rate required in schools often causes draught in winter.

To achieve the required air quality without any draught, a very careful design is required for natural ventilation. Also, with mechanical ventilation system, the air exchange volume should be limited to the necessary level for the air quality, in order to avoid draught risk and to reduce energy consumption.

Requirements for thermal comfort in summer conditions

Required operative temperature in summer

With a typical summer clothing (0.5 clo) and activity of persons in school (1.2 met) the operative temperature in school should be between 24 °C and 26 °C for new and modernised buildings and a normal level of expectancy for thermal comfort in summer [1]. The use of mechanical cooling systems is neither a common practice in the investigated countries nor planned for the schools of the future due to high energy consumption and investment costs. Therefore keeping the required operative temperature is challenge for the planners, especially in Germany and in Italy. But there exist several passive methods to achieve the desired indoor temperature in summer.

Reduce heat gain

For a typical office building, the best and first way for achieving thermal comfort in summer is to avoid heat gain by using good external shading systems and efficient equipment, related to the so called “Prevention is better than cure”. In schools, it is difficult since the highest heat gain source is coming from people. An adult emits in average 80 W sensible heat and a pupil emits between 60 W and 90 W into the room, depending on the body size and activity. Only regarding the heat balance of a pupil for emitting heat and producing heating demand due to necessary ventilation (not taking into account solar gains and transmission heat losses) there occurs cooling demand starting with outdoor temperatures of 5 to 10 °C (see Figure 3).

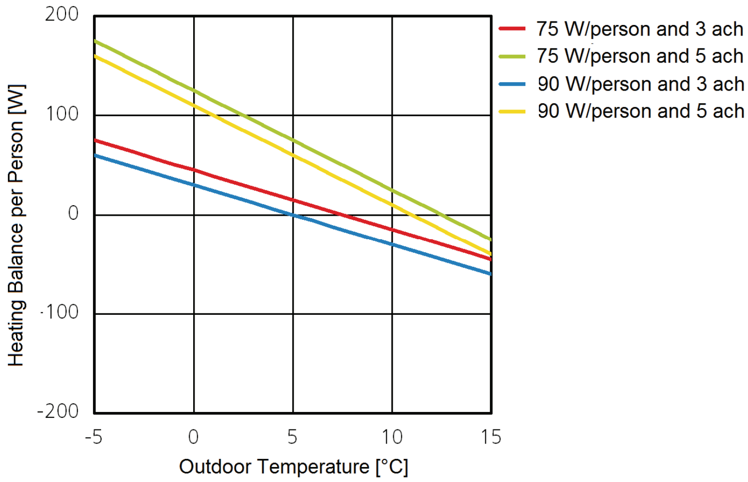

Figure 3: Heat balance for a pupil only regarding emitted heat from the person and ventilation heat losses for hygienic ventilation.

Although pupils are absent in the warmest months because of the school holidays, the high occupancy rate in schools of 2 m²/person, in comparison to 10 or 15 m²/person in office buildings, pushes up the indoor temperature in the early and late summer months over the comfort limit temperature of 26 °C. Therefore, the indoor air temperature in schools is often higher than the outdoor temperature, not only at night but also during daytime. In such circumstances, the high level of insulation and air tightness in the schools of the future will reduce the transmittance as well as the infiltration heat loss during nights and result in the increase of over temperature hours in summer, as the simulation results show in [2]. However, these measures are essential for the energy efficiency and the thermal comfort in winter.

Anyway, solar heat gains should be avoided in summer seasons esp. in the southern European countries to keep cooling demand and indoor temperatures in an acceptable range.

Besides the solar heat gain, which can have negative impact on overall thermal comfort, direct solar radiation can produce local discomfort due to radiation asymmetry, esp. for people sitting next to the windows, because solar radiation (direct and indirect) heats up the windows (see Figure 4). The higher radiation temperature has also to be compensated with lower air temperature to reach the same operative indoor temperature (see Figure 5).

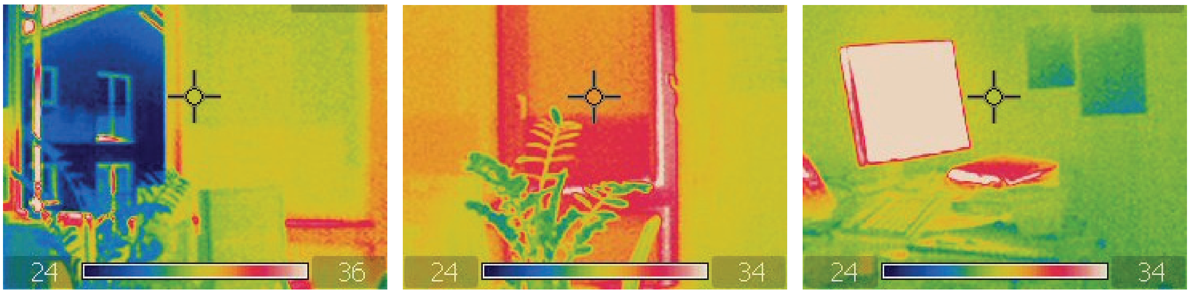

Figure 4: Inside view on façade with an open and closed windows (left), a up heated window from solar radiation (middle), both with no direct sunlight but summer outdoor conditions, in false colours for radiation temperature. View on inner wall with working place (screen and notebook) under equal conditions for comparison.

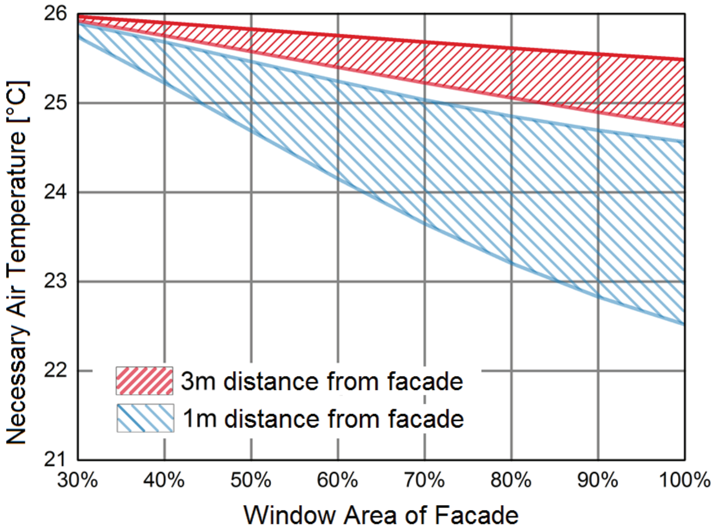

Figure 5: Necessary air temperature to reach an operative temperature of 26 °C having an outdoor temperature of 32 °C, a solar radiation of 500 W and g-values of 78 % (lower line) to 27 % (upper line) for the windows depending on the position of the occupant.

Sun light does not only heat up the windows, but passes also directly to the person. In [3] this effect was investigated (see Figure 6). It was concluded that esp. near the windows thermal comfort is not achievable without protection from direct sunlight.

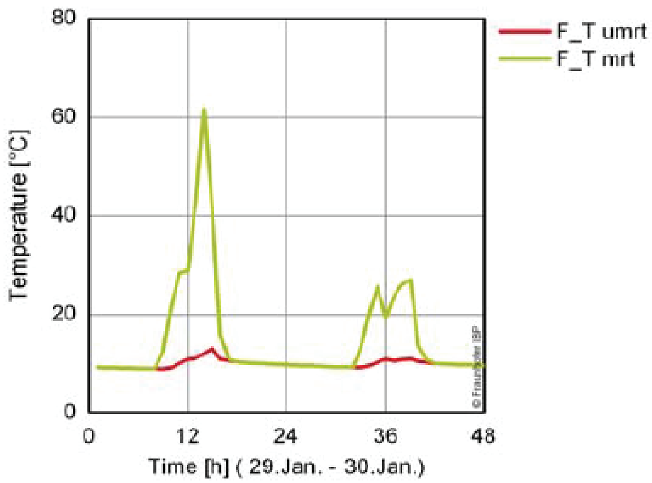

Figure 6: Mean radiation temperature with (Tumrt) and without (Tmrt) consideration of transmitted direct solar radiation by sunny winter days at places near a window with g-value of 79 % (source: [3]).

As the latter effect can also be avoided by internal shading systems, preventing solar heat gains in the room and high surface temperatures on the windows needs external shading systems. Windows with low g-values can also prevent overheating of the rooms and windows, but their effect cannot be reduced in winter time, when solar gain might be welcome. But the use of day lighting is to be considered by the selection of a solar shading product and also glare from direct sunlight should be avoided (see chapter “Lighting Conditions”).

Strategies for passive cooling

Increased day ventilation

As explained above, a high air exchange rate in the early and late summer months contributes to the thermal comfort with the reduction of the indoor air temperature. Additionally, it elevates the air velocity in a room, which can increase the maximum acceptable air temperature, if the occupants are able to control it. For example, 28 °C is accepted by an air velocity of 0.6 m/s in comparison to 26 °C by 0.2 m/s [4]. Therefore the air exchange rate in summer should be determined in respect to the thermal comfort rather than to the air quality.

Generally, mechanical ventilation systems are designed to satisfy the air quality and not to achieve a high air exchange rate for thermal comfort in summer. Thus, a mechanical system in most circumstances is either not sufficient (low ventilations rates) or not energy efficient (high ventilation rates) for passive cooling in comparison to a well-designed natural ventilation system. Hence, a natural ventilation concept should be developed during the initial planning phase for the thermal comfort in summer, even if a mechanical system is planned for the air quality in winter. But the potential of free cooling during day time depends mainly on outdoor temperatures during day time. Thus the effect is bigger in northern countries (see Figure 7).

If natural ventilation is not possible during lecture times due to the outside noise or air pollution, mechanical ventilation during lecture times in combination with rush natural airings during breaks will be an alternative in summer.

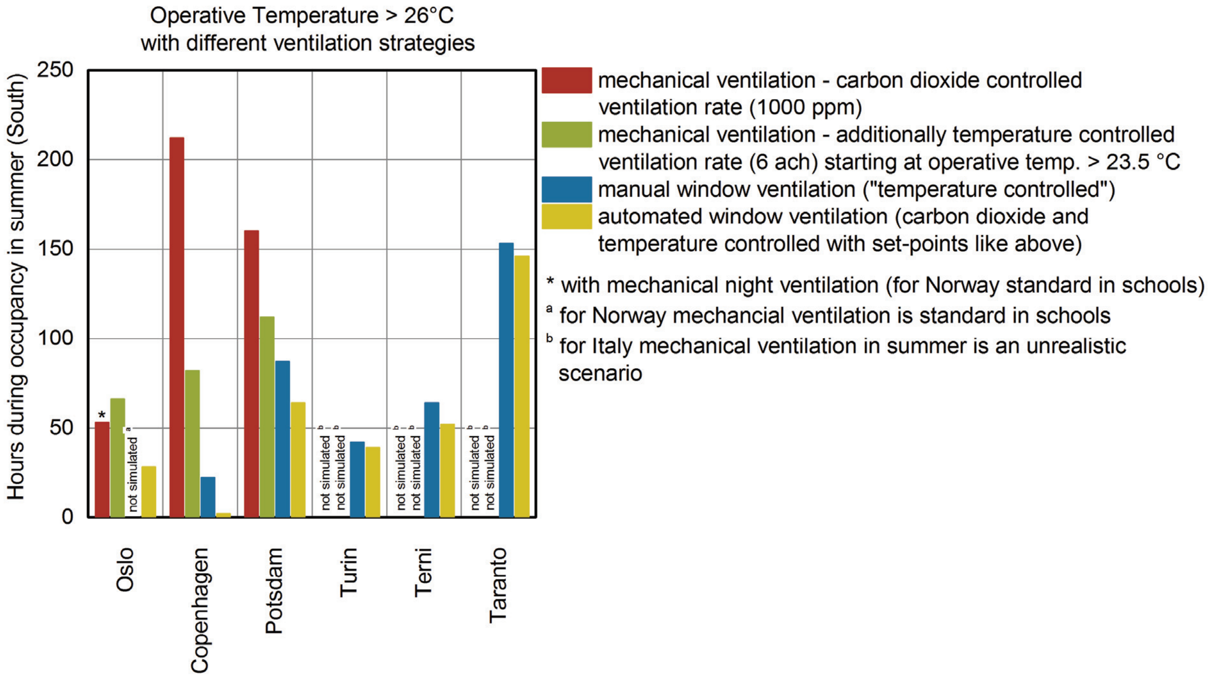

Figure 7: Overheating hours during summer in northern countries and during transient seasons in Italy (no classes during summer) with different ventilation strategies for passive cooling. For Potsdam calculations are done with external shading, for the other countries with internal shading elements. In the cases of Italy the windows are opened completely for manual passive cooling, for the other countries and all automated cases, the windows are tilted. For further information see the documentation of the simulation boundary conditions [2].

Night ventilation

Another passive cooling method for schools is the overnight ventilation using thermal mass night flushing. The high internal heat during daytime is stored in the building construction and released at night via ventilation to the outside. The efficiency of overnight ventilation depends on the outdoor air temperature at night, the air exchange rate and the thermal mass of the construction. The biggest effects can be seen in regions, where there typically exist big differences between daytime and night time outdoor temperatures in summer (see Figure 8).

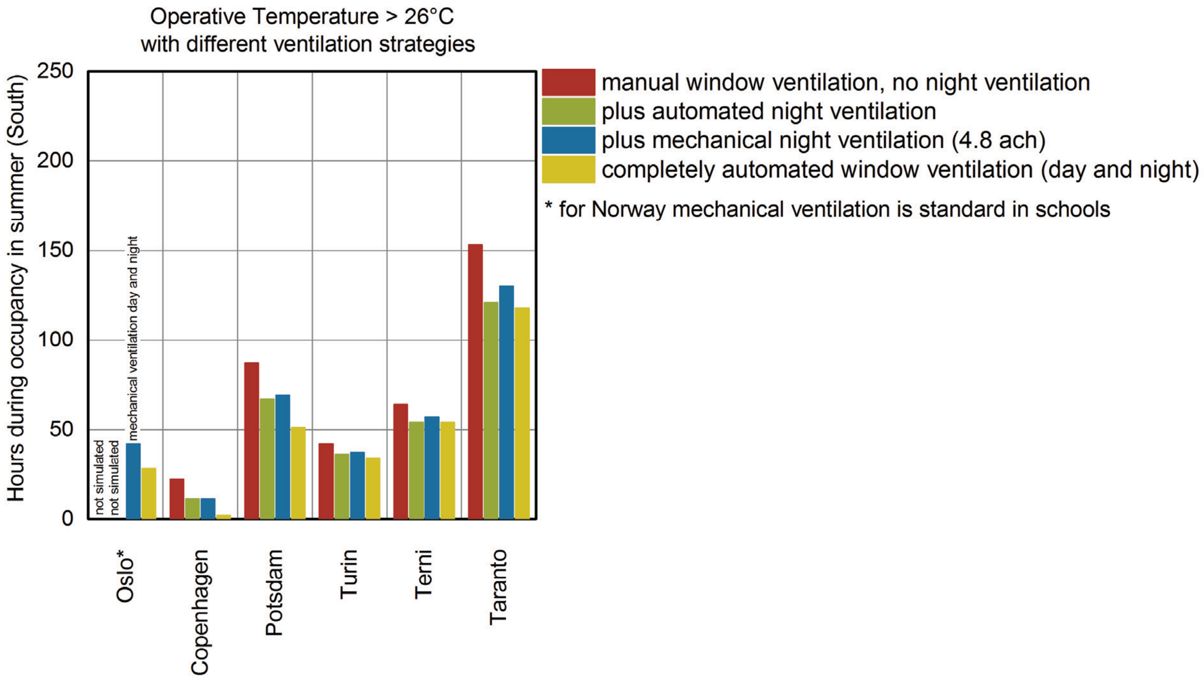

Figure 8: Overheating hours during summer in northern countries and during transient seasons in Italy (no classes during summer) with different combinations of day and night ventilation for passive cooling. For Potsdam calculations are done with external shading, for the other countries with internal shading elements. For further information see the documentation of the simulation boundary conditions [2].

Without sufficient overnight cooling, the high thermal mass can result in an increase in temperature, while an overcooling can require additional heating on the following day. For this reason, overnight ventilation should be controlled carefully depending on the outdoor and indoor temperatures. Additionally, a security concept is required for the successful application of natural overnight ventilation with windows in practice.

Figure 9: Security concept for night ventilation via overhead windows in the renovated Tito Maccio Plauto School in Cesena, Italy. Photo: M. Zinzi.

An alternative could be mechanical overnight cooling, if there is already installed a system for ventilation in winter. But here also the ventilation rates have to be adopted for passive cooling.

Ground ducts for precooling supply air

If there is installed a mechanical ventilation system ground ducts can be used for precooling supply air. Simulations (documentation of the simulation boundary conditions in [2]) show quite good improvement for northern countries with ground ducts of 50 m length compared to mechanical ventilation without any passive cooling. But the solution produces much higher indoor temperatures than manual window ventilation (which includes passive cooling during daytime due to an intuitionally higher opening frequency by persons in summer). For southern countries overheating hours for mechanical ventilation (hygienic air change rate) with ground ducts leads to quite the same overheating hours than manual window ventilation. There the system could be an alternative for window ventilation due to acoustic reasons without the necessity to raise the air change rate, which also raises installation and operation costs [2].

To improve the effect of ground ducts there should be used longer ducts for a better cooling effect (see Figure 10) and/ or the system should be combined with higher ventilation rates or night ventilation. But the latter ones both cause much higher energy demand for fans.

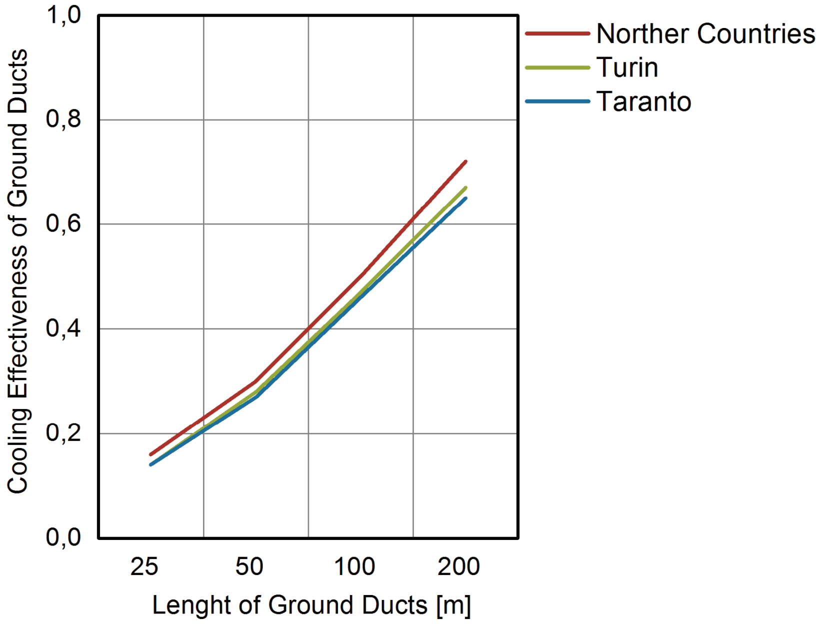

Figure 10: Cooling effectiveness for ground ducts with a diameter of 25 cm, buried 1 m below the surface and a ventilation rate of 1000 m³/h per duct (calculations made with GAEA [5]).

Heating and cooling management

Heating systems are designed to the required power at minimum outdoor temperature. So keeping this lowest required operative temperature will not be a problem in existing schools, but rather overheating or fluctuation of air temperature will be an issue in schools. A thermostatic valve for heating elements should be used in schools, also in warm regions, for energy efficiency and high thermal comfort [2]. Set-points for room temperatures should be reduced during nights and weekends to save energy, but raised again early enough to preheat rooms in the morning to a minimum comfort temperature (19 to 20°C), taking into account the necessary time esp. after weekends and holidays. It is not necessary to preheat the room to the optimal comfort temperature as pupils bring in a lot of heat and will warm up the room with their presence anyway. The heating system itself should rather be controlled or switched on and off due to outdoor temperatures than to certain date to be able to provide heating energy when necessary.

Passive cooling systems have to be controlled very carefully not to create draught risk during day or cause too low operative temperatures esp. in the morning. For this reason, overnight ventilation should be controlled depending on the outdoor and indoor temperatures. Thermal mass in the building should be used to its full potential without creating additional heating demand or causing uncomfortable temperatures due to overcooling (e.g. < 21°C in summer conditions). Passive cooling during daytime should be started early enough with indoor temperatures of 23 to 24°C due to the high internal loads.

To avoid solar heat gains in summer and transient seasons shading devices should be controlled by total solar radiation on the façade (> 150 to 300 W/m²) and indoor temperature also during the absence of persons. Solar shading should be active when direct radiation is causing glare or uncomfortable conditions for pupils due to radiation (see Figure 6). Additionally it should be active with indoor temperatures above 23 or 24°C or even lower temperatures, when cooling demand is expected during daytime. During the heating season solar heat gains should be used, when there is no direct negative effect from the solar radiation (e. g. glare).

Using solar shading should, if possible, not cause the necessity to use electrical lighting, which also creates even more internal heat load. Quite often, different bus systems will be used for the façade and the control of electric lighting in interior spaces, so that system integration becomes necessary to provide a satisfactory, integral solution.

Like for all automatically controlled systems an override for the user has to be foreseen which is set back during absence of the occupants.

INDOOR AIR QUALITY

Indoor air quality is related to air pollution from people, furniture, surface materials in the room (paint, carpet, etc.), cleaning detergent, dust, moist and mould in combination with cleaning quality and ventilation rates.

Requirements for good indoor air quality

The requirements for indoor air quality in schools are based on the organic chemicals concentration of building materials and the carbon dioxide concentration from occupants. These concentrations can be assessed using measurements during the utilization phase. However, there is no harmonized standard or regulation at the EU level governing the accepted indoor VOC or carbon dioxide concentration level. The EN 15251 [1] only provides the required ventilation rates regarding personal and material emissions.

Requirement on indoor air quality regarding organic chemicals

In European countries there exist different regulations for maximum levels of organic chemicals in indoor air.

Norway has general legal requirements without specific limit values regarding indoor air quality. The building code requires that "Materials and products must have properties that provide low or no contamination of indoor air". The code is supplemented by guidelines which state that emission data should be revealed. The Product Control Act requires enterprises using products containing chemicals that can cause adverse health effects or environmental disturbances, to assess whether there is an alternative with less risk. The alternative with less risk should be selected if it does not result in increased costs or inconvenience.

Folkehelsa ("People's Health", a public body) has designed a number of recommended standards for indoor air quality, which forms the basis for e.g. surveillance in schools and institutions. The guiding norm for formaldehyde in indoor air is max 100 $\mu g/m^3$ as 30-minute average [6]. These standards are not legally binding and occur mainly in municipal buildings. The Norwegian version of the standard EN 15251 [1] gives indicative values for TVOC and formaldehyde for two categories; low-emitting materials and very low-emitting materials.

Table 1: Indicative values for maximum permissible emission [1].

	Low-emitting materials	Very low-emitting materials
TVOC	<0.2 mg/m^2 h	< 0.1 mg/m^{2}h
Formaldehyde, H_2CO	<0.05 mg/m^2 h	< 0.02 mg/m^{2}h

BREEAM-NOR, a Norwegian adaptation of the certification scheme BREEAM, gives indicative values for emissions. BREEAM-NOR was launched in 2011 and has now been adopted by ambitious real estate developers. The certificates are issued by Norwegian Green Building Council.

Currently Denmark applies a general legal requirement for indoor air quality regarding organic chemicals without specified limit values for concentrations. A legal requirement does exist for formaldehyde emissions from wooden boards as well as a voluntary certification scheme for building materials.

Danish regulation of the indoor climate area is divided between several ministries and agencies, including the Environmental Protection Agency, the Business Authority, the Working Environment Authority, the Ministry of Social Affairs and the Health and Medicines Authority. The Building Act contains general requirements to healthy buildings, but the limits and the values are set by the Environmental Protection Agency. For emissions from building materials, the following applies: "Building materials must not emit gasses, vapours, particles or ionised radiation that can cause an unsatisfactory indoor climate conditions in terms of health" according to the Danish BR10 [7].

In Germany, the two guide values (GV) derived toxicologically for single substances and TVOC (Total volatile organic compounds) levels are recommended for the assessment of indoor air quality from the federal environment agency. GV I is a concentration below which no adverse health effects are to be expected even after a life-long exposure, while GV II represents a concentration, which can be a threat for sensitive people. The actual lists for GV I and GV II can be found in [8]. Regarding the assessment of TVOC concentration of indoor air there are five stages of assessment (see Table 2).

Table 2: Assessment of TVOC indoor concentration according to the German federal environment agency.

Level	Concentration	Comments	Recommendation
1	< 0.3 mg/m³	No hygienic objections	Target value
2	0.3 - 1 mg/m³	No relevant objections	Increased ventilation
3	1 - 3 mg/m³	Concerning hygienic aspects	Maximum of 12 months Search for sources
4	3 - 10 mg/m³	Major objections	< 1 month, restricted use only
5	10 - 25 mg/m³	Not acceptable	Only for short periods (hours)

In Italy there are no specific restraints for civil buildings regarding TVOC. But here also the EN 15251 [1] gives indicative values for TVOC and formaldehyde for two categories; low-emitting materials and very low-emitting materials to estimate necessary ventilation rates.

Since the assessment of the air quality cannot be performed during the planning period, it is based on the measurement after the building construction. The concentration of individual or total VOC will be reduced obviously using certified products according to the labelling schemes presented in the next section.

Prevention of emissions

Building construction products and furnishings emit organic chemicals which can cause irritation and unpleasant odour complaints from occupants. Limited emissions from products can be achieved by using materials which may not release pollutants, and which does not result in concentrations greater than the acceptable limits e.g. of volatile organic compounds (VOC). Such products can be selected in practice with the help of existing national or industry labelling schemes in the EU for the assessment or rating of VOC emissions of products [9].

In addition to mandatory national assessment schemes like the German AgBB and the French CESAT program, there are voluntary programs like GuT (community eco-friendly carpets), Blue angel (oldest ecolabel for products with low emissions into indoor air), natureplus, and EMICODE (label for showing low VOC emissions into indoor air from construction products) from Germany as well as M1 (lowest emission class of voluntary emission classification of building materials) from Finland, and ICL (Indoor Climate Label) from

Denmark. However, these different labelling schemes on the EU markets with different evaluation procedures are confusing for building designers and consumers as well as they are cost intensive for industries [10]. The requirements for evaluating product emissions in the same way by using a robust procedure and a harmonized labelling scheme at the EU level have increased in the past years. To answer these requirements, a new horizontal VOC test method was developed as a technical specification (CEN/TS 16516) in 2013. The European Collaborative Action (ECA) published in 2013 a report describing the harmonized evaluation scheme based on the EU-LCI approach [11]. For several product types, information on VOC emissions will be soon included in the CE marking of construction products. With this, the designer can better judge, which products can be used for the prevention of chemical emissions.

Requirements on indoor air quality regarding carbon dioxide level and hygienic ventilation rate

Persons emit carbon dioxide due to metabolic activity. This emission correlates quite well with the emissions of smelling gases and bacteria etc. Therefore the concentration of carbon dioxide is often used as the key indicator of the air quality in rooms without any other major pollutant. The recommended average concentration, which should not be exceeded during the occupied time varies from 1000 ppm to 1500 ppm, depending on the national guidelines (e.g. [12]). Outdoor air typically has carbon dioxide levels between 350 and 500 ppm.

The EN 15251 [1] provides the required fresh air supply separately regarding pollution based on contamination of person and based on emissions of building materials, which is divided once again into three building groups: Very low emissions building, low emissions building, non-low emissions building.

The total fresh air supply rate is determined under the consideration of both pollution sources (person and building) with one of three calculation methods: the sum of required fresh air supply for person and building materials, the highest value of both sources, intermediate value between the first and second calculation result.

Under typical occupancy rate of 2 m^2/ person in schools the person based ventilation rate is with 3.5 l/s-m^2 clearly higher than 0.35, 0.7 or 1.4 l/s-m^2 based on building materials.

According to the second calculation method (highest value of both sources), which will be the most applicable method considering air quality and other thermal comfort parameters like draught risk, a ventilation rate of 7 l/s person (25 m^3/h person) is for new and modernised buildings and a normal level of expectancy for indoor air quality. It corresponds to calculations in typical circumstances with about 1200 ppm of CO_2 concentration and 4.2 ach (air change rate) in 3 m height classrooms.

In Norway the national standards regulate the calculation method to be used. There the ventilation rates necessary due to person and building emissions have to be added up.

Table 3: Required ventilation rate regarding pollution caused by person and building in the case of occupancy rate of 2 m²/person according to the EN 15251 [1], with q_p=ventilation rate per person, q_b=ventilation rate for building and q_{tot}= total required ventilation rate.

Category II in the EN 15251	Source: Person (q_p)	Source: building (q_b)			q_{tot} Highest value method
		Very low emissions building	Low emissions building	Non low emissions building	
Per Person	7 l/s person	0.7 l/s person	1.4 l/s person	2.8 l/s person	7 l/s person
Per m²	3.5 l/s m²	0.35 l/s m²	0.7 l/s m²	1.4 l/s m²	3.5 l/s m²

The ventilation rate can be derived from the requirements on carbon dioxide concentration, which is determined based on the national guideline or regulation for schools.

The calculation results are given in Table based on the typical CO_2 production from the respiration of an adult and the outside CO_2 concentration (400 ppm). Because a child produces a smaller amount of CO_2 than an adult, the required ventilation rate will be reduced to 7 l/s, child for 1000 ppm and 4 l/s, child for 1500 ppm.

Table 4: Required ventilation rate depending on the carbon dioxide concentration in a typical classroom (occupancy rate: 2 m²/ person, outdoor CO_2 concentration 400 ppm, CO_2 production adult: 18 - 20 l/h, CO_2 production child: 14 l/h).

	1000 ppm	1200 ppm	1500 ppm
Adult	9 l/s person	7 l/s person	5 l/s person
Child (< 10 years)	7 l/s person	5 l/s person	4 l/s person

The ventilation rate based on manual window operations by users and air leakage should be considered for the determination of the ventilation rate for a mechanical system to prevent unnecessary high ventilation rate.

Strategies for ventilation

The starting point in ventilation design is to determine ventilation rates depending on the purpose. The requirement of the air quality in winter serves the minimal ventilation rate, whereas the passive cooling possibility in summer will determine a ventilation rate of minimum 5 to 6 ach [2]. It is important to note that the high requirement of air quality will mean high energy consumption and an increased risk of draught.

After determination of required minimal and maximal ventilation rates, the local situation like outside noise, outdoor air pollution and climate of the planned location should be analysed to determine additional measures e.g. filtering, sound attenuation, or conditioning of supply air. Users in rooms towards a road with busy traffic will not open windows during lecture times even if there is no draught risk. The analysis should be done depending on the orientations. In addition the local regulations for schools should be considered, e.g. limitation of the opening size or location of window based on the falling risk for pupils.

Afterwards, the most appropriate system or a system combination can be selected to ensure the above-mentioned diverse requirements. A whole-life cost calculation regarding initial capital, installation, maintenance, operational electricity and heating or cooling costs as well as resulted thermal comfort and air quality should be compared during the planning stage, before a ventilation strategy is determined.

There are three basic ventilation strategies: natural, mechanical and hybrid ventilation.

Natural ventilation

Traditionally, schools in the EU have been designed for natural ventilation with manual window opening. However, simulation results as well as diverse field measurements show that a conventional window airing in schools – 10 minutes rush airing between 45 minutes lessons – cannot ensure the required air quality [2].

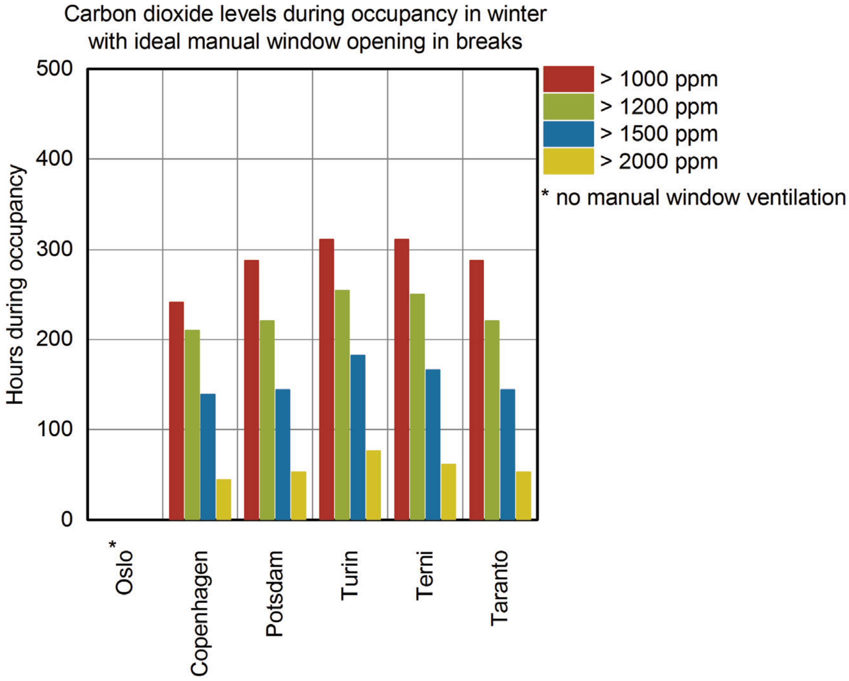

Figure 11: Carbon dioxide levels in classrooms during occupancy in winter from a simulation [2]. Window opening is simulated idealised only between lessons until outdoor carbon dioxide is reached or operative indoor temperature is falling below 17°C.

On the other side, manual window opening, e.g. tilting of window during lessons is not accepted by users because of draught in winter. The recommended additional rush airing of 20 minutes after the start of a lesson is in practice perceived by teachers as disruptive for lessons.

It means that instead of conventional manual window opening, either a mechanical ventilation system or another innovative natural ventilation system is needed to ensure the good air quality and high thermal comfort in winter.

One approach is the use of motorized windows, vents or other openings for ventilation, which can be controlled automatically by sensing of outdoor and indoor parameters. A field study in Germany shows that well-positioned, infinitely adjustable window openings can ensure thermal comfort and sufficient air quality, if the system has an intelligent control algorithm and the outdoor temperature is not under 5 °C [13]. It may be an alternative to mechanical system for regions with a relatively warm winter season, e.g. like Italy. For lower outdoor temperatures the automated windows should be placed as overheads as high as possible in the façade to avoid draught and restricted in opening width according to wind and outdoor temperature. The most effective way for natural ventilation is cross ventilation from façade to façade or façade to an atrium.

Natural ventilation can also be done via ducts, using earth-ducts or chambers below the building for preconditioning the supply air, (solar) chimneys to enforce temperature and wind effects. For this application the ducts have to be very big with very few resistances and air velocity should be at the best not be higher than 1 m/s to minimize pressure drops [5]. Also issues regarding fire protection have to be considered with this solution.

Mechanical ventilation

The biggest advantage of mechanical system will be the ensured air quality without detracting the thermal comfort in winter. In addition, the possibilities for cooling, filtering, sound attenuation and heat recovery belong to the benefits of mechanical ventilation systems.

However, mechanical ventilation cannot always provide high comfort and energy efficiency. It highly depends on individual performance of systems. For example, a mechanical system without preheating of supply air can cause draught in winter just like a window opening. Systems with preheated supplied air might cause draught risk due to the required high ventilation rate. In addition, mechanical ventilation systems are not always silent.

Also the heating recovery of mechanical systems should not be overestimated in schools. Because of the high internal heat gain, the heating period is shorter than for other utilizations like residential buildings. Therefore heat recovery will be cost efficient only in very cold regions, although it enhances the energy efficiency of mechanical ventilation systems [2].

In order to preserve the system-immanent advantages of mechanical ventilation the mechanical ventilation systems have to be designed carefully with respect to ventilation rate, supply air temperature, type and positioning of inlets and noise protection (esp. for decentralised systems). The ducts should be planned with few resistances and low air velocity (< 3 to 4 m/s) to reduce pressure drops and avoid unnecessary high power demand for fans.

Supply air should always be fresh air and not be mixed up with exhaust air.

Hybrid ventilation

According to the IEA Annex 35 [14], hybrid ventilation system combines natural and mechanical forces to provide acceptable indoor air quality and thermal comfort in an energy efficient way. For this purpose, different systems of hybrid ventilation are developed: fan assisted natural ventilation, stack and wind assisted mechanical system and mix modes.

Fan assisted natural ventilation uses an extract or supply fan in combination with e.g. a natural air intake through wall or window. Most of the developed inlet systems on the markets provide filtering or sound attenuation and can be controlled with indoor humidity or carbon dioxide sensing. Because of the required high ventilation rate in schools a careful planning is required for the application of these systems. The cold, unconditioned air from intake opening and continuous high air flow rate can cause draughts and more complains from users than by manual window opening. If a fan assisted natural system is applied in winter, the location and opening size of intake should be planned carefully so that the air temperature is acceptable to the user. An alternative is to precondition supply air through an earth channel and provide it to the rooms with low pressure losses in the distribution channels. Examples for fan assisted natural ventilation can be found in [5].

Figure 12: In the Tanga School, Sweden, outside air is supplied through air intakes in the exterior walls into a stub-duct hidden behind a bench (left). The fresh air is preheated using convectors under the stub duct. The exhaust air is extracted on the opposite side of the room into vertical ventilation ducts leading to solar chimneys (right) installed on the roof with leeward outlets and assisting exhaust fans (Source: [5]).

A combination of natural and mechanical ventilation using the systems alternating can combine the advantages of both systems. To ensure high thermal comfort and air quality in winter, the application of mechanical ventilation seems to be necessary at least in cold regions. On the other hand it will not be the intention of mechanical ventilation systems in schools to ensure the high ventilation rate in summer required for avoiding overheating. The dimensioning of mechanical systems to the maximal required supply rate will be cost and energy extensive. Natural ventilation should be used as far as possible in summer. Hence a mix-mode, natural ventilation in summer and mechanical ventilation in winter, especially a system which is controlled automatically between two modes will be one of the best solutions in the EU regions with cold winter and warm summer like Germany.

Therefore, a good design for successful natural ventilation is important, independently of the presence of a mechanical system. Especially in transitional seasons the temperature difference between indoor and outdoor is small and the natural ventilation should be optimized using wind effect.

Ventilation management

Controlling ventilation systems due to air quality directly by the level of carbon dioxide measured in a classroom will ensure the desired air quality and at the same time prevent the unnecessary air exchange, which will increase the energy consumption and the draught risk in winter as well as noise complaint. An alternative is to keep the air flow rate constant at a minimum level and switch on due to presence of persons or due to a timetable. The resulting carbon dioxide levels due to different ventilation strategies can be seen in Figure 13.

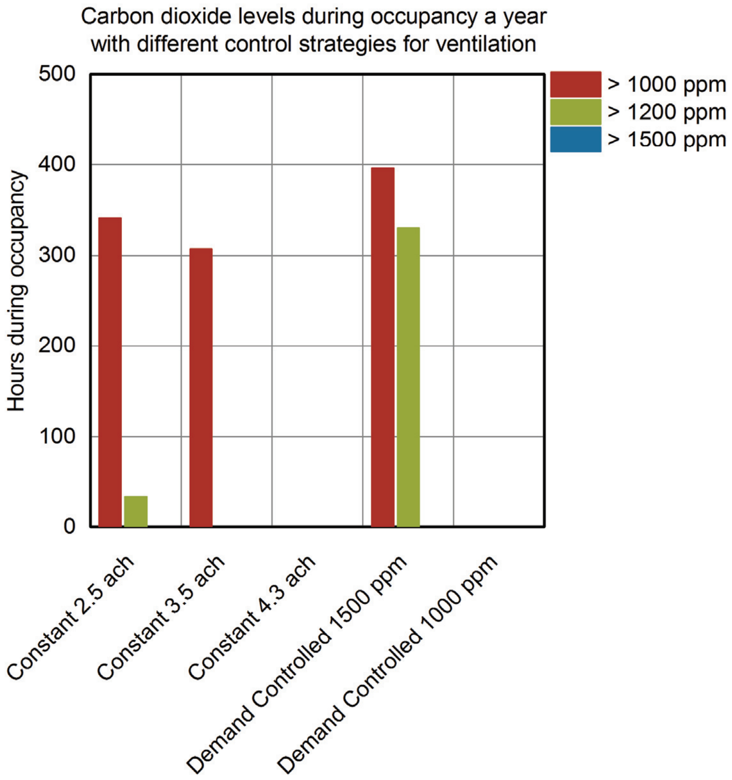

Figure 13: Carbon dioxide levels in a classroom during occupancy during a year with different control strategies for ventilation. Constant air flow rate can only be reached with mechanical ventilation. Demand controlled ventilation with regard to carbon dioxide levels can either be reached by continuously automated windows or mechanical ventilation, but natural ventilation is restricted to comfort issues in winter (e. g. in Norway). For further information see the documentation of the simulation boundary conditions [2].

Having classrooms, which are occupied inconstantly controlling ventilation rate due to presence of persons is definitely saving power demand. If also the number of pupils is varying during the day or between classrooms, carbon dioxide controlled air flow rate is the best way to save energy and ensuring good air quality at the same time. But therefore it is necessary to design the system with a separately controllable air flow rate for each classroom. The carbon dioxide sensors can be either located in the room at breathing level of pupils (ca. 1.1 m above floor) or in the exhaust duct. The former position allows a better control of indoor air quality and usage for natural and mechanical ventilation. Anyway, the quality of the sensor should be high with respect to measurement accuracy and observed during operation to avoid bad air quality or energy demanding surplus ventilation of the rooms.

For controlling passive cooling with ventilation systems see chapter “Heating and cooling management”.

If supply temperature can be controlled it should, during occupancy, not be lower than 17°C for an easier control of draught risk and not be higher than 19°C due the high internal heat load, when there is no heating demand in the room. If supply air temperature is lower, like for natural ventilation in winter or passive cooling in summer, it has to be assured that supply air is mixed with room air sufficiently before it reaches the occupancy zone. Overall, air quality is perceived as fresher and better, when air temperature is lower.

For hybrid ventilation the control strategy has to be developed very carefully. Every element in the system needs to be controlled automatically, to change operation mode whenever necessary. At the best case not only the ventilation system itself, but also the heating system and sun shading is integrated in the control system.

LIGHTING CONDITIONS

The human being perceives about approximately 80 to 90 % of information visually. Specifically designed lighting solutions allow performing diverse types of visual tasks. Light has an influence on the human psyche and the circadian cycles and is a central element in architectural design. Light provides orientation both indoors and outdoors.

Requirements for lighting conditions

To understand the effect of light on human beings, basically three different pathways of influence must be distinguished. Firstly, light exerts a visual influence; secondly, a perceptual influence and thirdly, an influence via circadian cycles (inner rhythms).

The visual path of influence is characterized by a purely physiological perception through the eye and subsequently the associated visual performance. The human eye is capable of recognizing a very large range of luminance (up to 12 decimal powers) - it is, however, not possible to process the entire range simultaneously. The eye is continuously adapting to the surrounding lighting conditions. Once the eye has adapted to a certain luminance level, luminances that are too high in relation to this level will be perceived to cause glare whereas objects characterized by a luminance that is relatively too low will appear to be dark and undifferentiated. This situation calls for balanced luminance conditions in the field of vision, which in planning is achieved by a general recommendation of a maximum factor of three between the immediate range of vision and the surroundings. In principle, the following applies below the threshold of absolute glare: the brighter the surrounding environment, the better the human visual performance. By using predefined, specific illuminance levels in connection with the assumed reflection characteristics of commonly used working materials / equipment it is indirectly ensured that adequate luminances for the visual task will be achieved (e.g. in specialized rooms due to stronger requirements to the visual task 500 Lux (lx) instead of 300 lx).

While the fundamental physiological interaction and effects of visual perception essentially are equal for all individuals, this is not true for the ensuing processing steps; rather, these are partly characterized by subjective assessments (psychological effects). For instance, glare (e.g. caused by insufficiently shielded lamps) which deteriorates the visual function not directly but can still be assessed as uncomfortable is described on the basis of regression approaches derived from empirical studies (e.g. Unified Glare Rating (UGR) for artificial lighting, Daylight Glare Probability (DGP) for daylight). Recent studies suggest that there exist further psychological effects, for instance that in particular situations warm light colours and low illuminance levels may stimulate creative processes. By contrast, higher colour temperatures and higher levels of brightness will activate more analytical and functional capabilities and improve performance. At present, however, it is not yet possible to give any specific reliable recommendations for general lighting.

In 2002 scientists discovered a circadian photoreceptor in the eye, which is directly connected to the 'internal clock' of human beings. Here, the basic rule is that cold-white light, which is in the blue spectral range has a particularly activating effect. Apart from the absolute level of the spectral radiation supplied, its time of occurrence is also crucial in this context. According to the recommendation given by the German Society for Lighting (LiTG), illuminance levels of 600 lx (horizontal) and 300 lx (vertical) at 8,000 K (Kelvin) (or slightly higher levels of illuminance at daylight colour temperatures of about 6000 K) are considered appropriate for young people under the aspect of the biological (circadian) impact of light. These are composed of the available daylight supply and a share of artificial lighting. Over large periods of the year, daylighting will provide the majority of this level of illuminance. Consequently, in the light of current knowledge there has been no perceived need to abandon the usual planning practice for electrical lighting.

Based on our knowledge of physiological and partially psychological perception, planning and installation of current lighting systems consider the lighting level, the light distribution including glare limitation, and the colour-rendering index. Minimum requirements were specified in normative terms e.g. in European standard EN 12464-1 [15]. For the relevant lighting systems in schools, the design illuminances are 300 lx in classrooms (500 lx in classrooms for adult learning) and up to 500 lx in special-subject classrooms. With these values, such luminances are generally achieved that allow the human eye to adapt its performance adequately to the visual tasks. The colour temperatures of lighting systems, that are mainly used during daylight hours and thus to complement natural lighting, range between 4000 and 6500 Kelvin. A recommended value of 150 lx for cylindrical illuminance in classrooms aims to improve visual communication by ensuring sufficiently bright lighting of faces. For these areas, direct/ indirect lighting systems should be preferred over exclusively direct lighting systems. For typical school uses like classrooms, special-subject rooms, teachers' rooms, sports halls or preparation/ workrooms more differentiated specifications are given. When evaluating glare in interior spaces one proceeds on the assumption that only the psychological part of glare is of importance; corresponding values of glare evaluation according to UGR (Unified Glare Rating) are also specified in EN 12464 (e.g. classrooms UGR < 19).

Strategies for daylighting

Given the usage times of schools, daylight is the dominant and cost-free type of lighting. With regard to planning the use of daylight in school buildings, the information given below may prove useful. Daylight (and facade design) depends on latitude and climate. As for instance, cloudy skies are prevailing in northern and central European latitudes, light transmission through the façade should be maximized when the sun shading systems are deactivated. This should be done by selecting glass types featuring high light transmission values, preferably very low shares of window bars/grids and frames, and by optimizing size and position of the windows. Lintel heights should be designed to be rather low (intensive zenith light!). It is not necessary to have glazed parapets, as the light more or less 'goes by the board' and hardly contributes to brightening the room. Rather, there is a risk that these areas will increase solar heat gains, which may cause overheating of interior spaces in months receiving high solar radiation. Use of permanent structural shading (overhangs in front of windows) or due to façade components (solar control glass, stationary sun protection blinds) should be avoided in northern and central European latitudes. Concepts for southern Europe have to be adapted accordingly.

Sunlight/ glare protection systems need to provide adequate protection against glare (protective function) and to prevent undesired thermal radiation, while ensuring sufficient supply of the spaces with daylight (supply function). During direct incidence of sunlight, the goal is to reduce the luminance at the internal façade of the classroom such that lectures inside the space can take place without disturbance. On the other hand, the room should be sufficiently provided with daylight, so that - even and particularly during periods of direct insolation - the use of artificial lighting will become unnecessary. It is a proven concept to divide the façade above eye-level and insert a window area for light-redirection and to de-glare the lower window area by means of appropriate systems (Venetian blinds, the slats of which are opened in the upper area of the blinds, or blinds in the lower part, light-redirecting glass in the upper part). "Cut-off" slats reflect direct sunrays, guiding only indirect light into the room, thus ensuring the sufficient supply of daylight inside the space. Moreover, they also allow occupants to have a view to the outside during most hours of usage time. A small lower part of the window can also be without any shading system to assure the direct sight contact to the outdoor surrounding.

Transparent sun-shading systems (like metalized foils) do not provide sufficient protection against glare. They do not sufficiently reduce the high solar luminance, which may cause direct glare in the field of vision or reflected glare on monitors. In addition, the poor light transmission and the associated reduced incidence of light received from the sky will considerably darken the spaces. Though markisolette style blinds or drop-arm awnings may cause colour distortions (depending on the respective type of tissues used), they seem to be an appropriate means to ensure the combination of solar protection devices with a view to the outside. Also, susceptibility to wind needs to be considered here.

Roof lights are characterized by a luminous exposure which is about 50 % higher than at vertical façades, related to the surface area. They are much less critical with regard to glare problems and allow for a more even distribution of light across the room. Wherever possible under structural aspects, this type of daylight aperture should be considered. This is also the case for Atria, where it will ensure good daylight supply in winter, too (see Figure 14).

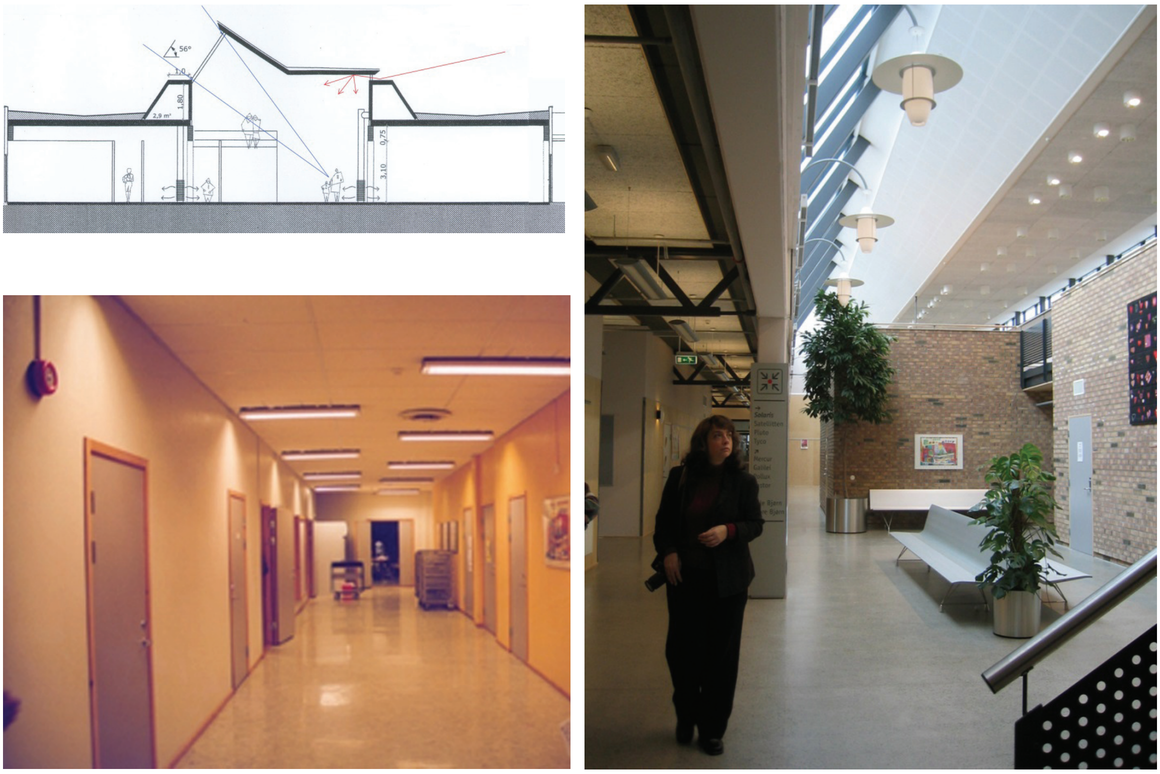

Figure 14: Retrofitting Borgen School in Asker, Norway. Drawing: Preliminary daylighting study by Prof. B. Matusiak, NTNU. Photo left: Central corridor before retrofitting. Photo: B. Matusiak. Photo right: Communication area after retrofitting. Architects: HUS Arkitekter. Photo: K. Buvik.

In classrooms, where the so-called bus formation is still used, the orientation of the workplaces to the façade should follow the needs of right-handed persons (with a share of 85-90% of the population), i.e. light incidence from the left side and there will be no shading by the student's own hand when writing.

Strategies for electric lighting

Electric light should provide good conditions for visual tasks in situations where the supply of daylight is insufficient (sections in the deep interior of the building far away from the façade, night-time hours). Special areas of visual tasks need to be defined correspondingly and have to be planned and implemented in addition to general lighting (like blackboard lighting, see Figure 15). For areas where visual communication has to be ensured by sufficiently bright lighting of faces, direct/ indirect lighting systems should be preferred over exclusively direct lighting systems. The spaces should be painted and furnished in bright colours, as this also has a significant influence on the power to be installed (a difference of about 30 % between a space that was painted in light grey and a white classroom). To guarantee the long-term functionality of the lighting system, it should be serviced and maintained at regular intervals. These intervals should be defined by the respective technical planner in a maintenance schedule (fixed dates for the replacement of lamps, luminaire cleaning, re-painting).

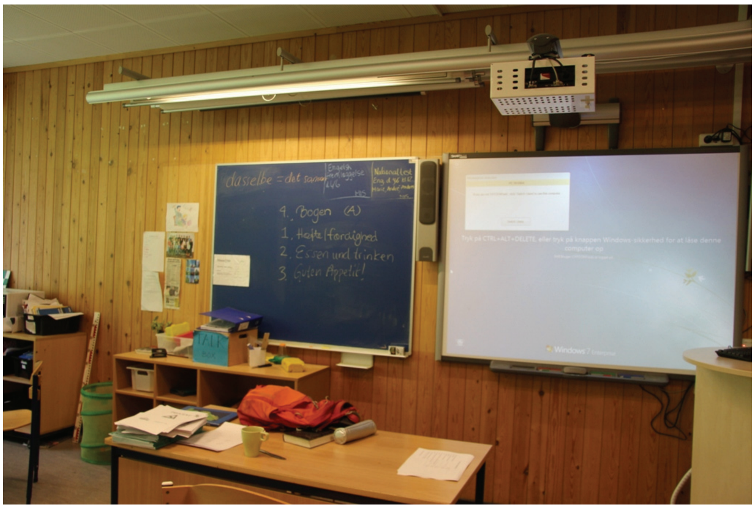

Figure 15: LED blackboard lighting in the retrofitted Hedegaard School in Ballerup, Denmark. Additional potential in this case lies in the increase of reflection coefficients (paint wall white). Photo: O. Moerk.

According to estimated figures by ZVEI (German industrial association) about 80 % of the lighting systems in Germany are either not planned at all or not according to the current state of requirements and/ or technology. This is the reason for some massive over-installations. To avoid misinstallations, e.g. planners are recommended to refer to the good, tried and tested and cost-free tools like DIALux or Relux which are continuously updated by the lighting industry. In some cases, manufacturers of luminaires include planning services in their offers.

For information, some benchmarking figures for installed power and annual electricity consumption values of typical new lighting systems and of existing systems are given below. In new school buildings, the typical specific installed power of lighting systems in classrooms (300 lx) with linear luminaires is equal to about 6.5 W/m², with an annual specific energy need of about 5 kWh/m²a without and 3 kWh/m²a with the use of a light management system. In the case of special-subject rooms featuring stricter lighting requirements (500 lx), the installed power per unit area amounts to 9 W/m² while the energy demand is 7.5 kWh/m²a without and 5 kWh/m²a with light management. Presently, LED solutions are at level with efficient T5 fluorescent lamp solutions but will have soon overtaken these, just like in other sectors. In existing buildings, the installed power of lighting systems that were established back in the 1980s exceeds today's commonly used technology by factor 3 or more. For a better estimation of potentials, the 'reLight' app (Google play store) is available for download to be used in inspections of existing lighting systems.

The lighting industry is undergoing a change of technology. According to forecasts, about 60 % of all lighting products will be based on the LED technology by 2020. This will also include lighting systems in schools. At present, investment costs for LED lighting systems still exceed the costs for conventional systems (fluorescent lamp technology). Due to the (partly) significantly longer service life of LED systems, these feature more favourable operating costs and meanwhile generally also higher efficiencies. Thus the total cost of ownership (TCO) of conventional systems for specified uses has been undershot already now. Regarding corridors and passageways, for instance, LED downlights are the economically preferable solution compared to downlights based on compact fluorescent lamps. For projects which presently are still in their early planning stages LED solutions for classrooms and teachers' rooms may already be the more economical and more efficient solution. This dynamic development of both cost structure and efficiency should be considered by e.g. contracting consultation services by lighting designers or electrical engineers during the project period.

Light management

Light management aims at supporting pupils, students and teachers in providing high-quality visual conditions. This should be preferably implemented by operating the system in a resource-efficient way. Experience has shown that automatic systems are usually only accepted if (teaching) staff members can easily override them.

Nowadays, solar shading systems like blinds can be controlled in a highly differentiated manner. For instance, conventional blinds may be operated in the 'cut-off mode' (see above), with a computer determining the position of the sun and the corresponding optimum slat inclination for a specified operating time and façade orientation. Apart from central wind sensor and frost protection functions façades in an existing building management system (BMS) infrastructure should be operated according to their thermal optimum state when the spaces are not occupied to use passive solar gains and avoiding risk of overheating.

A daylight-responsive, occupancy-related control of lighting in classrooms is recommended. This requires luminaires with dimmable electronic ballast and a corresponding control circuit. These solutions can be implemented as part of the building management system BMS or as autonomous solutions. Autonomous solutions may be realised at a starting price of about 10 €/m²; however, they do not include the above mentioned logical connection with the façade.

ACOUSTICS AND NOISE PROTECTION

The acoustic design of schools comprises characteristics of building physics and room acoustics of the entire complexes of buildings, including the outdoor environment. This includes all classrooms along with rooms for music and sports, corridors and stairways and other. In principle, there are no exceptions, just different types of acoustical requirements.

High-quality acoustics can be easily combined with all other substantial, physical, and use-related organisational requirements concerning spaces and buildings. Today, there are many options in terms of structural measures to ensure protection against fire, thermal protection in summer and winter as well as noise protection. Likewise, indoor climate, space lighting, and room acoustics can be harmonized [16].

Requirements for noise protection

In terms of building acoustics, acoustical measures comprise sound proofing of walls, ceilings, roofs / attics, doors and windows against noise from the outside (e.g. traffic noise) as well as from the inside (e.g. speech, music), of ceilings and stairways against impact noise (caused by persons walking around, moving chairs etc.), and against noise emitted by technical building systems and installations.

Various noises, like external traffic noise, speech, music or impact sound from other rooms as well as noise generated by building services systems will be superimposed in a space. There are a few basic rules regarding this kind of superimposition: the loudest noise determines the overall sound level and several approximately equally loud extraneous noises will add up. One single 'underestimated' sound source can thus compromise all other efforts and each sound source must be suppressed at least to the extent that it will observe the target value in the overall addition of all other sources.

In view of the various kinds of acoustic disturbances from both outside and inside, structural noise protection measures should actually provide adequate silence in the spaces used, no matter where the noise comes from. This aim is also contained in the mandatory requirements specified in the German standard DIN 4109 [17], which are based on the use of spaces. The noisier the usages of a room, the fewer disturbances are perceived.

Outdoor noise

As with other issues of building physics as well, urban reality (including long-term local building and construction schemes) provides first key information for defining the acoustic characteristics of the building. In addition, related outdoor facilities of the school, e.g. sports- and playgrounds, also need to be included in planning and evaluation processes. Here, the focus is on balancing the need for noise protection and the conflict potential due to noise. Well-founded and foresighted planning not only enable to achieve a high-quality acoustic school environment but also to ensure its cost-efficient implementation, e.g. by zoning of functions and installing appropriate noise-control windows.

Structural noise

In most cases, the method / type of construction and the individual building components are selected under aspects which are not primarily guided by the aim of noise protection. Regarding exterior building components, mainly issues of e.g. thermal insulation are prioritized; regarding interior construction components, protection against fire and load bearing characteristics are most important. Notwithstanding, all known types of construction can be realised ensuring a high level of noise protection.

Subsequent to selecting the building components, many other details need to be considered to ensure the acoustic integration of the respective element in the building context. Here, a key factor of influence is the so-called flanking transmission, i.e. paths of sound transmission via building components, which are flanking the actually dividing component. A number of details, e.g. all wall or door apertures designed for venting purposes as well as the ubiquitous joints at doors and the like need to be given particular attention, as these may - though not necessarily - cause unpleasant weak spots. Perimeter sealing and drop-down seals eliminate e.g. problems with doors and require only minimal effort.

The layout of the floor plan must be given first priority when planning noise control measures, even if not all the requests can be considered. In addition to avoiding the use of adjacent spaces for diverse, differently noise-intensive purposes, 'buffer zones' can improve the acoustical quality and reduce the amount of structural measures.

Problems may arise when changes of use occur or appear to be desirable. Particularly, the improvement of structural soundproofing properties by retrofit measures usually requires great effort and high costs.

Noise from technical building systems

Regarding noise generated by technical building systems, installations and other facilities, the focus is both on continuous noise and on noise peaks. The latter in particular are disturbing because of their audible nuisance. While related standards only consider technical systems pertaining to the building (e.g. heating system, ventilation, sanitary installations) - which cannot be controlled by the user - plants operated by the users themselves (e.g. machinery in workshops) should also be included and adapted to an all-embracing concept of noise control.

Requirements for high-quality room acoustics

Room acoustical properties include mutual speech intelligibility and the room's contribution to boost or attenuate sounds and noises, particularly in relation to speech. Due to physical reasons, characteristics related to building and room acoustics influence each other to different degrees. For instance, the resultant sound insulation between adjacent rooms depends both on the soundproofing of the wall components and on the sound attenuation achieved inside these spaces.

In this context, the focus is on two key parameters: sound attenuation and speech intelligibility. Compared to these, optimum conditions e.g. for music listening or for the students playing music themselves, are merely desirable. In the interest of all persons involved, the acoustic quality of the classrooms should therefore meet the strictest requirements. Here, both adequate noise levels and good speech intelligibility are required. Mostly, these rooms are characterized by a high occupancy rate, while hosting people who perform rather diverse activities. However, for common-type, not too complex layouts and room dimensions, the various measures of room acoustics are quite manageable. This means that both targets can be realised by applying effective measures to achieve sound damping inside a space and, in some cases, noise screening. Measures designed to direct or even scatter the sound can be neglected. Consequently, planners in most cases will recommend installing sound absorbing surfaces.

The relevant parameter for characterising the sound insulation of interior spaces is given by the reverberation time. In conventional school rooms (with the exception of the assembly hall, for instance) reverberation time directly correlates with speech intelligibility and the reduction of the noise levels, so that an adequate reverberation time in school rooms can be seen as a primary requirement in acoustic planning, which can be quantified according to the German standard DIN 18041 [18]. In open-plan solutions without any structural separation of spaces and which are used for different purposes, it is recommended to implement the sound insulation level for classrooms everywhere. This will save the option of versatility in usage and for short-term alterations. There is no need for concern that spaces with mixed usage will suffer disadvantages if the above-recommended high level of sound insulation is realised.

In the case of larger sports halls, however, an expert-defined reverberation time should be observed, which takes into account the often rather diverse uses of such a hall.

Entrance areas and central corridors are often overlooked or at least treated insufficiently. Precisely when there is no separate entrance area, they are important places of communication, e.g. in primary schools, where the informal exchange among parents and teaching staff takes place.

Strategies for good room acoustics

To implement sound absorption measures, a wide spectrum of products made of many different materials is available on the market. The reasonable combination of various building components, which cover the entire relevant frequency range, is deemed most promisingly. Here, the lower part of the frequency range is the most difficult to implement. It is therefore recommended to ensure a minimum plenum depth of 200 mm when mounting customary suspended acoustic ceilings. Special low-frequency absorbers are best positioned at corners and edges of indoor spaces. When choosing the materials, attention should be given to issues regarding fire protection, indoor-air hygiene and mechanical strength. For freely suspended acoustic screens, practical cleaning options should be planned. Likewise, regular renovation measures or minor decorative repairs have to be taken into account. For instance, many room acoustics solutions do not allow simple re-painting, thus sometimes requiring the interior layers of building components to be completely replaced.

In open-plan learning environments, partitions or screens which are known from applications in office landscapes provide potential solutions, either as a mobile individual element or integrated with furniture. Mobile partitions can be used as storage space, design elements and variable visual separation while providing valuable surfaces for sound absorption.

It should be noted at this point that there is yet another potential solution for re-designing interior spaces to reduce noise, which may be limited, but is widely recognized and should be used, namely the choice of floor coverings and furniture as well as sports and playground equipment. For instance, the interface of floor coverings and the chairs moved around on top of it allows implementing several known options for noise reduction without affecting mobility or daily cleaning. Similar 'sources of noise' (squeaking, creaking, knocking) are also associated with other furniture and can also be optimized.

REFERENCES

[1] DIN EN 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

[2] Mørck, O., Paulsen, A. Steiger, S., Erhorn-Kluttig, H., Erhorn, H., Zinzi, M., Buvik, K., Thomsen, K.E. 2013. Screening of Energy Renovation Measures for Schools – Germany, Denmark, Norway, and Italy. Deliverable from an international project within the 7th Framework Programme of the European Union project, School of the Future.
Available:
http://www.school-of-the-future.eu/index.php/project-results

[3] In German:
Stratbücker, S.; Park, S.; Bolineni, S. R.: Efficient radiation simulation for a thermal comfort model (Effiziente Strahlungssimulation für ein thermisches Behaglichkeitsmodell), Bauphysik, 35 (2013), 1, S. 30-37.

[4] ISO 7730:2005. Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria

[5] Erikson, J.; Nielsen, J. R. 2002: Ventilation in educational buildings. Report from the EU-THERMIE project: MEDUCA – Model Educational buildings for energy efficient integrated design. SP Swedish National Testing and Research Institute.

[6] In Danish:
Øien, T. B.; de Place Hansen, E. J.; Gunnarsen, L. 2012. Volatile organic compounds in indoor air (Flygtige organiske forbindelser i indeklimaet). Statens Byggeforskningsinstitut, Aalborg Universitet.

[7] In Danish with parts in English:
BR 10 - Danish Building Regulation 2010 (Bygningsreglement 2010). Danish Enterprise and Construction Authority. The Danish Ministry of Economic and Business Affairs.
Available:
www.bygningsreglementet.dk

[8] In German with English abstract:
Umwelt Bundesamt, 2007, Evaluation of indoor air contaminants by means of reference and guideline values (Beurteilung von Innenraumluftkontaminationen mittels Referenz- und Richtwerten), Bundesgesundheitsbl-Gesundehietsforsch-Gesundheitsschutz 7.

[9] Kephalopoulos, S., Koistinen, K., Kotzias,D. et. Al. 2013. Harmonisation of indoor material emissions labelling systems in the EU: Inventory of existing schemes, European Collaborative Action: Urban air Indoor environment and Human exposure, Report No.24.
Available:
http://www.inive.org/medias/ECA/ECA_Report24.pdf

[10] AgBB Committee for Health-related evaluation of Building Products (AgBB). 2012. A contribution to the Construction Products Directive: Health-related Evaluation Procedure for Volatile Organic Compounds Emissions (VOC and SVOC) from Building Products
Available:
http://www.umweltbundesamt.de/sites/default/files/medien/377/dokumente/agbb_evaluation_scheme_2012.pdf

[11] Kephalopoulos, S., Geiss, O., et. al. 2013. Harmonisation framework for health based evaluation of indoor emissions from construction products in the European Union using the EU-LCI concept, European Commission, European Collaborative Action: Urban air Indoor environment and Human exposure, Report No.29.
Available:
http://ihcp.jrc.ec.europa.eu/our_activities/public-health/indoor_air_quality/eca/jrc-published-harmonisation-framework-health-based-evaluation-emissions

[12] In German:
Innenraumlufthygiene-Kommission des Umweltbundesamtes. 2008. Guideline for indoor air hygiene in school buildings (Leitfaden für die Innenraumhygiene in Schulgebäuden).

[13] In German:
Steiger, S., Hellwig, R. 2011. Hybrid ventilation system for schools (Hybride Lüftungssysteme für Schulen): FGK Nr. 183.
Available:
http://www.downloads.fgk.de/183_Abschussbericht_Hybride_Lueftungssysteme_fuer_Schulen.pdf

[14] Jagpal, R., 2006, Technical synthesis report IEA Annex 35: Control strategies for hybrid ventilation in new and retrofitted office and education buildings (HYBVENT).
Available:
http://www.ecbcs.org/docs/annex_35_tsr_web.pdf

[15] EN 12464-1: 2003. Lighting of indoor workplaces.

[16] In German:
Leistner, P.; Erhorn, H.; Reiß, J.; Geiger, M. 2013: Energieeffiziente, energetisch nachhaltige und lernförderliche Sanierung von Schulgebäuden – Anhang.
Available:
http://um.baden-wuerttemberg.de/de/pilotprojekt-energieeffiziente-energetisch-nachhaltige-und-lernfoerderliche-schulgebaeudesanierung/

[17] In German:
DIN 4109-1:2013. Sound insulation in buildings - Part 1: Requirements for sound insulation (Schallschutz im Hochbau – Teil 1: Anforderungen an die Schalldämmung).

[18] In German:
DIN 18041:2004. Acoustical quality in small to medium-sized rooms **(**Hörsamkeit in kleinen bis mittelgroßen Räumen).