Methodology Proposal for the Evaluation of Environmental Quality in Inhabited Indoor Facilities from Measurements of Carbon Dioxide Concentration.

CONSTANZA MOLINA C.[1], LEONARDO VEAS P.[1], FELIPE OSSIO C.[2]

[1]**Escuela de Construcción Civil, Pontificia Universidad Católica de Chile, Santiago.**
[2]**Architecture et Climat, Université catholique de Louvain, Louvain-la-Neuve, Belgium**

ABSTRACT: The indoor air quality (IAQ) and thermal comfort in public and residential buildings is relevant when in operation. However, to date it is not regulated nor subject to control in Chile, despite the consequences of a poor IAQ due to high concentrations of CO2 on learning, concentration, productivity and health.
At a first stage, the IAQ of 2 classrooms in the south of Chile (latitude 45°23'71''S and 47°115'11''S) was monitored and evaluated using the ASHRAE 62/2010 13,779UNE international standards, being finally contrasted with the results of occupant satisfaction polls. Starting from this point, a new methodology to rank campuses in a dynamic regime in accordance to indoor air quality is proposed, especially for those with a high density of occupation, which can be used to manage patterns of ventilation, to allow IAQ verification in a post-occupational regime, and to achieve a healthy environment adjusted to the space's own profile.
Keywords**: Indoor Air Quality (IAQ), Carbon dioxide (CO_2), Ventilation.**

THEORETICAL FRAMEWORK

Indoor air quality (IAQ) in classrooms is a subject that has been deeply investigated abroad, however, in Chile there are a few studies. Investigations in diverse parts of the world accounts for high CO_2 levels that could be reached in facilities with insufficient ventilation and high density of occupants, rapidly exceeding recommended values [15]. Among them, the behavior in classrooms [12, 4] is noted, and in some countries, housing or offices are also affected by high CO_2 concentrations. In general, concentrations during the winter are higher than in summer season by limiting natural ventilation with outdoor air temperature [1]. A number of investigators have studied the cognitive and emotional behavior of the human being by being exposed to high concentrations of this gas during short and medium time periods in controlled chambers. Results were consistent, intellectual performance is significantly decreased in children under school age from 1,500ppm, while the rest of cognitive activities are affected at higher concentrations [1, 4].

Oxygen consumption depends on the metabolic activity of the body. During the school stage, it is important to keep oxygen concentrations and IAQ in healthy levels. On the one hand, this is due to the fact that basal metabolism in this stage is higher like the quantity of energy (Kcal/(kg*day)), and on the other hand, the type of intellectual activities carried out demands a better air quality.

Carbon dioxide concentration is widely used as indicator both to quantify the indoor air quality and the ventilation rate in inhabited facilities [9,1] such as in evaluations and follow-up of greenhouse effect gases at a higher scale, where there are effects converted in "equivalent of carbon dioxide" for each of them. Although the IAQ depends on multiple factors, such as CO2, CO and formaldehyde concentration, volatile particles, COV, pathogen microorganisms, among others, the ventilation level or air renewals is the mechanism that as user it is possible to manage and control in order to keep all these contaminants under healthy limits, and thus avoid symptoms related to the Sick Building Syndrome (SBS) [15].Although this gas does not represent indoor quality in a specific manner, it is - in fact - related to the concentration of other exhaust gases derived from human breathing and materials, and its low concentration determines a proper ventilation and high dilution of the other components [8].

The ventilation of the place should be calculated based on the number of persons inhabiting it, the facility volume, the time they will stay in the place and the CO_2 production rate that depends on the metabolic activity that is being performed. There is a great number of international standards and recommendations to do it and from these calculations, it is possible to know the minute when the CO_2 concentration will be unacceptable. Currently, in Chile there is no standard that regulates the IAQ and the CO_2 is not considered a hazardous contaminant for the health of people either, reason why there are no limits established in Primary Standards of Air Quality and, from the 11 monitoring stations existing in Santiago none of them measures the CO_2 concentration in the atmosphere.

CO_2 in the Atmosphere and Indoor Environment

Normally, CO_2 is in concentrations near 0.03% in volume in the atmosphere equivalent to 300-400 ppm, and is increasing at an approximate rate of 2.04 ppmv/year [5]. It is estimated that a concentration near 350ppm of this gas in the atmosphere is the higher healthy limit “in order to keep the climate to which wild life and the rest of the biosphere have been adapted” [7]. This limit was already exceeded by the end of the 80’ decade and currently, it reaches to 394ppm, a value obtained from the Mauna Loa observatory in Hawaii [5].

CO_2 is not toxic in its normal concentrations. However, when being responsible for regulating the breathing frequency and volume, symptoms of asphyxia appear by displacing air oxygen and decrease its saturation level in the bloodstream.

From 1% of the CO_2 in an indoor environment symptoms of intoxication with carbon dioxide appear, increasing the breathing rhythm; exceeding 0.3% headache, sweat and dyspnea symptoms begin. At 6% of concentration, trembling and visual disorders initiate, and above 10% at a prolonged time you could experience an unconsciousness state (Table 1).

The increase of CO_2 concentration indoors has been statistically correlated to a deterioration of health (symptoms of SBS) and/or in the response to perceive air quality by their occupants [15].

Table 1: Symptoms related to a bad air quality and its CO_2 concentration. Source: Own elaboration [13,2].

Concentration % in volume	Symptoms	Ppm
0.03%-0.04%(Normal) Fresh Air, outdoors	-	300-400
0.07% Urban air	-	700
0.095%	Feeling of vitiated air, perception of bad odors. Lower in sensitive persons.	950
0.5%	Lower exposure limit	5,000
1%	Breathing rhythm increase.	10,000
4%-5%	Human breathing	40,000-50,000
3-6%	Headache, sweat, dyspnea.	30,000-60,000
6-10%	Headache, sweat, dyspnea, trembling, visual disorders, emotional instability, fatigue.	60,000-100,000
>10%	Unconsciousness. Neuronal necrosis, death.	>100,000

In general, international standards propose an air quality classification of a facility according to the CO2 concentration calculated from the difference of concentration between indoors and outdoors. However, these methodologies are considered for static and permanent regime (by being analyzed from a measurement), and the CO_2 behavior in classrooms represent a dynamic behavior (that varies with time, reason why it should be analyzed with all the data taken within a period), consequence of class hours, activities and breaks. On the other hand, CO_2 level outdoors depends on multiple factors, such as the existing combustion, environmental contamination level of cities, industrial activity, proximity to streets and avenues, vegetation, among others, reaching levels that could come to 700ppm in urban and contaminated zones. Using this methodology, two identical buildings, one located in a zone with low CO2 concentration and the other in a contaminated zone would have the same standard, but a different air quality, since in this latter air would exceed 1,400 ppm before (1,000ppm above 400 ppm outdoors considered by standards), highly above recommendations for these facilities under study. With this environmental quality, in extended time, concentration and behavior of students, who could feel restless upon increasing stress or with feelings of being closed-in, seems highly affected.

For this reason, the IAQ should not be conditioned by outdoor air, and the building, through its bioclimatic design, should ensure a healthy and comfortable labor environment, using physical and environmental variables of the place where it will be sited and talking into account the standard that it intended to be achieved. Thus, the type of land, temperature and relative humidity, CO_2 outdoors levels and CO_2 indoors production should also be considered to properly design and manage air quality and ventilation of inhabited facilities.

METHODOLOGY PROPOSAL

A methodology is proposed to classify facilities according to their indoor air quality from two international standards, ASHRAE 62/2010 and UNE EN 13,779 [3, 17].

This new methodology submits an evaluation of the indoor air quality in dynamic regime, especially for facilities with high occupation density, such as classrooms in educational establishments, waiting rooms, cinema rooms or public transportation means rooms, and likewise it could be used to manage a ventilation pattern and achieve a healthy labor environment according to the own profile of the facility. Levels established refer to symptoms appearing in individuals when being exposed to certain levels for undefined time and for hygiene and health conditions [15, 2, 13].

It is possible to predict the CO2 concentration that would have a facility from the number of persons present, the volume of the place, metabolic activity and the time they would stay there without ventilation. This concentration will vary according to the ventilation level existing in the classroom through not wanted air infiltrations and the natural or mechanical controlled ventilation. In case of having a CO_2 sensor, the analysis of the indoor air quality would be conducted with the data compiled thereof.

In this study, and from the data obtained from the facilities monitored, the time calculation is estimated where the CO_2 level is in each range proposed and from there every time quantity (in hours) is multiplied with the corresponding factor to the highest value closest to the range. The use of the highest limit of every range is aimed at supposing the most unfavorable case and, in consequence, ventilation should be projected based on said case. On the other hand, the behavior throughout time will show moments where it is essential to use or increase some type of ventilation.

The result generated (result of the dynamic calculation) is approximately indicated in the area below the curve of CO2 concentration in air, a value that could be compared in a percent manner with the acceptable limit, as with the maximum limit before entering to a “Dangerous” status. The acceptable limit comes when a maximum concentration of 1.000ppm exists during all the time, and the worst standard thereof, or maximum limit will be with a 5,000ppm concentration during the whole period.

$$\sum_{i=A}^{F} t_i * [CO_2] = N$$

Where: t_i is the time in hours [h] with a CO2 concentration in the range i, where i=(A;F)

$[CO_2]$ is the concentration in ppm of the range, highest limit.

Six proposed levels of CO2 concentration are shown as follows. Qualitative scale similar the one used by the MINSAL to classify outdoor air quality through ICAP (Index of Air Quality per Particles. MP10) (Ministry of the Environment, Government of Chile, 2007)

Table 2: Source: Own elaboration, based on a job developed in INNOVA/CORFO No. 09 CN 14-5706 by CITEC UBB and DECON UC.

Level N_i	Range of CO2 concentration present in the facility to be evaluated. **Static value.**	Result of the dynamic calculation	Qualitative scale of indoor air quality[1].
N_A	**CO_2** ≤700ppm	**<70%**	**Good (Acceptable)**
N_B	**700<CO_2** ≤1,000ppm	**70%-100%**	**Innocuous (Acceptable)**
N_C	**1,000<CO_2** ≤2,000ppm	**100%-200%**	**High**
N_D	**2,000<CO_2** ≤3,000ppm	**200%-300%**	**Bad**
N_E	**3,000<CO_2** ≤5,000ppm	**300%-400%**	**Critical**
N_F	**CO_2> 5,000ppm**	**>400%**	**Dangerous**

Being N_i: CO2 ***concentration*** *level, where i=(A;F)*

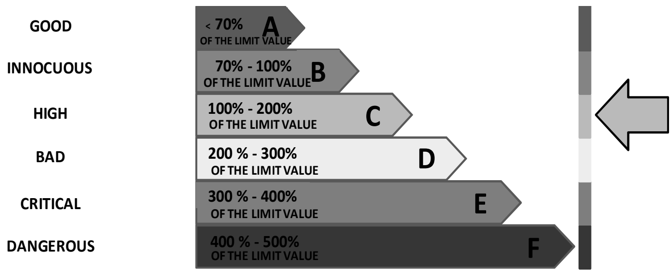

Figure 1: *Graphical scale of results of the evaluation of indoor air quality.*
Source: Own elaboration based on a job developed in INNOVA/CORFO No. 09 CN 14-5706 by CITEC UBB and DECON UC.

These ranges were determined from the effects of CO_2 that in these concentrations have in health of people for an extended time, which in general are not indifferent to effects of high concentrations of the other contaminated air components (SBS symptoms), but that could be related to CO_2 as general indicator [13, 2].

METHODOLOGY APPLICATION

Profiles of CO2 concentration of Schools 1 and 2 during winter and summer campaigns and the limits of each level proposed are shown below.

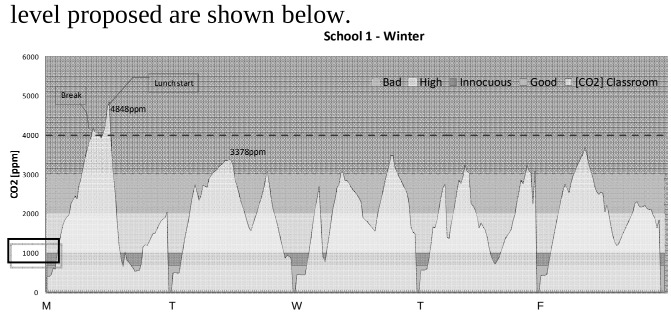

Figure 2: *1,000ppm of CO2 are exceeded at 40 min in the classroom of School 1 in winter season. From this concentration air quality is considered unacceptable. Source: Own elaboration.*

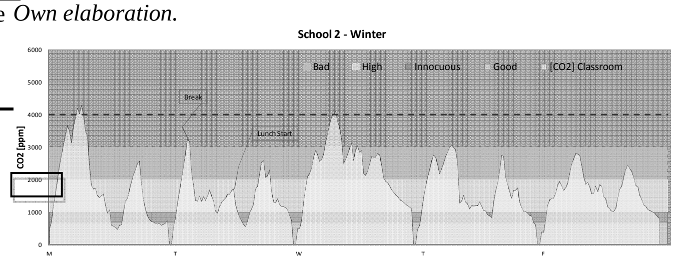

Figure 3: *The 1000ppm limit of CO2 is exceeded at 20 min after starting classes in School 2 during winter season. Source: Own elaboration.*

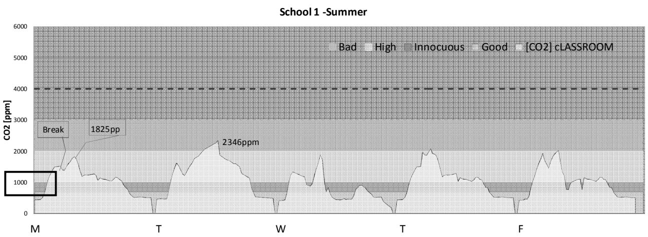

Figure 4: *CO2 concentration in a classroom of School 1 in summer season. Source: Own elaboration.*

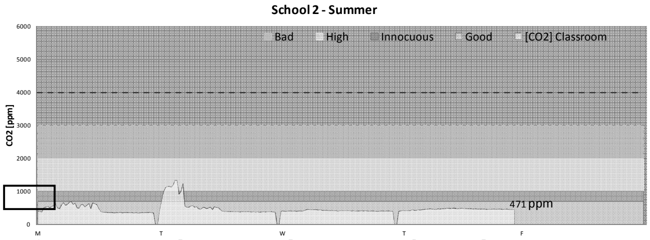

Figure 5: *Good IAQ conditions are shown during summer season in School 2 in the city of Cochrane. Source: Own elaboration.*

From the measurements of the CO2 concentration in each facility in 1 week, it is proceeded to calculate the time it is in each class (A-F). Then, each value is multiplied by the corresponding highest limit of the CO2 concentration. This sum shows a value of 126,000 ppm during 1 week of classes in School 1, and the weighed value is 2,524 ppm.

Table 3: Methodology example of analysis for School 1 and results. Optimal value is exceeded in 252% (considering 1,000ppm during all the time) and reaches 50% of the maximum value (considering 5,000ppm during all the time measured). Source: Own elaboration.

Concentration ranges	Equivalent Time ET [h]	% of total time h·%t (%t)	Reference Concentration (RC)	Weighed by concentration %t x RC	Accumulated ET x RC
Good <700 PPM	**4.7**	**9%**	**700**	**65.116**	**3267**
Innocuous 700-1000 PPM	**3.3**	**7%**	**1000**	**66.445**	**3333**
High 1000-2000 PPM	**16.5**	**33%**	**2000**	**657.807**	**33000**
Bad 2000-3000 PPM	**17.0**	**34%**	**3000**	**1016.611**	**51000**
Critical 3000-4000 PPM	**7.3**	**15%**	**4000**	**584.718**	**29333**
Dangerous 4000-5000 PPM	**1.3**	**3%**	**5000**	**132.890**	**6667**
5000-6000 PPM	**0.0**	**0%**	**6000**	**0.000**	**0**
Totals	50.2	100%		2,524	126,600

Value obtained accumulated in time	126,600	
Optimal value accumulated (h*ppm)	50,167	252%
Maximum value (h*ppm)	250,833	50%

The following chart summarizes the results for the 4 measurements carried out in the project.

Table 4: Results of the analysis and its ranking according to the method proposed. School 1.Own elaboration.

	Winter	Summer
Value obtained accumulated in time.	126,600	73,917
Acceptable Value accumulated (h*ppm) and percent of the limit value.	50,167 252% (BAD)	50,000 148% (HIGH)
Maximum value (h*ppm) and percent of the maximum value	250,833 50%	250,000

Table 5: Results of the analysis and its ranking according to the method proposed. School 2. Own elaboration.

	Winter	Summer
Value obtained accumulated in time.	113,250	30,050
Acceptable Value accumulated (h*ppm) and percent of the limit value.	50,000 227% (BAD)	40,000 75% (INNOCUOUS)
Maximum value (h*ppm) and percent of the maximum value	250,000 45%	200,000 15%

With the results obtained, it is possible to show them through the following graphical scale:

Result School 1- Winter:

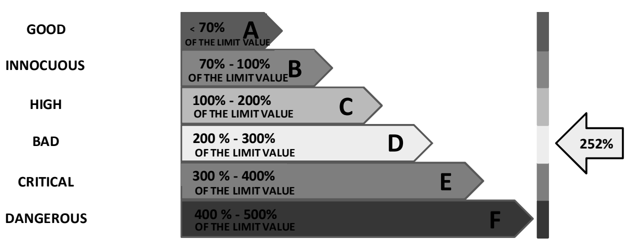

Figure 6: Graphical scale of the analysis of air quality and the result obtained by School 1 during winter. Source: Own elaboration, based on the job developed in INNOVA/CORFO No. 09 CN 14-5706 by CITEC UBB and DECON UC.

Result School 1- Summer:

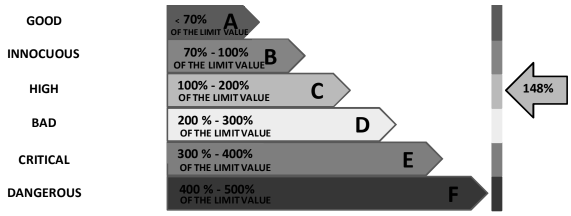

Figure 7: Graphical scale of the analysis of air quality and the result obtained by School 1 during summer. Source: Own elaboration, based on the job developed in INNOVA/CORFO No. 09 CN 14-5706 by CITEC UBB and DECON UC.

The time in which the facility is in each class during the period under analysis is shown below.

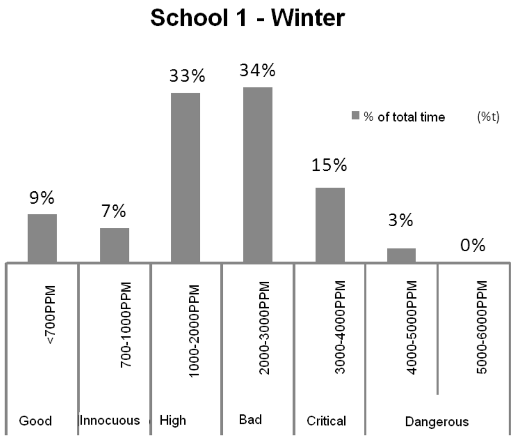

Figure 8: Distribution of CO2 concentration during 1 week of classes in School 1. 84% of the class time acceptable limits are exceeded, and most part of the time are in "Bad" conditions.

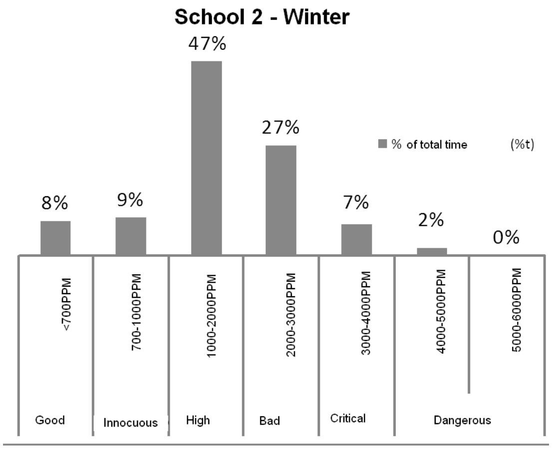

Figure 9: Distribution of CO2 concentration during 1 week of classes in School 2 and its respective qualitative scale. The classroom shows "Good or innocuous" indoor air quality only 17% of the class time.

CONCLUSIONS

Currently, Chilean regulation [16] in subjects of ventilation in educational facilities requires a certain minimum air volume per student. However, this does not ensure a good IAQ. No guide values are established nor reference values, reason why only recommendations, regulations and international studies can be reviewed.

In general, there is a dilemma in classrooms in relation to keeping comfortable indoor environmental temperature, decreasing heat losses, and generate conditions for a good air quality naturally ventilating through openings of doors and windows.

Two classrooms of 45 students each, in 2 cities of the extreme south of Chile were monitored from the INNOVA/CORFO CORFO No. 09 CN 14-5706 project during 2 campaigns in winter and summer, taking records of the physical-environmental variables every 10 minutes.

By comparing the IAQ of the classrooms monitored with standards of the reference and international investigations (3, 17), it is observed that limit concentrations are exceeded from the first 20 and 40 minutes of classes, respectively without meeting any regulation. This is mainly because there is no proper ventilation system, an aspect that up to the date is not required in any manner.

Pressurization tests, in turn, showed Moderate and Tight air-tightness results for Schools 1 and 2 respectively, which is consistent with climatic conditions of the zone, allowing counting on a good control of heat losses, but few air renewals.

The proposed methodology allows evaluating inhabited facilities dynamically obtaining values accumulated in time, and so, compare them with acceptable and maximum limits. When conducting the analysis for the two monitored classrooms during winter, results of 252% and 227% higher than those acceptable for Schools 1 and 2 respectively, were obtained, resulting both in class D or BAD. During summer season conditions improved slightly for School 1, with 148% higher than acceptable, obtaining class C (HIGH). In turn, School 2 obtained 75% of the acceptable limit, classifying it as class B, namely, with INNOCUOUS air quality.

This methodology is applicable to any number of measurements and sampling frequency adjusting to the variable behavior of CO2 in an inhabited environment, where this gas is the main contaminant.

From the other methodologies mentioned it is not possible to have an evaluation of air quality during a determined period of time, but for a specific moment, which makes the class reached varies constantly during the time of use. On the other hand, with this evaluation it is possible to have a general vision of the behavior in time with a final result.

A proper controlled and regulated natural ventilation of classrooms, depending on the number of students, their production of carbon dioxide, in addition to the volume available per student, the time of permanence in the classroom, the duration of breaks, among others factors, are extremely relevant upon designing these educational facilities. This issue is minor in office facilities, as air volume per person is higher, and in general some kind of mechanical ventilation system is provided.

ACKNOWLEDGEMENTS
This article was partly made with the results of the INNOVA/CORFO No. 09 CN 14-5706 project.

REFERENCES

1. AG, Ad hoc, 2008. Gesundheitliche Bewertung von Kohlendioxid in der Innenraumluft, *Bundesgesundheitsblatt,* 51(11), p. 1358–1369.
2. AIVC, 2010. *Air Infiltration and Ventilation Center.* [En línea] Available at: www.aivc.org [Último acceso: 20 07 2011].
3. ASHRAE (2007). ASHRAE Standard 62.1:2007 “Ventilation for Acceptable Indoor Air Quality”. (No. de publicación), Atlanta, USA.
4. Clements-Croome, D. y otros, 2008. Ventilation rates in schools. *Building and Environment,* 43(3), p. 362–367.
5. CO2 Now, 2011. *CO2 Now.* [En línea] Available at: http://co2now.org/Current-CO2/CO2-Trend/acceleration-of-atmospheric-co2.html [Último acceso: 27 Junio 2011].
6. Gray, V., 1999. *Climate Change Guest Papers.* [En línea] Available at: http://www.john-daly.com/bull120.htm [Último acceso: 27 Junio 2011].
7. Hansen, J., 2008. *Cornell University Library.* [En línea] Available at: http://arxiv.org [Último acceso: 27 06 2011].
8. Mahyuddin, N. & Awbi, H., 2010. The spatial distribution of carbon dioxide in an environmental test chamber. *Building and Environment,* 45(9), pp. 1993-2001.
9. Mandalena, C., 2006. *Elaboration et application d’une méthode d’évaluation et d’amélioration de la qualité environnementale de bâtiments tertiaires en exploitation.* Ph.D. thesis, L’Universite Bordeaux
10. Matus, P. & Lucero, R., 2002. Norma Primaria de calidad del aire. *Revista chilena de enfermedades respiratorias,* 18(2), pp. 112-122.
11. Ministerio del Medio Ambiente, Gobierno de Chile, 2007. *Sistema Nacional de Información Ambiental.* [En línea] Available at: www.sinia.cl [Último acceso: 27 junio 2011].
12. Mumovic, D. y otros, 2009. Winter indoor air quality, thermal comfort and acoustic performance of newly built secondary schools in England. *Building and Environment,* 44(7), p. 1466–1477.
13. Nitrox, C.A., 2007. *Grupo Nitrox.* [En línea] Available at: http://gruponitrox.com.ve/seguridad/files/Dioxido_de_Carbono.pdf [Último acceso: 20 6 2011].
14. Salthammer, T., 2011. Critical evaluation of approaches in setting indoor air quality guidelines and reference values. *Chemosphere,* 82(11), pp. 1507-1517.
15. Seppänen, O. A., Fisk, W. J. & Mendell, M. J., 1999. Association of Ventilation Rates and CO2 Concentrations with Health andOther Responses in Commercial and Institutional Buildings. *Indoor Air ; 9,* 9(4), p. 226–252.
16. Ministerio de Vivienda y Urbanismo (2011) “Ordenanza General de Urbanismo y Construcciones”. Santiago, Chile.
17. Asociación Española de Normalización y Certificación (2008). *Ventilación de los edificios no residenciales – Requisitos de prestaciones de sistemas de ventilación y acondicionamiento de recintos* UNE-EN 13779:2008.España: AENOR