ASSESMENT OF PERFORMANCE OF INNOVATIVE VENTILATION SYSTEMS: USE AND LIMIT OF MULTICRITERIA ANALYSIS

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ABSTRACT

Building sealing may affect the total air change by decreasing the leakages and question the ability for ventilation systems to reach their goal of providing an acceptable indoor air quality. Improving energy performance must not impair indoor air quality.
The QUAD-BBC study has led to define four groups of pollutants representative of similar behaviour, use or effect: CO_2 as a marker linked to human occupancy, NO_2, SO_2 (dwellings) and O_3 (offices) linked to occupants activities, CO and 7 VOC linked to materials, activities and behaviour and $PM_{2.5}$ and PM_{10}. The indexes related to these pollutants are calculated in occupancy periods only. Scenarios for pollutant emissions and occupancy have been determined and used as inputs for simulation through an improved version of SIMBAD (coupling airing and thermal effects). Calculation results have provided flows and patterns for each room, energy needs for auxiliaries and heating, pollutant concentrations for each species and in each room as well as more synthetics indexes.
The initial objective of the project was to develop a single criteria of indoor air quality (multi-pollutants) and to provide a reference system for each building based upon this index. Calculations have shown huge difficulties in reaching this objective. The lack of reliability of pollutant emissions' data in particular have led to propose a set of indexes and a method for comparison of systems rather than an absolute reference. Yet a graphical representation of these criteria helps a fast comprehension of the pros and cons of different systems and help comparison.

KEYWORDS

IAQ, criteria, pollutants, simulation

INTRODUCTION

Improving the airtightness of buildings modifies the distribution of air flow balanced between the air inlets and infiltrations. In this context, the issue of the ability of ventilation systems, as designed today, to ensure acceptable air quality is raised. Everyone agree that objective of energy efficiency shall not be to the detriment of the quality of indoor air; the matter is to determine how to evaluate it. Demand control ventilation is usually based on humidity ratio and CO_2 levels. Those criteria might not be enough to represent IAQ.

The QUAD-BBC project examines the building / user / system interactions using data sources of pollution related to the occupation, materials and user behaviour as well as several ventilation systems [1]. The initial goal of QUAD-BBC project was to propose an aggregated IAQ index from several pollutants and to provide a “reference system” for various buildings with an acceptable level of IAQ index. This project has been carried out on five different buildings: a single family house, a dwelling in a collective building, an office and a school. For each type of building, several ventilation systems have been designed, from very usual to very innovative ones in order to create various results: constant air flows, demand control ventilation (DCV) based on humidity, CO_2, and/or occupation, airing, ...

We used the simulation tool, SIMBAD, a Building and HVAC Toolbox developed by CSTB [2]. This tool implements multizone and nodal building models in MATLAB/Simulink environment by combining heat and mass transfer phenomena. On the one hand, the thermal model is composed of detailed wall models describing the material layers and their properties, window models, heating and cooling devices, lighting systems, etc. It so deals with conduction, convection and radiation phenomena for calculating surface temperatures, mean radiant and indoor air temperatures. Sources of pollutants were introduced in the model with their respective scenarios. Therefore, the level of pollution obtained in each room is due to the inner source itself, and also to the transfer of pollutants between parts of the building studied.

To achieve this goal several assumptions were set on the building (Nearly Zero Energy buildings with low level of infiltration), the use of it and the pollutants emissions and acceptable level. The use of the building is a major set of assumptions as the type of pollutants and their emissions levels are highly correlated to it.
Another major set of assumptions is the acceptable level for each pollutant and the way they are combined in a single index.

USE OF BUILDING – POLLUTANTS EMISSIONS

The uses of the building were described in terms of scenarios of presence and activities in the different rooms. For each type of building, scenarios describe week days, week-ends and holydays. Typical days have been cut into “slices” related to presence and type of activity in each room. The sum of these “slices” gives a yearly scenario which can be connected to pollutant emission for each species through the use of scientific literature and databases on pollutants (examples in Figure 1, Figure 2 and Figure 3).

For the IAQ evaluation of the QUAD-BBC project, five types of pollutants from indoor environments were identified:

- Moisture for its impact on the building, namely the risk of condensation on the walls, and occupant comfort;
- Carbon dioxide (CO_2 metabolic) considered as a tracer of the occupation. It is therefore linked to humans bio-effluents pollution;
- Volatile organic compounds (VOC) emissions due to materials and building equipment, whose production is proportional to the surface of the walls;
- Products of combustion activities (in kitchen and living room);
- Particulate pollutants from indoor air and incorporating sources deposition phenomena, coming from cooking and cleaning.

Pollutant source	Room	Week	Week-end
Cleaning	Living room, rooms	-	9:00-10:00 (Saturday)
Cigarette	Living room	- - 18:00-18:10 22:50-23:00	13:00-13:10 14:00-14:10 18:00-18:10 22:50-23:00
Incense	Living room Kitchen	- -	16:00-17:00 14:00-15:00

Figure 1 : Pollutant emission scenario relative to activity in dwellings

Room	Metabolism	Activities	Equipment	Construction materials	Cleaning products
Residential	H_2O, CO_2	$PM_{2,5}$, PM_{10}, H_2O, CO, NO_2, SO_2	HCHO, $PM_{2,5}$, PM_{10}	VOC	HCHO, VOC
Offices	H_2O, CO_2	O_3	HCHO, $PM_{2,5}$, PM_{10}		VOC
Classroom, nursery	H_2O, CO_2		HCHO, $PM_{2,5}$, PM_{10}		VOC

NB: pollutants from metabolism, coming from human occupancy, are found in all rooms.

Figure 2 : Examples of pollutants sources for each type of building

Room	H_2O	CO_2	VOC's	HCHO	$PM_{2,5}$	CO	NO_2	SO_2	O_3
Bedroom, living room	X	X	X	X	X				
Office	X	X		X	X				X
Classroom, nursery	X	X	X	X	X				
Hospital	X	X		X	X				
Kitchen	X	X	X	X	X	X	X	X	
Bathroom, shower	X	X							
WC	X	X	X						

Figure 3 : Examples of pollutants emitted in various rooms

The choice of emission levels is crucial but very difficult: the variability of data sources is a major complication. At the beginning of the study we chose one source almost arbitrarily for each pollutant. Our bibliographic references were principally the PANDORE [3] database, the IA-QUEST [4] tool and also Annex 27 European project [5].

IAQ LEVEL

The choice of maximum level was also difficult as the sources again are very different: they do not refer to the same duration (peak, average 1h, 2h, 8h, …) and do not address the same level of concerns (WHO, OEHHA, Anses, ATSDR, USEPA, …). The choice was made to use the most demanding level as a maximum for each pollutant (Table 1).

CAT.	POLLUTANT	Limit value for 1 h exposure
A	Carbon dioxide, CO_2	10 000 ppm
B	Nitrogen dioxide NO_2	0,20 mg/m^3
	Sulfur dioxide, SO_2	0,66 mg/m^3
	Ozone, O_3	0,12 mg/m^3
C	Carbon monoxide, CO	30 mg/m^3
	Formaldéhyde, HCHO	0,05 mg/m^3 for 2h
	Acétaldéhyde	0,47 mg/m^3
	Éthylbenzene	43,36 mg/m^3
	Styrene	21 mg/m^3
	Toluene	3,8 mg/m^3
	o-Xylene	8,7 mg/m^3
	Acetone	31 mg/ m^3
D	Particles 10 µm	50 µg/m^3
	Particles 2,5 µm	25 µg/m^3

Table 1: Reference values used for Indoor Air Quality index

The index for individual pollutant is $I = C_p/C_{\lim,p}$, where C_p is the average concentration of the pollutant on a specific period, and $C_{\lim,p}$ is the maximum value recommended for the same period. The index shall then be lower than 1 to be acceptable. The lower I is, the better is Air Quality.

The combination of indexes to provide a single index is another difficulty as several possibilities exist in the literature. We decided to use combination of all pollutants and additivity of effects. The initial global index is:

$$I_{QAI} = \sum_{p=1}^{Np} \left(\frac{C_p}{C_{\lim,p}} \right) \tag{1}$$

Each pollutant is taken in the index only during occupancy period and the index refers to room (one index per room). The main problem with this index is of course that it is very sensitive to the number of pollutants (20 at the beginning) for its absolute value.

All these arbitrary choices (emission levels, maximum concentration, index …) were supposed to be neutralized in the context of comparison of systems to a reference system, as well as simulation tool assumptions.

The first shots of calculation and their analyses raised a number of questions leading to change the initial goal.

One of the first difficulties found was to match consistent assumptions for calculation model of physical phenomena (for example treatment of humidity in the wall) and design of Demand Controlled Ventilation (DCV). Physical models might have an impact on indoor air environment and therefore on the reaction of DCV systems, their regulations, and so the airflows and the final result.

The construction of a reference system (included it own regulation) is also linked to the model and the assumptions. Therefore we decided not to define a reference system.

Another outcome from the calculations was the presence of a "main pollutant" which level was so important that the index became almost constant in some rooms. The impact of other pollutants, although their levels were different from one system to the other, disappeared in the global index. So, we decided to split the original global index in 4 specifics indexes related to common activity or impact and add specific information on humidity:

- $I_A = CO_2$ as index of confinement linked to occupation,
- $I_B = NO_2$, SO_2 (dwellings) and O_3 (offices) linked to occupant activities,
- I_C = CO and 7 VOC linked to materials, activities and occupants behaviour,
- I_D = PM $_{2.5}$ and PM $_{10}$ linked to activities.
- Relative humidity (number of hours above 80%) linked to occupants and their activities

Specific indexes are built with the same equation than the original one but their extent is limited to the same category of pollutant. The additivity of effects is there more relevant. The information is also more specific and usable for the choice of the system.

For example, the index for occupant activities I_B is calculated as followed:

$$I_B = \frac{C_{NO_2}}{C_{\lim, NO_2}} + \frac{C_{SO_2}}{C_{\lim, SO_2}} \quad (2)$$

Humidity is taken specifically into account as it is not really a pollutant but it is still a major problem in specific conditions. The impact is calculated for a one year period, during both occupancy and no-occupancy periods.

The number of VOC has also been reduced to a short list for which the data seemed to be more reliable.

INFLUENCE OF ASSUMPTIONS

Equipment – occupant behaviour

Several shots of calculations with specific assumptions (climate, infiltration level …) have shown some recurrent difficulties on the equipment and user activities levels of emission.

In the kitchen the presence and use of oven leads to an excessive value of the index, whatever the system (Figure 4). For the collective dwelling simulations by example, the 5 mechanical ventilation systems named LC 0 to LC 4 present almost same pollutant concentration during cooking activity. Those 5 ventilation systems are either single extract single flow system or balanced supply and extract systems, with constant airflows or control on humidity, CO_2, presence. In the living room the tobacco smoke leads to excessive values of the index, whatever the system. Figure 5shows for the example for one ventilation system the influence of activity pollutant source scenario on formaldehyde concentration. The value of the index can also be very high, because people smoke of use incense, and not because airflow from ventilation system is not enough.

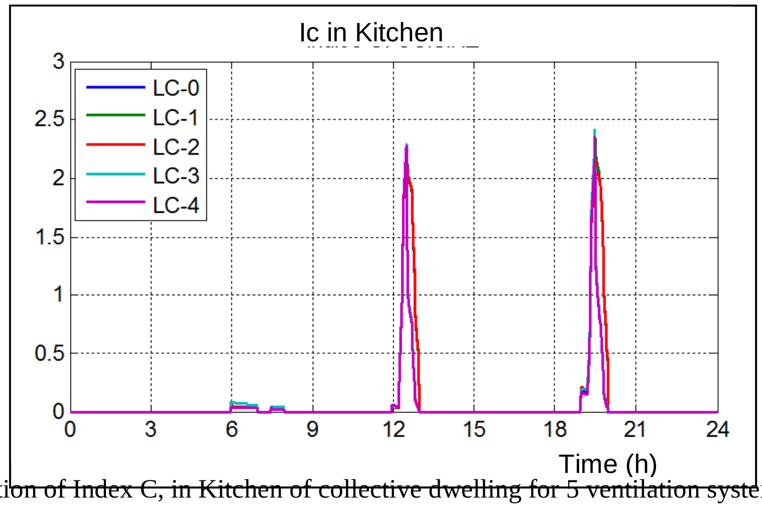

Figure 4 : Evolution of Index C, in Kitchen of collective dwelling for 5 ventilation systems (LC0 to LC4)

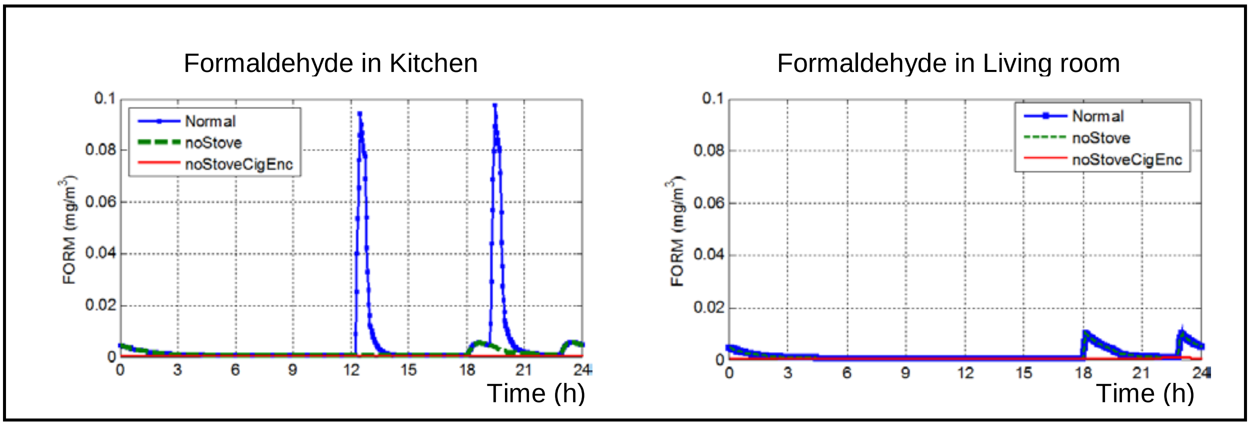

Figure 5: Formaldehyde concentration in the kitchen and in the living room, with constant airflow ventilation (LC0), comparison with emission from stove or not and with cigarette and incense or not

For particles from incense we found very different levels (10 mg/h to 240 mg/h) depending on the type or trademark, being very different from aromatic candles: the final concentration is more related to the user than to the ventilation system.

At this step it must be assert that the index will widely change with the choice of pollutants: for instance alpha-pinene or limonene are widely used in home perfumes: if they are included in the list, the index will be high if the occupants use this type of product. If they are not in the list there will be no effect on the index. Some products on the market detect “odours” with a VOC sensitive sensor and provide another VOC to mask the first one …

The final index level may finally be more influenced by the occupant behaviour than by the system.

Material emissions

The use of database for material emission led to constant values, mainly for formaldehyde. The emission is constant whatever the indoor conditions are and not declining with time. The concentrations found with all systems are very low, far away from the acceptable limits (example in Figure 6 and Figure 7).

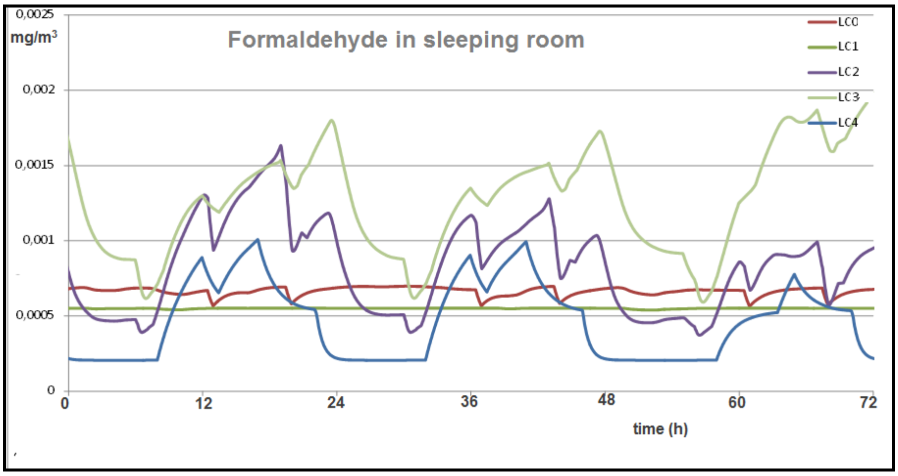

Figure 6: Formaldehyde concentration in a sleeping room for 5 ventilation systems

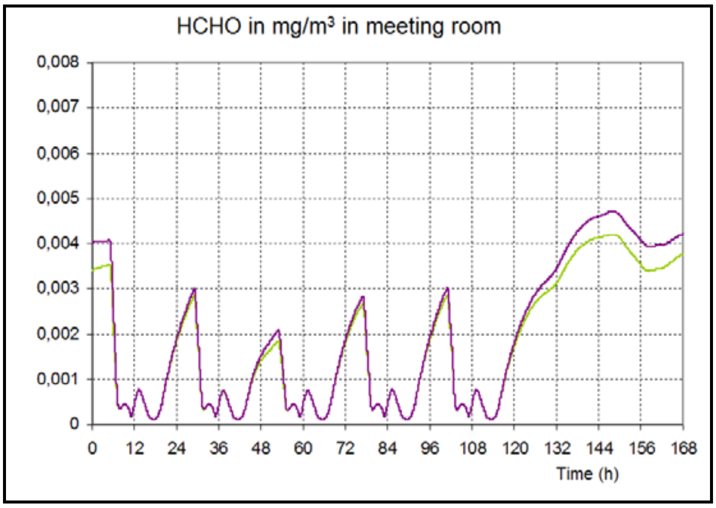

Figure 7: Formaldehyde concentration in a meeting room of an office building during one week, for 2 ventilation systems, with no airflow during night and week-end

This result is surprising as many measurement campaigns have shown relatively high values in real dwellings or offices, without a clear relationship with the system.
We can try to explain these differences in two ways:

- The measurements include all VOC, from the material (new or not) and from the occupant behaviour, and we know that the occupant behaviour can be of a major importance – this would be in line with the weak relationship between systems and levels.
- The data used for the calculation are wrong, either too low emission levels, either missing.

Both of these explanation lead to be very careful in giving any limit to a calculated result for a single system.

If we rely on the results, it could be possible to reduce the flows in bedrooms and living rooms by a factor of 10 without any problem on material related VOC levels. The temptation of reducing the flows from the study or from any calculation model including VOC must not be followed as some important VOC may be missing and the use of cleaning or masking products may not be correctly handled.

PROPOSAL FOR IAQ INDEX AND USE

The use of a single aggregated index is not pertinent, four groups of pollutant, plus humidity, are relevant for the analysis of the reaction of systems installed in a building. The proposal of one single reference system is also not relevant; it is linked to the type of pollutants and the building use.

A set of annual average indexes for the same building with the same conditions of use allows comparing systems between themselves in these conditions (the result cannot be extended as a general proposal). As energy efficient is now a major criterion to choose the system, IAQ indexes have to be associated with energy. The simulation, combined with climate files allows calculating the energy needs to heat air renewal. Assumptions shall be done on the heating system and its efficiency. This affects the weight of the heating consumption compared to fans consumptions.

The presentation of the indexes in the “radar” shape makes it relatively easy for systems comparison. The matter of this representation is the scale which should be the same for every branch. For the energy and the humidity criteria, we decide to divide by the greater one.

To facilitate the readability of the radar for comparison of systems, it is recommended to rescale it (0-100%) on each branch from the higher value of each pollutant category. In order to evaluate the importance of each branch between each over, it is then recommended to note the absolute value of the maximum. The absolute value is also useful to know if the differences are relevant (ie big scale) or if all systems are quite good (small scale). We need to remain that Index lower than 1 is consistent with acceptable air quality.
We chose an intermediate presentation, meaning the same scale for all the pollutant indexes. In this way, differences on indexes are not hidden by the value of energy, and the hierarchy between maximum levels of each category is still respected.

The interpretation of the radar whether the indexes are in absolute values or rescale for indexes will not be the same (Figure 8).

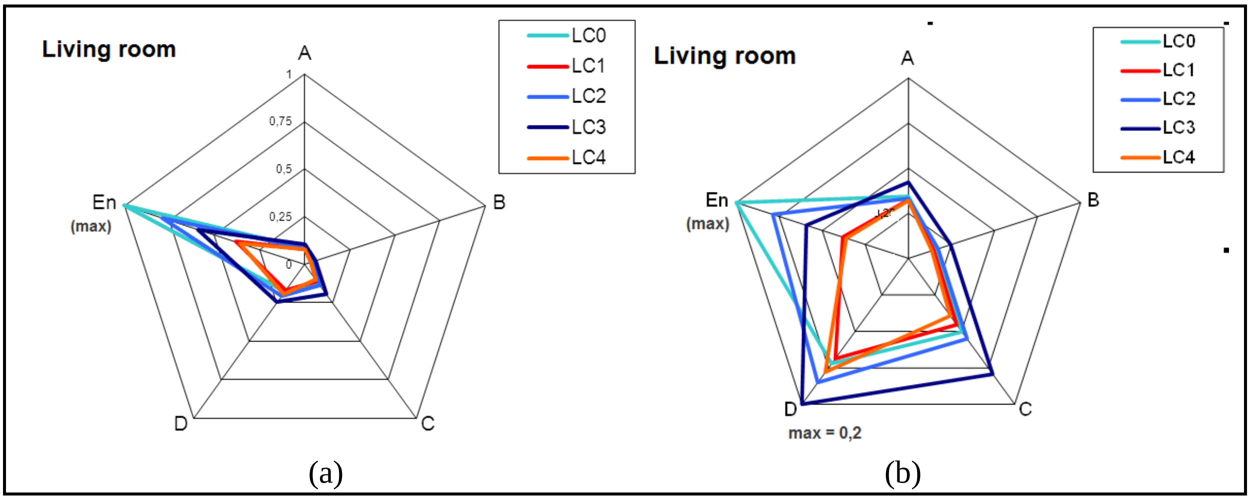

Figure 8: Multi criteria radars in living room; Energy in percentage of maximum
and pollutant indexes A, B, C, D in absolute value (a) or rescale, same values for all indexes (b)

CONCLUSION

One of the conclusion of the study is to choose a set of pollutant which is not linked to the occupant behaviour regarding the emission of substances (tobacco, incense, candles, perfumes…), the ventilation systems would then be ranked with their ability to remove metabolism linked substances (H_2O, CO_2, human related VOC) and material emissions and to keep humidity in the safe range.

The following questions remain:
Which emission levels for material?
What about cleaning?
What about cooking?

If the occupancy and activities are documented enough, it is possible to use a set of indexes (per room) linked to the actual use of the building and to compare systems between themselves with these assumptions with a "radar" shape presentation that gives a quick global view.

Designers must be aware of the limitations of the method and the accuracy of the results, linked to the reliability of the emission data from sources. The radar presentation must also be taken with care as the rescaling of the branch may overestimate some impacts and differences between systems.

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