Evaluation of ventilation solutions for retrofitting of schools

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ABSTRACT

In 2011, the Danish Energy Agency initiated a study into ventilation solutions for the retrofit of schools to identify the most promising technologies. The reason was an increasing awareness that the ability of school children to absorb, adapt and use knowledge was affected negatively by inadequate ventilation rates. This paper presents an output of this study. A method for evaluation of the ventilation systems is proposed. The method consists of three categories with a clear separation to create a scoring board that facilitates transparent and unbiased evaluation. The method was applied in an analysis of ventilation solutions in schools and the finding was that centralized or decentralized balanced mechanical ventilation activated by CO2 and temperature sensors in the individual classrooms has the highest score and has the best market maturity. Other solutions are possible but unacceptable performance on some performance issues thus has to be accepted. Furthermore, a set of design rules for ventilation solutions in the case of school retrofit is presented. The design rules require an analysis of the building typology before the best solution can be chosen for a specific school.

KEYWORDS

Ventilation, indoor air quality, schools, retrofitting

1 INTRODUCTION

Children spend more time in school than in any other environment besides their home. It is therefore thought-provoking that several investigations have shown that the ventilation rate in schools across the world is below recommended levels (Corsi et al., 2002; Daisey et al., 2003; Sohn 2009; Andersen et al., 2009) and that there is solid scientific evidence that this affects the ability of school children to absorb, adapt and use knowledge (Wargocki, 2015).
As a consequence of this, the Danish Energy Agency initiated a comprehensive study (Hviid et al., 2014) to identify well-functioning ventilation solutions for retrofit of schools. A similar German study was published by FGK (2004). The present study included a survey of existing knowledge, analysis and qualification of different solutions and specific recommendation of the solutions that best meet a number of criteria, such as indoor climate, energy consumption, costs and aesthetics. This paper presents the method for evaluation of the ventilation systems used in this study and the main findings from a study where the method was applied for analysis of the ventilation solutions in schools.

2 METHOD FOR EVALUATION OF VENTILATION SYSTEMS

The primary motivation for establishing ventilation in schools is to ensure a healthy and productive learning environment by providing good air quality. The secondary objective of

ventilation is to provide a mean to minimise overheating. However, there are other important issues to consider in relation the performance of a ventilation solution. The section provides a method for performance evaluation of ventilation systems.
The key performance issues of a ventilation solution are listed in the first column in Table 1. Each key performance issue has an assessable performance criterion. These performance criteria are divided into three categories with a clear separation to create a scoring board that facilitates transparent and undisputable evaluation. A newly installed ventilation system in a school is in general expected to be within category in performance issues. If the ventilation solution demonstrates *significantly* better performance than legal requirements, current standards and practice – that is for example the case if the ventilation system meets the future energy requirements of the legislation – then the category becomes "excellent". The score becomes "Unacceptable" if a performance issue is outside the range of the category "Acceptable".

There is not suggested any weighing of the performance issues in this method because it is a subjective task. The authors recommend that all evaluation parameters are considered to be equal because they all are highly relevant to any well-functioning ventilation system in a classroom. However, the user of the method is free to assign any greater weight to an issue if desired.

Table 1: Three levels of evaluation criteria ranging from unacceptable to excellent

Performance issues	Unacceptable	Acceptable	Excellent
Indoor air quality, CO_2	Above 1500 ppm	1000-1500 ppm	Below 1000 ppm
Temperature	Regularly outside 20-26 °C	Within 20-26 °C	20-23 °C
Cooling by night ventilation	-	Night ventilation is a possibility	Night ventilation by default
Draught risk	Occurring	Low risk	Not occurring
Noise, mechanical (traffic)	Above 30 (33) dB(A)	27-30 (30-33) dB(A)	Below 27 (30) dB(A)
Aesthetics	-	(Very) visible	Integrated or invisible
Filtration	-	Filtration is a possibility	Filter class F7
Specific fan power, SFP	Above 2100 W/(m^3/s)	1000-2100 W/(m^3/s)	Below 1000 W/(m^3/s)
Heat recovery	Below 70 %	70-85 %	Above 85 %
Installation costs	-	On par with central mech. vent.	30 % cheaper
Maintenance costs	-	On par with central mech. vent.	30 % cheaper

3 ANALYSIS OF VENTILATION SOLUTION IN SCHOOLS

The method presented in section 2 was used for analysis of the ventilation solutions for schools. The analysis was carried out on the basis of data from CO_2 and temperature logs of 85 different schools, and on data from manufacturer's data sheets. The CO_2 concentration was logged in selected classrooms equipped with different types of air exchange principles:

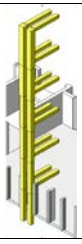
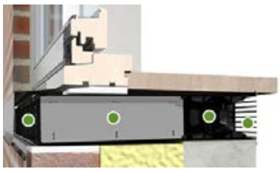
- 31 with balanced central mechanical ventilation
- 11 with mechanical exhaust
- 42 with manual airing
- 1 with automatic airing in a combined stack and cross ventilation configuration

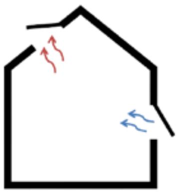
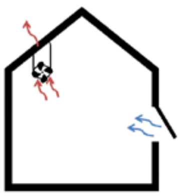
The actual air exchange (ventilation rate) was approximated from the CO_2 peak concentration and the number of students in the class.

The analyses of draught risk, aesthetics and costs were based on qualitative data collected by interviewing a number of practioneers, e.g. contractors, manufacturers, engineers, and service personnel in the European school ventilation industry. A full list of the interviewees is available in Hviid et al. (2014). The assessment of aesthetic performance was based on discussions with an architect with substantial experience in school refurbishments.

3.1 Ventilation principles

Various types of ventilation principles have been identified, examined and assessed, see the tables below. These systems cover what is considered by the authors to be representative for up to 95% of the types of ventilation solutions that can be found in schools today.

Central ventilation	**Decentral ventilation**	**Micro ventilation**	**Mechanical exhaust**	**Exhaust w/ pre-heat by air-to-water heat pump**
				
Dual ducting	Compact unit in room	Micro units in facade	Central fan and intake in facade	Heating coil in facade intake

Airing	**Automatic airing**	**Fan-assisted automatic airing**	**Hybrid ventilation**
			
Manual opening of windows	Automatic windows in cross flow configuration	Auto. window opening with fan-assistance	Airing and central mechanical

4 RESULTS

The results presented constitute only a short exempt of the comprehensive study presented by Hviid et al. (2014).

Figure 2 depicts the ventilation rate in 78 of the logged 85 schools sorted by the ventilation installation or renovation year. The figure illustrates the tendency that schools with manual airing or simple mechanical exhaust, even in newer schools, are not able to meet the current target value in the Danish Building Code. For comparison, the legal requirement in Belgium is on par with Denmark, whereas Sweden, Norway and Holland require approx. 40% more fresh air per pupil. Only newer central mechanical systems perform satisfactorily today and seem able to meet the expected future demands.

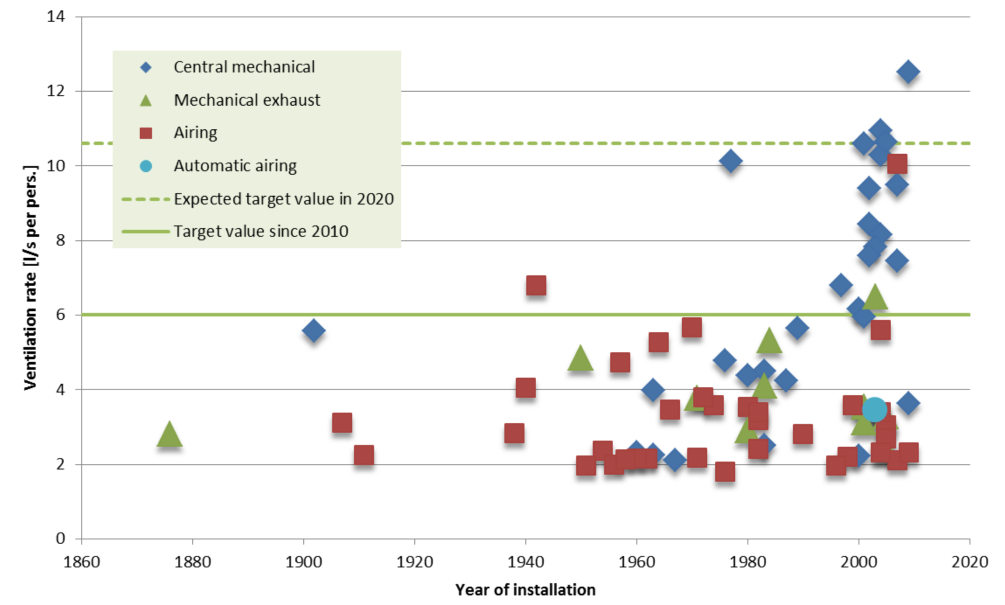


Figure 1: Ventilation rates from classrooms in 78 different schools. The target values are approximately identical to the current and the future requirement in the Danish Building Code

The costs of installing and maintaining different ventilation systems over a period of 20 years are shown in Figure 3. Airing has no costs because it only requires the openable windows to be serviced. The cost for this is considered to be part of the general building maintenance. Installing systems for automatic window opening only requires a rather small extra installation and service costs whereas combining automatic airing with mechanical ventilation in a hybrid solution is quite expensive. The maintenance costs for micro ventilation reflects the expected lifespan of the mini fans which by build quality and sheer number poses a significant service risk.

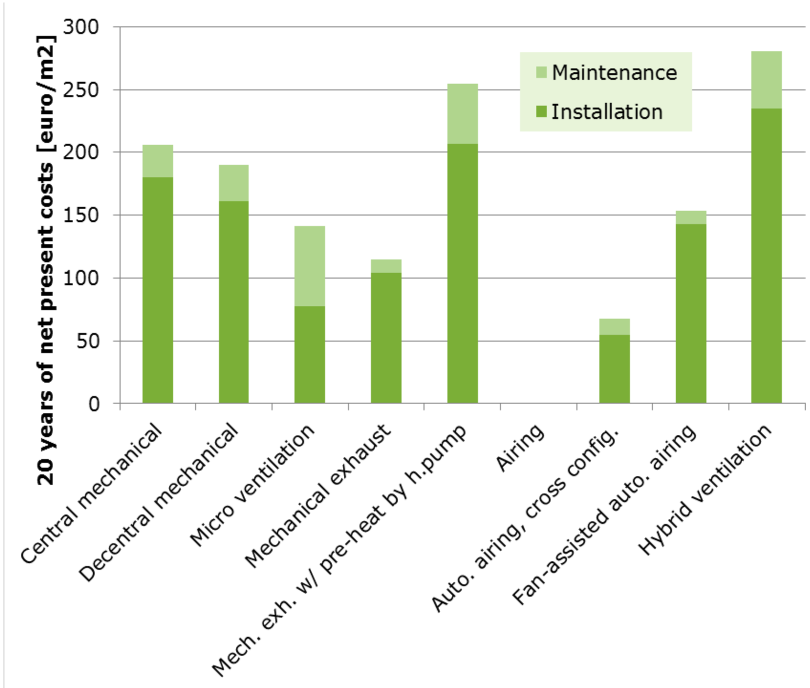


Figure 2: The costs of installing and maintaining different ventilation systems over a period of 20 years in a classroom. Discount rate 2.0%

It has been difficult to measure the exact energy consumption of the logged ventilation systems and the information sources were error prone. Instead we presumed that future installations are more energy efficient than the old ones due to continuous product development. Figure 4 shows the yearly heating and electricity consumption per m^2 in a classroom on the basis of the expected efficiencies of new installations listed in Table 2. The simulation was carried out in a simple building simulation tool based on the quasi-static method in ISO 13790 (2008). Cooling down the building thermal mass by night ventilation was crucial to keep the temperature within comfortable range and it is in general recommended to use night ventilation whenever possible. Furthermore, figure 4 shows that heat recovery should be of major concern in a new ventilation installation and that care should be taken not to let the introduced extra electricity consumption exceed the heatingsavings.

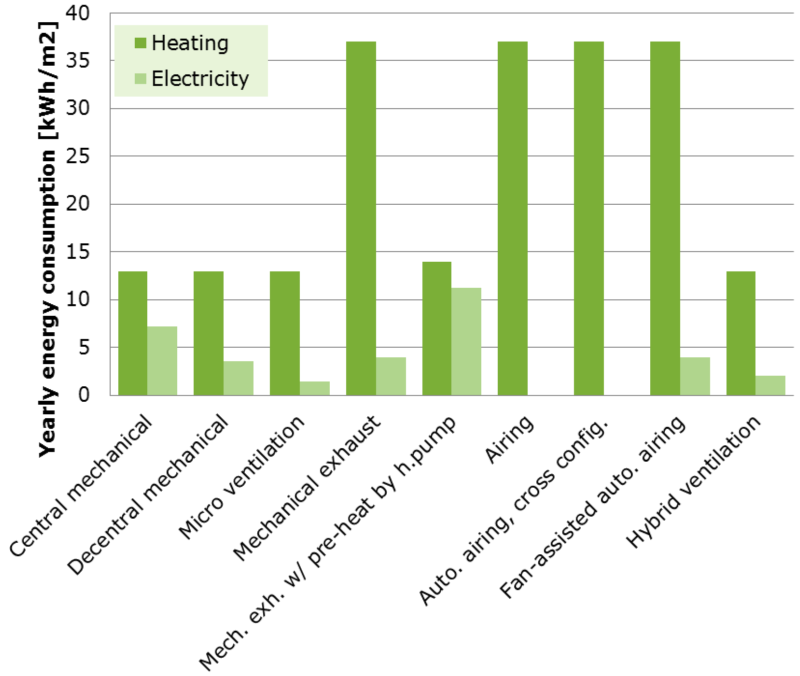


Figure 3: The yearly energy consumption for different ventilation principles in a classroom

Table 2: The energy-related ventilation properties used to simulate the total energy consumption in a classroom in a Danish climate. Specific fan power

	SFP W/(m^3/s)	Heat recovery	Night ventilation
Central mechanical	1.500	85 %	Yes
Decentral mechanical	700	82 %	Yes
Micro ventilation	300	85 %	Yes
Mechanical exhaust	800	0 %	Yes
Mech. exch. w/ pre-heat by h.pump	2.300	80 %	Yes
Airing	0	0 %	No
Automatic airing	0	0 %	Yes
Fan-assisted automatic airing	800	0 %	Yes
Hybrid, two-mode	1000	80 %	Yes

Table 3 depicts the scoring chart of different ventilation systems based on the logs in 85 different schools, interviews with practioneers at all levels in the European school ventilation industry, energy simulation results based on the expected or required performance of future installations and other national and international sources.

Most noticeable are the draught risks that were reported for some of the systems. The common denominator of these systems is that they supply air directly into the comfort zone and even when the air was pre-heated in the façade, significant problems with draught risks were still reported. Some of the systems do not filter the air (marked with a white cell and a “d”), and this could pose a problem in areas with a lot of pollen allergies or in polluted urban areas.

Table 3: The scoring chart of different school ventilation systems. Dark indicate excellent performance, light is acceptable (legal), and stripes indicate illegal or troubling performance. White cells mean either that the variable has no meaning in this specific context, or that is does not constitute a violation of the legislation

	Central mechanical	Decentral mechanical	Micro ventilation	Mechanical exhaust	Mech. exhaust w/ preheating by air-to-water heat pump	Airing	Automatic airing, cross configuration	Fan-assisted automatic airing	Hybrid, two-mode
Indoor air quality, CO_2				a					
Temperature									
Cooling by night ventilation									
Draught risk							b	b	
Noise mechanical/traffic							c	c	c
Aesthetics									
Filtration			d	d		d	d	d	e
Specific fan power, SFP									
Heat recovery				f		f	f	f	
Installation									
Maintenance									

a) Evidence suggests that simple mech. exhaust performs usually ok to keep the CO2 level acceptable.
b) Without special measures the draught risk is eminent. The risk should be evaluated carefully in each application with detailed simulations
c) Acceptable performance requires silencer devices in the facade (Hviid et al., 2014), if the facade openings are oriented towards traffic. School yards my also require similar sound dampening devices to be installed.
d) For ventilation principles with facade openings filtration is not a legal requirement.
e) Hybrid two-mode uses facade openings in the summer but for a large part of the year, the intake air is filtrated through the mechanical ventilation system. Consequently the performance is acceptable.
f) Heat recovery is not a legal requirement in this type of ventilation system

5 DESIGN RULES

The evaluation method described in section 2 covers the aspects of ventilation in schools However; in the case of school retrofit the building's design typology is crucial to the appropriate choice of ventilation system. Especially the constructive principle is often decisive when the optimal ventilation solution is to be recommended as changes that compromise the structural system are expensive. For example, it is expensive (maybe even impossible) to install a central balanced ventilation system in a building with heavy load-bearing interior walls due to the need of ducts penetrating the existing bearing structure. Table 4 provides a design for choosing the most appropriate ventilation solution for different building typologies. For further details see Hviid & Petersen (2012).

Table 4: Recommended design rules for retrofitting of schools with ventilation

Principle	Recommended design rules
Central mechanical	Best suited for buildings with mainly light partitions that are cheap to penetrate with ducts or one-storey buildings where ducts can be routed on the roof. If the systems are visible, aesthetics should be considered. Height in corridor > 3.2 m Room height for diffusers in the ceiling > 2.5 m: Room height for inlets in the wall > 2.8 m, if height from inlet to ceiling is < 0.3 m
Decentral mechanical	Best suited for schools with many load-bearing walls that blocks easy routing of ducts Does take up floor space or space in the façade which will reduce the available daylight. Internal and external aesthetics must be considered. Room height > 2.8 m Room depth > 5x room height To ensure the ventilation effectiveness and minimize the risk of draught, the inlet should be placed close to the ceiling. Distance from inlet to ceiling < 0.3 m Avoid objects in the jet path, e.g. lighting fixtures or beams A mockup is recommended for assessing noise issues
Micro ventilation	Best suited for schools with many load-bearing walls that blocks easy routing of ducts Should be placed as high as possible above the comfort zone to avoid draught. Distance from inlet to ceiling < 0.3 m
Mechanical exhaust	The largest potential is in schools with existing vertical shafts but the air distribution is critical and the intake through openings in the façade creates significant draught risks. The analyses shows inadequate performance Room depth < 5x room height
Mechanical exhaust with pre-heating by air-to-water heat pump	Intake through openings in the façade creates significant draught risks, even if the intake air is pre-heated. Façade coils suffers from freezing if the heating and ventilation system controls are not aligned
Airing	Should be avoided or at least supplemented with nudging features, e.g. a CO2 traffic light that compels the user to open the window (Wargocki and Da Silva, 2015). Room height > 2.7 m Room depth < 2x room height Not possible in facades towards traffic
Automatic airing, cross configuration	Requires special room designs, e.g. large room volumes and ventilation between facade-facade or facade-skylight. Detailed simulations of the performance is recommended to assess the indoor air quality and to avoid the risk of draught Room height > 3.2 m Room depth < 5x room height Not possible in facades towards traffic
Fan-assisted automatic airing	Room height > 2.7 m
Hybrid, two-mode	The design rules for airing and central mechanical apply.

6 CONCLUSIONS

This paper presents a score chart for transparent and unbiased evaluation of different school ventilation solutions. Nine different ventilation principles has been evaluated and compared on the basis of quantitative and qualitative analyses. The main conclusion is that centralized or decentralized balanced mechanical ventilation activated by CO_2 and temperature sensors in the individual classrooms has the highest score in the method and has the best market maturity. Automatically controlled hybrid ventilation, i.e. automatically controlled airing and mechanical ventilation in combination, is performing excellent on many performance issues except costs. The cheapest solution is airing in combination with some nudging feature that persuades the user to open the windows. Another promising principle with very low installation costs and low energy is micro ventilation. However, it suffers from lack of filtration and from uncertainties concerning the exact service costs and lifespan.

A set of design rules for ventilation solutions in the case of school retrofit is presented. The design rules require an analysis of the building typology, e.g. structural principle, room height, room depth, possible location of ventilation inlet and routing, before the best solution can be chosen for a specific school.

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