A STUDY OF CARBON DIOXIDE CONCENTRATIONS IN ELEMENTARY SCHOOLS

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ABSTRACT

The present study aims at investigating carbon dioxide (CO_2) concentrations inside elementary schools' classrooms and how students' productivity is affected. Measurements were conducted in 9 naturally ventilated schools of Attica from April to May 2013. Monitoring lasted for 7 hours per day, for a period of one to five days per school. CO_2 concentrations were monitored simultaneously in the inside and the outside environment of the classrooms. Indoor concentrations of CO_2 in almost all schools were higher than the ASHRAE threshold limit values. In order to examine the effect of CO_2 concentrations on students' productivity, they were asked to take two productivity tests during their stay at school. Results showed that, higher concentrations of CO_2 have a negative impact on students' productivity. Also, the effect of window opening on CO_2 concentration was further examined and there has been an effort to correlate indoor and outdoor CO_2 concentrations. Finally, the correlation between the occupancy density and the increase of CO_2 concentrations was also investigated.

KEYWORDS

Schools, student performance, ventilation, occupant density, CO_2

1 INTRODUCTION

Air quality in school buildings is a matter of great concern with students spending almost 30% of their time inside classrooms, more time than in any other building environment except their home (Mendell and Heath 2005; Grimsrud et al. 2006). Furthermore, schools present a much higher occupancy than any other building, having four times as many occupants per unit of area compared to office buildings (EPA 1995). In addition, students belong to a quite vulnerable group of people who can easily be affected by chemical factors emitted in schools' premises (EFA 2001).
For the past decade there has been a scientific interest on the effects of the degraded indoor environment to students and office workers performance and productivity (Wargocki et al. 1999; Wargocki et al. 2000; Witterseh et al. 2004; Mendell and Heath 2005) however knowledge on that area is insufficient.
The main objectives of this study are to examine: 1. the effect of CO_2 to students' productivity, 2. the effect of occupancy density, window opening and ventilation rate to the CO_2 concentration, 3. the correlation between indoor and outdoor CO_2 concentration and 4. to evaluate the schools' ventilation rate.

2 METHODOLOGY

In this paper secondary data analysis is conducted, based on existing data, in order to investigate research questions other than the ones raised during the original study. Details on the original methodology can be found in Dorizas' papers (Dorizas et al. 2013a; Dorizas et al. 2013b; Dorizas et al. 2013c). In brief the above mentioned studies were carried out in 9 naturally ventilated primary schools of Attica, Greece (Figure 1), for a 32 days period, between April and May 2013. Details on the schools and the classrooms where the measurements were conducted are shown in Table 1. In total 193 students participated in the survey and undertook 1310 performance tests.
The current study comprises the effect of CO_2 concentration on students' performance and the correlation of occupancy density to CO_2 concentrations and diurnal CO_2 concentrations. Also it involves the comparison between indoor to outdoor CO_2 concentrations, the correlation of CO_2 concentration to window opening, ventilation rate and lastly the evaluation of the schools' ventilation rate.

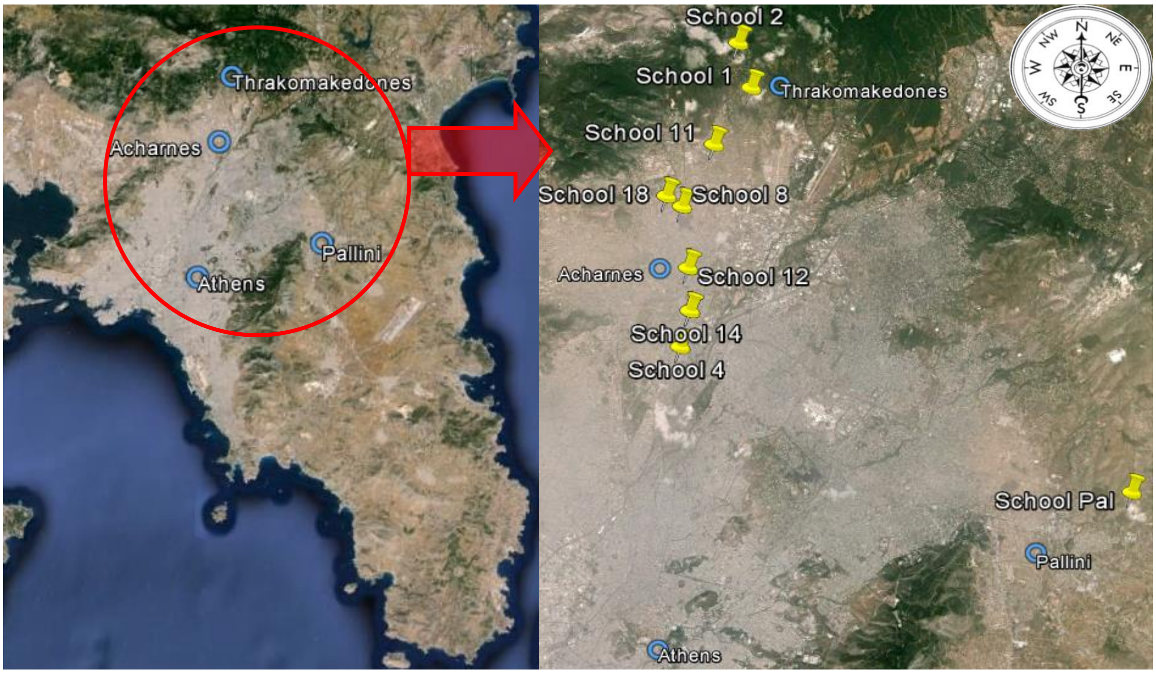

Figure 1 : Map of Attica (left) and locations of schools under study (right)

Table 1: Schools' characteristics

School Code	School Name	Classroom's Volume (m^3)	Number of Students in the Classroom	Measurement Period
School 1	Thrakomakedones 1	198	25	8-12/4/13 (5 days)
School 2	Thrakomakedones 2	162	25	20-24/5/13 (5 days)
School 4	Acharnae 4	155	24	14-18/4/13& 24/4/13 (5 days)
School 8	Acharnae 8	159	19	27-29/5/13 (3 days)
School 11	Acharnae 11	172	15	31/5/13 (1day)
School 12	Acharnae 12	157	25	13-17/5/13 (5 days)
School 14	Acharnae 14	165	17	1-5/4/13 (5 days)
School 18	Acharnae 18	138	18	23/4/13 (1 day)
School Pal	Pallini	137	25	19&22/4/13 (2 days)

2.1 Measurements of CO_2 and Ventilation

The concentrations of CO_2 were measured in one classroom of each school from 7.30 a.m. to 2.30 p.m. Inside the classrooms the measurements were conducted using the MultiRAE IR (RAE Systems) while outside the classrooms, the concentrations were measured using the Innova 1312 & 1303. Both instruments calculated CO_2 concentrations in units of parts per million (ppm). In order to be able to compare the indoor to the outdoor concentration, lab tests were conducted, under controlled conditions, so as to calculate a correction coefficient between the two instruments. Classroom ventilation was also measured with Innova 1312 & 1303. The "Rate of Decay" method (Hitchin & Wilson 1967) was used in which, a quantity of sulfur hexafluoride (SF6) was released in the classrooms near a low speed fan, after school hours. The purpose of the fan was to produce a uniform concentration inside the classrooms. The concentration decay was exponential and by sampling the air at several times the apparent ventilation rate was determined in air changes per hour (ach).

2.2 Performance tests

The performance tests and operative protocol were taken from the SINPHONIE project, the Schools Indoor Pollution and Health: Observation Network in Europe aiming to improve the air quality in schools. Students were given a 'code' of symbols, in which each symbol was associated to a digit number. They had 120 sec. to complete the relevant symbols at a given series of numbers. They were asked to fulfil two tests each day, one in 10.00 a.m. and one in 13.30 p.m. Full detail of the methodology followed for the productivity tests is described in Dorizas' paper (Dorizas et al. 2013c).

3 RESULTS AND DISCUSSION

3.1 Performance Scores vs CO_2 Concentrations

In order to be able to compare the concentration of CO_2 to the results of the productivity test, a 15 minutes average was calculated (approximately 15 minutes was the duration of the test). Figure 2 shows the average test scores of each day of each school for the code test (1st and 2nd). Also the figure illustrates the average concentration of CO_2 at the time students took the test. From the graph we can see that, in 26 out of the 28 days the score of the second test was higher compared to the first. Also, the concentration of CO_2 during the second test was lower than the CO_2 concentration of the first test. As a result, in the great majority of the cases (24 out of 28), lower CO_2 concentration led to a higher test score. Taking into consideration the above finding, we can conclude that there is a negative correlation between the performance scores and CO_2 concentrations. This result comes in agreement with Dorizas' result (Dorizas et al. 2013c) where, there had been a similar analysis calculating the average productivity test score for each school (not for each day of the measurements).

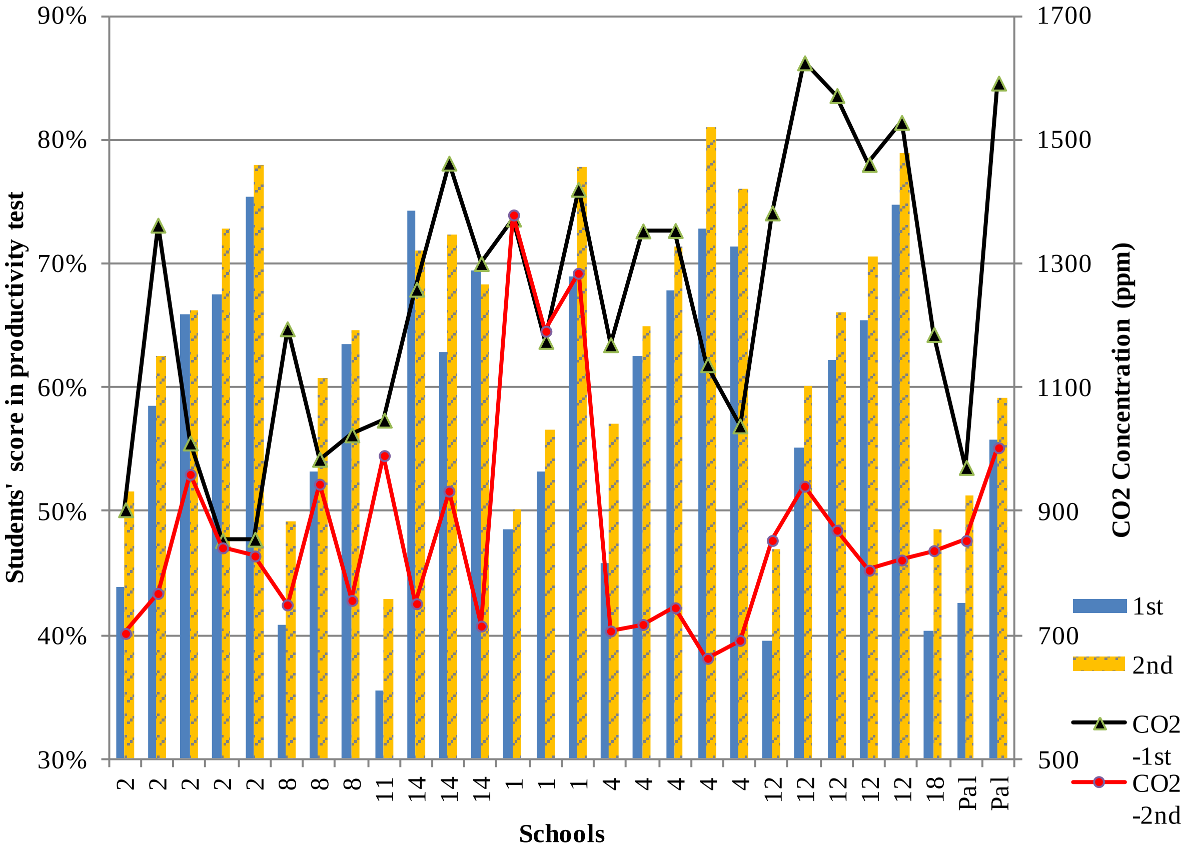

Figure 2 : The trend of test scores per school per day and corresponding CO2 concentrations

3.2 Increase of CO_2 Concentration due to Occupancy Density

Occupancy density was correlated to CO_2 concentration so as to investigate the impact of the class' area available to each student to the increase of CO_2. In order to calculate the effect of students' presence on CO_2 concentrations, we subtracted from the CO_2 peak the background concentration (the one that was measured before the arrival of the students). The results were divided into three groups depending on the window opening surface in square meters (m^2) during the lessons. In order to do that division, the surface area of the windows of each class was measured and then the average value for each group was found. The first group comprises the cases that the classroom's windows were closed during the lesson and opened in the break (Figure 3). In the second group, one window was opened halfway the lesson hour (Figure 4). This scenario corresponds to a mean opened window surface of 1,56 m^2. The third group includes the cases during which two windows were open throughout the lesson time (Figure 5). This scenario corresponds to a mean opened window surface of 3,28 m^2.
It is obvious from all the diagrams that, there is a clear correlation between occupancy density and CO_2 concentrations. All figures indicate that the higher the occupancy density, the lower the CO_2 concentration, meaning CO_2 concentrations reach lower rates when there is more space available per person. It is also found that the value of the correlation coefficient decreases with the window opening. That indicates that, window opening plays a key role in CO_2 concentrations. From Figure 3 it can be seen that, when the windows are closed there is a strong correlation between CO_2 and occupancy density (R^2 = 0,68) with occupancy density affecting primarily CO_2 concentrations when outdoor air is not entering the classroom. For the cases where air from the outside of the classroom comes to the inside the figures indicate that the occupancy density does not significantly affect the CO_2 concentrations. In particular, a moderate correlation is observed for a window opening of 1,56 m^2 (one window open) in

Figure 4 (R^2 = 0,57) while a weak correlation is observed for a window opening of 3,28 m^2 (two windows open) in Figure 5 (R^2 = 0,32).

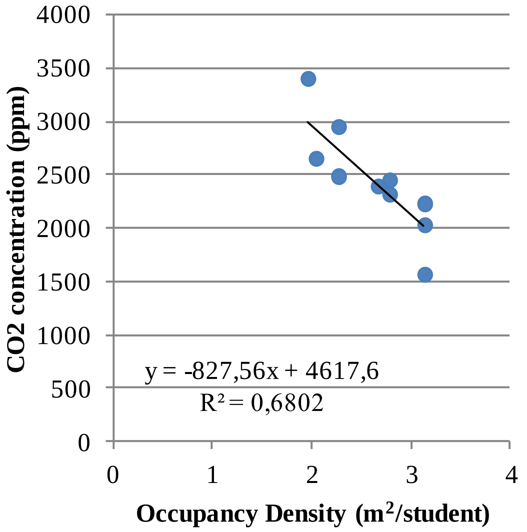

Figure 3 : Occupancy density correlated to CO_2 concentration for closed windows during the lesson time

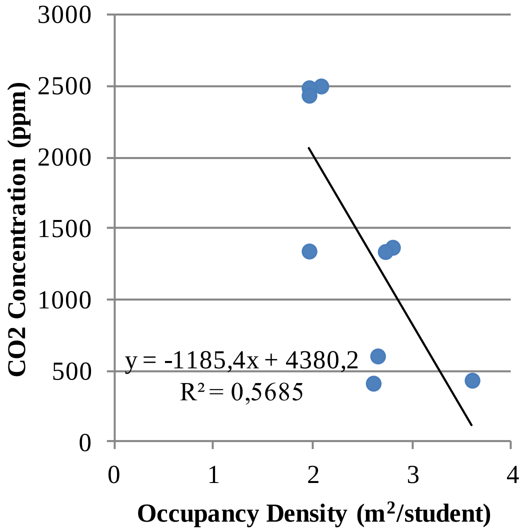

Figure 4 : Occupancy density correlated to CO_2 concentration for opened window surface of 1,56 m^2

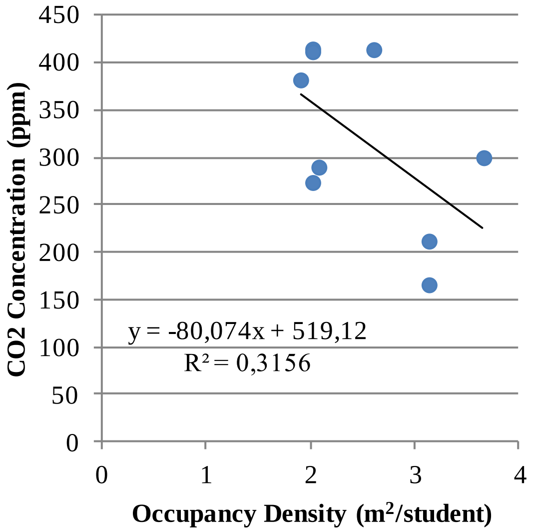

Figure 5 : Occupancy density correlated to CO_2 concentration for opened window surface of 3,28 m^2

The average contribution of each student to the concentration of CO_2 was also estimated for a 1 hour period. Results are shown in table 3. To calculate the average student contribution to the CO_2 concentrations, we subtracted from the CO_2 peak the background concentration (the one that was measured before the arrival of the students) and we divided the result with the number of the people that were present during the lesson. This process was done for all three categories mentioned above (closed windows, one open window and two open windows). The results of the table come to an agreement with the results of the above figures, as they indicate that when the open window area gets bigger, the average student contribution to the CO_2 concentration drops significantly.

Table 3 : The average student contribution to the CO_2 concentration for a period of one hour

Window Opening	Average Student Contribution to CO_2 concentration (ppm)
All windows closed	116,8
One window opens halfway the lesson hour (open window surface = 1,56 m^2)	77,5
Windows open the whole lesson (open window surface = 3,28 m^2)	13,8

3.3 Diurnal CO_2 Concentration and Ventilation Rate

In order to examine the effect of ventilation rate to the concentration of CO_2, the diurnal variation of CO_2 was plotted in the same graph with the ventilation rate. Figure 6 presents data from 5/4/2013 for School 14. That day was chosen because the variation of CO2 is representative compared to the ones that were measured in the other schools. The coloured areas indicate the times of the day that 17 students were inside the classroom. The changes in ventilation occurred because the teacher of the class changed the window opening. For a ventilation rate of 0,53 ach all windows were closed, for 5,9 ach one of the two windows of the classroom was open and for a rate of 15,6 ach both windows were open.

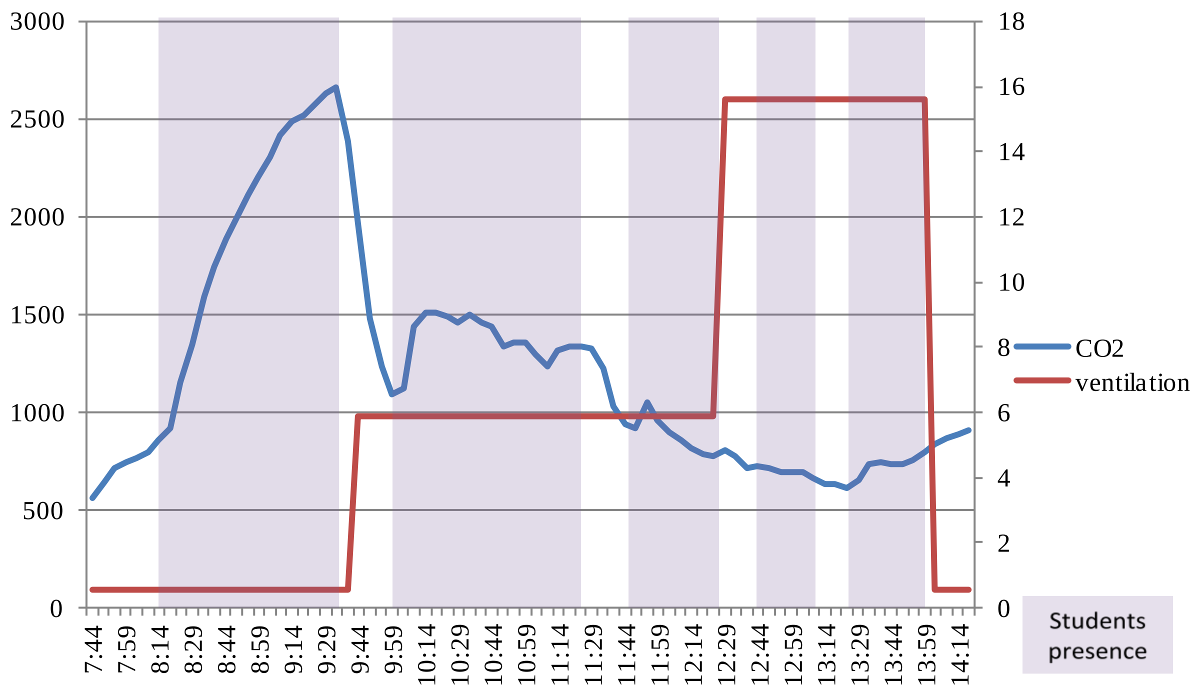

Figure 6 : Diurnal variation of CO_2 concentration correlated to ventilation rate

From Figure 6 it is obvious the highest CO_2 concentrations were achieved for closed windows and students presence. Around 9:30 a.m. (when the students had their first break and the teacher opened one of the classroom's windows) there is a sharp drop in concentration and then a rise at 10:00 a.m. when the students returned to the classroom. The lowest concentration of CO_2 was reached for both classroom's windows opened and an empty classroom. The conclusions from the graph are that the students' presence increases the CO_2 concentration regardless the window opening. Also, there is an inverse proportion between CO_2 concentration and ventilation rate. The above conclusions were observed for all the measured school days.

3.4 Indoor to Outdoor Concentration of CO_2

The indoor and outdoor concentrations of CO_2 were measured in order to identify if the indoor concentration is affected primarily by the outside concentration or by indoor sources. From Figure 7 it is easy to see that, excluding School 2, all daily mean indoor concentrations are above ASHRAE's threshold limit value (1000 ppm). Also, the indoor concentration of CO_2 is larger than the outdoor for all schools (Figure 8). The I/O ratio has its lowest rate in School 2 because in that school the windows were open during the whole lesson. As a result, there is neither a big difference in the CO_2 concentrations nor a very high indoor concentration. On the other hand, the I/O ratio has its highest rate in School 1 which was the only school where the windows remained closed during the whole lesson and were opened only during breaks. Due to the fact there had been no chemical analysis of the pollutants in order to identify their sources, we can't be certain if the high concentration in School 1 occurs primarily from the number of students inside the classroom (25) or not. What we can assume from the graphs is that, because the outdoor concentration is much lower than the indoor, it is highly likely the increased CO_2 concentration to originate from the lack of ventilation in the lesson hours.

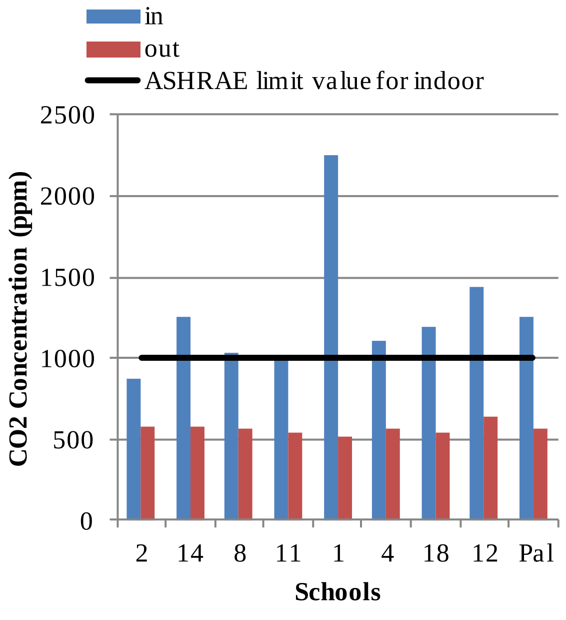

Figure 7 : Daily mean CO_2 concentration for the inside and outside environment of the schools

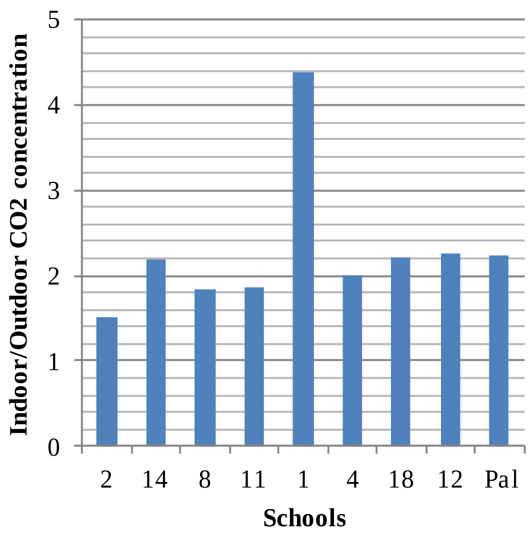

Figure 8 : Indoor/Outdoor concentration for each school

For the rest seven schools, the windows may had all three positions throughout the day (all windows closed, one window open or two windows open), so we assumed in general the window positions were the same for these schools. The correlation between indoor and outdoor concentration for these schools is shown in Figure 9, where the correlation coefficient is $R^2 \approx 0,63$ which indicates a significant correlation between indoor and outdoor CO_2 concentration.

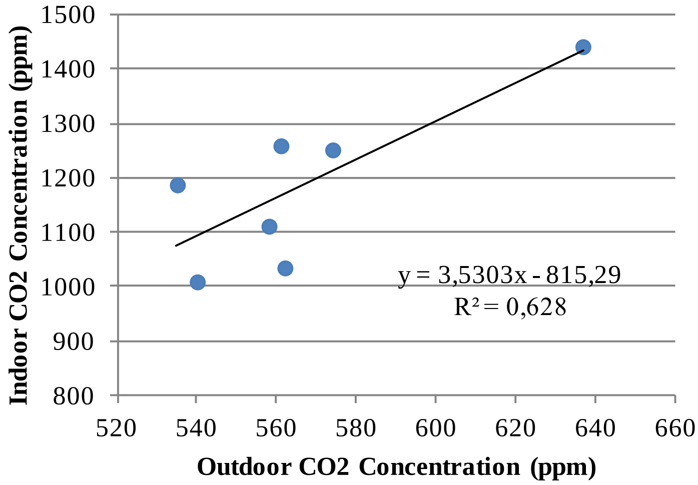

Figure 9 : Correlation of indoor CO2 concentration to the outdoor CO2 concentration

3.5 Drop of CO_2 vs Window Opening and Ventilation Rate

The drop of CO_2 was calculated during brakes where no students were inside the classroom and all schools had at least one open window. To calculate the drop (ppm/min), CO_2 concentrations were plotted over time (for a period of 15 minutes) in order to find the gradient of that curve for each school. That process was done in order to identify if the drop of CO_2 concentration over time is primarily affected by the window opening (m^2) or the ventilation rate (ach). Figures 10 and 11 illustrate the two correlations for all nine schools.

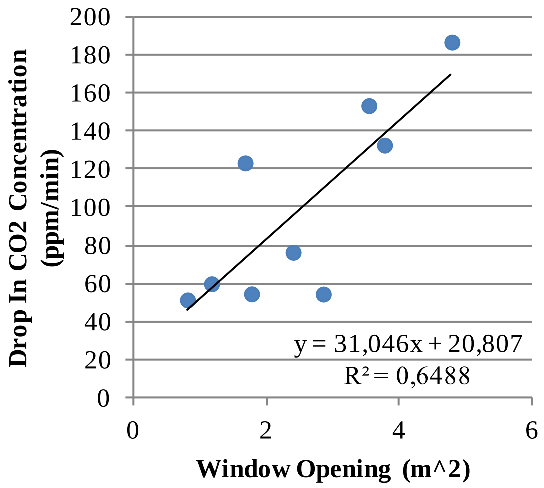

Figure 10 : Correlation of the drop of the concentration of CO_2 to the window opening

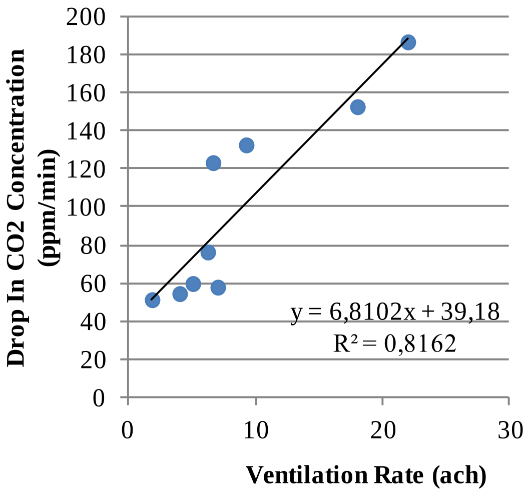

Figure 11 : Correlation of the drop of the concentration of CO_2 to the ventilation rate

It can be seen that, there is a strong correlation between the ventilation rate and the drop of CO_2 concentration ($R^2 = 0,82$) and a moderate correlation between the window opening and the drop of CO_2 concentration ($R^2 = 0,65$) indicating ventilation rate has a greater impact on the decrease of CO_2 concentration than just the window open surface. In general, the lowest drop rate for the CO_2 concentration is achieved for the lowest ventilation rate and the smallest window opening as well as the highest drop rate for the CO_2 concentration is achieved for the highest ventilation rate and the largest window opening. It must be noted for the case where the CO_2 concentration drops with a rate of 120 ppm/min, there is a rapid decrease in CO_2 concentration despite the fact that there is a low ventilation rate and a relatively small window opening. This paradox could be justified probably by a strong wind current that was present at the day of the measurement.

3.6 Evaluation of the School's Ventilation

Finally, there has been an evaluation of the ventilation rates for the different cases that occurred during teaching hours. The ventilation rates, although they were primarily measured in ach, they were converted to l/p/s in order to be compared to the ventilation's rate threshold as it is set by ASHRAE (ASHRAE 2007), which is 8 l/p/s. The results are shown in Table 4. All cases with closed widows during the lesson had inadequate ventilation rate (below 8 l/p/s). The cases of the second category had all, except one, sufficient ventilation rates. Also sufficient ventilation rate was observed when two windows were open throughout the lesson.

Table 4 : Ventilation rates (l/p/s) for different window opening for each school

Window Opening	School	Ventilation Rate (l/p/s)
Closed windows the whole lesson time	14	1,43
	1	0,99
	4	0,57
	12	1,18
One window opens halfway the lesson hour (open window surface = 1,56 m^2)	8	11,72
	14	12,98
	4	11,09
	12	3,19
	18	16,55
Two windows open the whole lesson (open window surface = 3,28 m^2)	2	15,85
	4	39,31
	Pal	14,52
	11	9,39

4 CONCLUSIONS

The conclusions from this paper are:

- There is a negative correlation between the students' scores in productivity tests and the concentration of CO_2.
- Occupancy density affects primarily CO_2 concentrations if outdoor air is not entering the classrooms. For the cases that air from the outside of the classrooms comes to the inside, occupancy density does not significantly affect CO_2 concentrations.
- As the open window area gets bigger, the average student contribution to the CO_2 concentration drops significantly.
- Students' presence increases CO_2 concentration regardless the window opening. Also, there is an inverse proportion between CO_2 concentration and ventilation rate.
- Excluding one school, all daily mean indoor concentrations are above ASHRAE's threshold limit value (1000 ppm). Also, the indoor concentration of CO_2 is larger than the outdoor for all schools. In addition there is a significant correlation between indoor and outdoor CO_2 concentration.

- Ventilation rate has a greater impact on the decrease of CO_2 concentration than the window open surface.
- All cases with closed widows during the lesson time had inadequate ventilation rate (below 8 l/p/s), while sufficient ventilation rates were observed when there were open windows throughout the lesson.

5 ACKNOWLEDGEMENTS

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