Energy consumption, thermal comfort and indoor air quality in schools

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ABSTRACT

School buildings in Flanders are quite old. They cause concern not only about energy efficiency but also about thermal comfort, indoor air quality, speech intelligibility and visual comfort. To evaluate the correctness of the concerns, energy consumption was monitored in 18 schools, while in each of them a classroom was selected for detailed measurements on comfort and indoor air quality. The results justify the concern. Energy consumption per pupil varies significantly, from low to really high. The reasons for that are quite clear: poor heating system control, hardly a nighttime and weekend setback, un-insulated buildings. CO_2 in almost all classrooms peaks at values far beyond 1500 ppm, which underlines that the air quality is a problem. Thermal and visual comfort anyhow did not pose many problems. The research resulted in a series of design guidelines for school buildings with low energy consumption, good comfort and excellent indoor air quality.

KEYWORDS

School buildings, energy consumption, thermal comfort, CO_2 measurements, indoor air quality, ventilation

INTRODUCTION

School buildings in Flanders are quite old. Of the eighteen schools that participated in the actual study, one dated from 1895. Six were built between 1918 and 1940; five between 1945 and 1975 while only six were rather recent, built between 1975 and 2002. The aging school building stock causes concern, not only about energy efficiency but also about thermal comfort, indoor air quality, speech intelligibility and visual comfort.

All countries that are confronted with aging school buildings, share that concern. Nielsen (1984) monitored the CO_2 concentration in eleven schools in Denmark. Norback et al. (1990, 1995) did the same in six schools in Sweden. Lee et al. (1999) looked to five classrooms in Hong Kong and Kolokotroni et al. (2002) analyzed four classrooms in the UK. They all had to conclude that even the average CO_2-concentrations were too high during teaching. Heath et al. (2002) searched for a relationship between the indoor environment and student performance. Daisy et al (2003) reported on a literature review on health, ventilation and indoor air quality in schools. Both concluded that students' activity suffers from bad air quality.

In Belgium, Vermeir et al. (2003) measured the speech transmission index and reverberation time in 47 classrooms. A too low value was recorded in 20 of them, indicating a net shortage in sound absorbing surfaces. Wouters (1989) evaluated indoor air quality a first time. The results were disappointing as peaks up to 5000 ppm were noted.

In the schools selected for the present study, energy consumption was analyzed while detailed measurements on thermal comfort, indoor air quality and visual comfort were performed in one classroom per school.

PERFORMANCE REQUIREMENTS

Requirements differ between countries. For thermal comfort for example, European countries use the same standard (EN ISO 7730) but they handle other criteria, table 1. The same holds for CO_2, table 2.

TABLE 1
Thermal comfort criteria

	Metabolism Seated people	Winter		Summer	
		I_{clo}	Operat. temp. °C	I_{clo}	Operat. temp. °C
Belgium			20-24		
The Netherlands	1.2 met	0.9 Clo	20-24	0.7 Clo	21-25
Germany	1.2 met	1.0 Clo	21±2.5	0.5 Clo	
France			20-21		

TABLE 2
Acceptable CO_2-concentration

	ppm
Belgium	-
The Netherlands	1200
Germany	1500
France	2000
EU	IDA 1 800 IDA 2 1000 IDA 3 1500

In the case being, no requirements could be imposed on energy as schools are not subjected to any legal performance in Flanders. Thermal comfort was judged using Fanger's approach: percentage of dissatisfied $\leq$ 10%, predicted mean vote $\leq$ |0.5|, operative temperature between 19 and 23°C, PD for draft<20% (Fanger, 1970). Indoor air focused on relative humidity between 30 and 70% and maximum $C0_2$-level not beyond 1500 ppm. Visual comfort was checked by looking to the illuminance on the black board ($\geq$ 500 Lux), the illuminance on the desks ($\geq$ 300 Lux), the illuminance uniformity and the daylight factor ($\geq$ 3%)

SCHOOLS

The schools that participated in the research were quite different in size and number of scholars (table 1). Some are primary schools, other gymnasiums and technical schools or so called 'special' schools. Two follow 'alternative' didactics, most keep it 'traditional'.

MEASUREMENTS

Information on energy came from the analysis of the bills of the last two or three years. Thermal comfort was studied through (1) measuring air temperature and relative humidity from October 2003 to January 2004 on a 10' basis, using calibrated HOBO data loggers, (2) measuring the air temperature, the radiant temperature, the air velocity and the relative humidity during a 48 hours period using a calibrated B&K comfort meter the meter in the middle of the classroom and the sensors at head-height of the seated scholars, (3) conducting an enquiry between the scholars, based on the ASHRAE seven point scale. Indoor air quality was monitored indirectly, by measuring CO_2 on a 30” basis during 2 days with a Vaisala Carbocap sensor. The CO_2-meter stood near the comfort meter. CO_2 and partial inside water vapor pressure excess were used to evaluate ventilation. Illuminances finally were measured with a Testoterm Lux meter.

RESULTS AND DISCUSSION

Energy consumption

Table 3 gives the heating and primary energy consumed per scholar, standardized for the reference year. The differences between schools are striking. Some are quite efficient, see school 15, others demand huge amounts of energy, see school 3. No correlation exists between the primary energy consumed, the type of school, the number of scholars and the age of the building. On the contrary, the most recent schools (10 and 14) are not the most efficient ones! Likely reasons for the differences are: (1) a too simple control (see column 6 in table 3), (2) quite high temperatures in some classrooms, (3) differences in heated volume per scholar, (4) insulation quality of the envelope.

TABLE 3
Annual primary energy consumption per scholar

School	Age	Type	Number of scholars	Heating energy per scholar MJ/(a.scholar)	Nightime and weekend setback?		Primary energy per scholar MJ/(a.scholar)
1	1975	Gymnasium	800	10110	YES	YES	12393
2	1950	Gymnasium	1050	3624	NO	NO	5126
3	1988	Technical	925	13781	NO	NO	21809
4	<1940	Primary	185	6204	?	YES	9609
6	1980	Gymnasium	320	7963	YES	YES	8427
7	1905	Gymnasium	2006	9902	NO	NO	13217
8	<1940	Special	183	9625	NO	NO	12365
10	2002	Special	288	3185	YES	YES	8668
11	1895	Primary	600	8309	NO	YES	10378
12	1985	Gym.+Tech.	661	3047	NO	YES	3887
13	<1940	Gymnasium	641	4293	NO	NO	6515
14	2002	Primary	240	10179	NO	NO	11908
15	<1940	Primary	207	3462	YES	YES	3874
16	1990	Primary	163	6613	NO	NO	9256
17	<1940	Gymnasium	1256	4316	YES	YES	5476
18	1962	Gym.+Spec.	510	8448	YES	YES	9230
			Average	7066			9509
			Standard dev.	3114			4215

Thermal comfort

The three evaluation methods gave opposite results, see figure 1 and 2. The two days check with the comfort meter and the long term measurement with the Hobo-loggers both show that on the average winter comfort during class hours is not a problem. The enquiries instead reflected quite some dissatisfaction with the thermal environment. That difference learns that when enquired, scholars and teachers react on the extremes they experienced during the past months, while the comfort meter and hobo results are calculated average votes over 2 days, respectively 3 months. Clearly, the information measurements and enquiry give is different.

This was not the case for draft. There the measured PD-value and the enquiry result both showed that the number of dissatisfied hardly passed 20%. Globally, winter comfort in classrooms does not seem to be an issue.

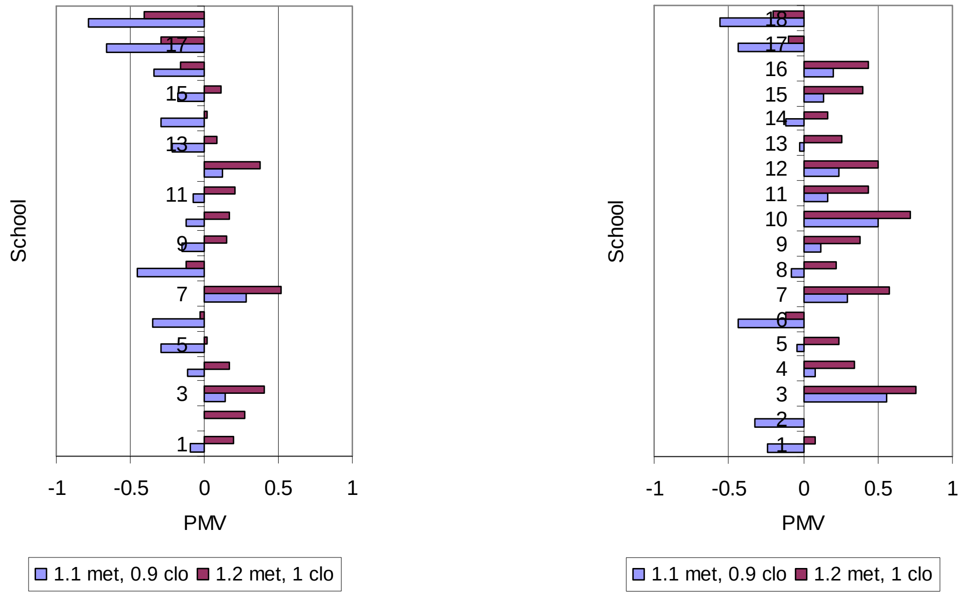

Figure 1: Two-days check (left) and long term measurement of wintertime thermal comfort in the 18 class rooms

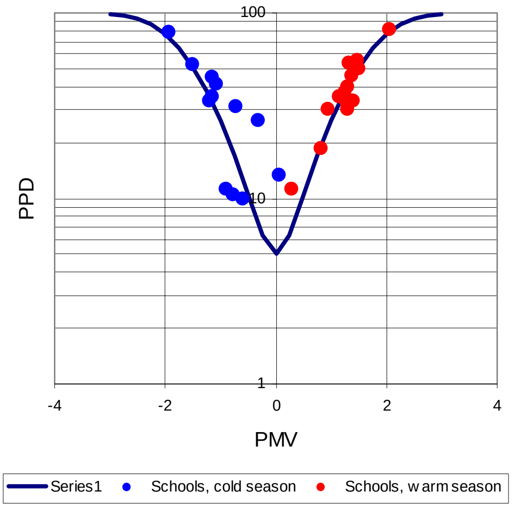

Figure 2: Comfort enquiry, scholars mean comfort vote for cold (blue) and warm days (red)

Indoor air quality

Figure 3 summarizes the results of the CO_2 measurements in 19 classrooms. In fact, in school 6, two classrooms, one with adventitious ventilation and the other with forced ventilation, were monitored. From the results, it appears that the air quality during class hours is not acceptable. In all classrooms except two, the CO_2 peak largely passes the 1500 ppm limit, while in nine classrooms, even the average goes beyond that limit.

The reason is straight forward. Eighteen classrooms (7 is the exception) are ventilated by opening windows. Hence, teaching with open windows is not an attractable choice: too much draft, too cold in winter, too noisy, paper that flies, etc. With closed windows, only infiltration is left, resulting in a dramatic drop in ventilation flow. A classroom has a volume of 170-200 m^3. The infiltration rates calculated from the CO_2 increments were as low as 0.5 h^{-1}. That brings the ventilation flow down to 85-100 m^3/h. Classes may be quite populated, 30 scholars is no exception. Included the teacher, only 2.7 to 3.2 m^3 fresh air per hour and per person is then delivered. For a metabolism of 1.2 met and a CO_2 maximum of 1500 ppm, a ventilation flow of $\approx$16 m^3/(person.h) is needed, which means a total of 500 m^3/h during class hours. In the case being, that condition was only fulfilled in the classrooms 3, 8, 10 and 12. All others, i.e. 76% of the total, gave problems. See figure 4.

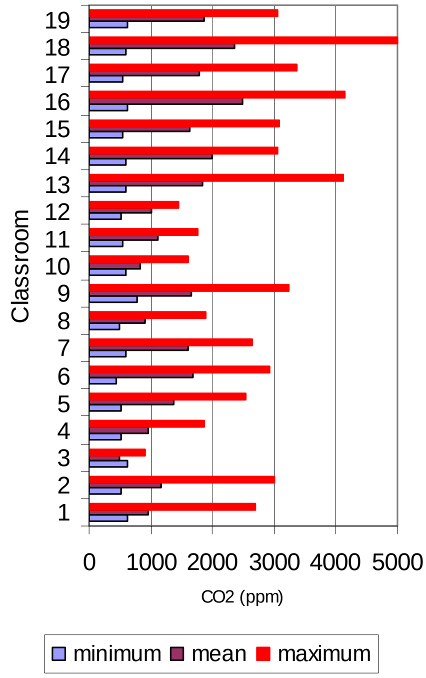

Figure 3: CO_2 concentrations in 19 classrooms during teaching, minimum, mean and maximum value measured

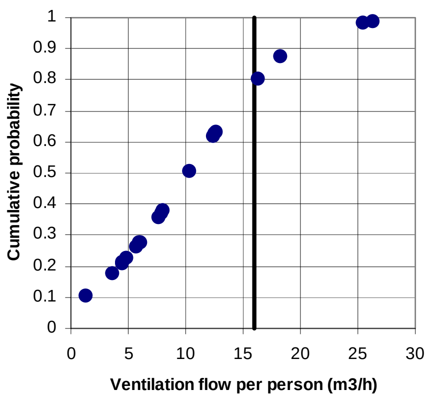

Figure 4: Measured ventilation flow per person in case the classrooms monitored are used by 30 scholars. Cumulative curve

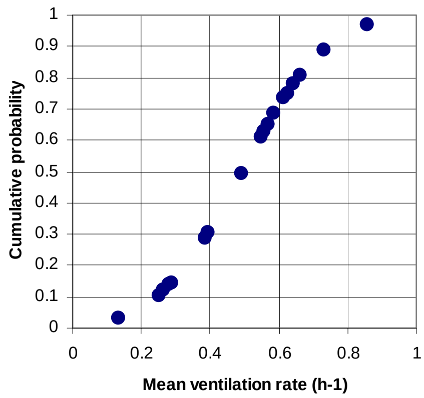

Figure 5: Mean ventilation rate in the 18 classrooms as deduced from the inside vapor pressure excess.

Looking to the poor ventilation, one could expect that relative humidity and vapor pressure also touch high values. This was not the case, mainly because the outside vapor pressure in a moderate, cool climate is quite low in winter and the vapor release by teacher and scholars remains restricted and block-wise. In fact, after each class hour of 50’ tot 90’, in most classrooms windows are opened during 10’. As a result, in nine of the eighteen classrooms, relative humidity even dropped periodically below 30%. The inside vapor pressure excess in turn was used to evaluate the average ventilation rate in the classrooms over the whole test period. The results are summarized in figure 5.

Visual comfort

The measurements showed that desk illuminance in most classrooms passed 300 Lux. In none of them however, a daylight factor even touching 3% was measured, while illuminance uniformity was worse than the 0.7 demanded between the minimum and the mean. Also blending could pose problems. Yet, despite these negative items, visual comfort was not perceived as a problem.

CONCLUSIONS

Eighteen schools were evaluated on energy consumption, thermal comfort, indoor air quality and visual comfort. The results confirm the concerns about high energy consumption and bad indoor air quality. Indeed, although quite some variation was noted, most schools do not use energy efficiently. Not a possible excessive ventilation, but a heating system with too simple controls, sometimes the quite high temperatures in classrooms, the large building volume per scholar and the absence of any insulation are the main reasons for that. Thermal and visual comfort is not an issue but indoor air quality is. The high CO_2-concentrations noted are a direct consequence of the absence of any designed ventilation system. Compared to the situation encountered by Wouters in 1988, nothing changed. Still, adventitious ventilation should but cannot deliver the fresh air needed during class hours.

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