TOWARDS THE DEFINITION OF AN INDOOR AIR QUALITY INDEX FOR RESIDENTIAL BUILDINGS BASED ON LONG- AND SHORT-TERM EXPOSURE LIMIT VALUES

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ABSTRACT

In the Framework of the IEA EBC Annex68 Subtask 1 working subject, we aimed at defining an indoor air quality index for residential buildings based on long- and short-term exposure limit values. This paper compares 8 indoor air quality indices (IEI, LHVP, CLIM2000, BILGA, GAPI, IEI Taiwan, QUAD-BBC and DALY) by using the French IAQ Observatory database that includes pollutant concentration measurements performed in 567 dwellings between 2003 and 2005. This comparison allows to make a relevant analysis of each index and determines their pros and cons i.e. the calculation method, selected pollutants, threshold concentrations, sub-indices and their aggregation. From this analysis, a new index is proposed in order to be as consistent as possible in regards of health impacts by taking both long- and short-term exposure limit values into account.

KEYWORDS

IAQ, Indicator, Indices, Guideline value, Health assessment, Good IAQ, Bad IAQ

1 INTRODUCTION

Due to the huge number of various sources of emissions, pollutants, health impacts and toxicity levels, assessment of Indoor air Quality (IAQ) is a complex task (Hulin et Al., 2010, Wolkoff, 2013; Haverinen-Shaughnessy, 2015). One of the required tools to achieve that goal is a single Indoor Air Quality Index that would describe air quality in regards of health impacts. During the last decades, such indices were defined, yet, none was accepted as sufficiently relevant by the international scientist community. In this paper, we analyze 8 of them to evaluate their main pros and cons, expanding a first comparison study performed by Wei et al. (2016). Selected Indoor Air Quality Indices are IAPI (Sofuoglu and Moschandreas, 2003), LHVP (Castanet, 1998), CLIM 2000 (Castanet, 1998), BILGA (Castanet, 1998), GAPI (Cariou and Guillot, 2005), IEI Taiwan (Chiang and Lai, 2002), QUAD-BBC (Quad-BBC, 2012) and DALY (Logue et al., 2011). In a first part, the methodology used to compare the different indices is presented along with the description of the 8 IAQ indices, the pollutants of concern and their associated Exposure Limit Values (ELVs). Comparison and discussion are given in a second part which results in the definition of a new IAQ index.

2 METHOD

2.1 IAQ Indices

A total of 8 indices are studied in this paper: IEI, LHVP, CLIM 2000, BILGA, GAPI, IEI Taiwan, Quad-BBC, and DALY. Table 1 gathers all calculation equations of the different indices along with the reference studies that defined them.

Table 1: previously proposed approaches to define IAQ index

Index	Equation	Reference
IAPI	$I_{IAPI} = \frac{1}{I}\sum_{i=1}^{I}\frac{1}{J}\sum_{j=1}^{J}\frac{1}{K}\sum_{k=1}^{K} 10 \times \left[1 - \frac{C_{i,j,k}^{max} - C_{i,j,k}^{obs}}{C_{i,j,k}^{max} - C_{i,j,k}^{min}}\left(\frac{ELV_{i,j,k} - C_{i,j,k}^{obs}}{ELV_{i,j,k}}\right)\right]$ *(1)* where *I* is the number of level-3 groups, *J*, the number of level-2 groups in each level-3 group, *K*, the number of level-1 pollutant variables in each level-2 group and *max* and *min* are the measured maximum and minimum concentrations of the BASE study (Girman et al., 1995), respectively.	Sofuoglu and Moschandreas (2003)
LHVP	$I_Q = \frac{[CO]}{5} + \frac{[CO_2]}{1000} + \frac{DTB}{1000}$ *(2)* where *[CO]* and *[CO₂]* are carbon monoxide and dioxide concentration (ppm) respectively and *[DTB]* is the total airborne bacteria concentration (cfu/m^3).	Castanet (1998)
CLIM 2000	$I_{CILM2000} = \frac{1}{4}\left(\frac{[CO]}{30} + \frac{[CO_2]}{4500} + \frac{[NO_2]}{0.4} + \frac{[HCHO]}{0.06}\right)$ *(3)* where *$[NO_2]$ and [HCHO] represent the concentration of nitrogen dioxide and formaldehyde respectively;* concentrations are expressed in mg/m^3.	
BILGA	$I_{BILGA} = \begin{cases} max\left(\frac{E_{mean}^{P} - ELVc_T^P}{ELVa_T^P - ELV_T^P}\right),\ if\ E_{mean}^{P} < 0 \\ max\left(\frac{E_{mean}^{P} - ELVc_T^P}{ELVc_T^P}\right),\ if\ E_{mean}^{P} \geq 0 \end{cases}$ *(4)* where E_{mean}^{P} is the mean exposure to pollutant p over the period of time T and $ELVc_T^P$ and $ELVa_T^P$ are the Exposure Limit Values for chronic and acute effects.	
GAPI	$GAPI = \sum_i W_i C_i$ *(5)* where C_i is the concentration of pollutant *i* and W_i is the impact weight coefficient of pollutant i	Cariou and Guillot (2005)
IEI Taïwan	$GAPI = \sum SxWx$ *(6)* where S_x is the score of category x and W_x is the impact weight coefficient of category x	Chiang and Lai (2002)
Quad-BBC	$I_{Quad-BBC} = \sum_{i=1}^{p}\frac{C_{obs}}{ELV}$ *(7)* where *p* is the number of pollutants in the group and *obs* is the measured concentration.	Quad-BBC (2012)
DALY	$DALY_{disease} = YLL_{disease} + YLD_{disease}$ *(8)* where $YLL_{disease}$ are Years of Life Lost due to premature death from the disease and $YLD_{disease}$ are Years of Life Disability, weighted from 0 to 1 depending on disease severity.	Logue et al. (2011)

Most indices from literature are based upon the same principle: an average indoor concentration is divided by an ELV, quite similar to hazard quotients used for health risk assessment. ELV are usually health-based but may be different to toxicological reference values and vary according to the index. Many indices use sub-indices dedicated to one pollutant that are aggregated to obtain a unique index. Nevertheless, the presence of sub-indices and its aggregation are important questions that induce debates. From Table 1, 4 main types of aggregation emerged:

- Sum-average: Most indices are based on a sum of pollutants' concentrations compared to a reference value. Sometimes the sum is divided by the number of studied pollutants. The aim is to quantify average level of quality in a room by considering each pollutant as equally important.
- Maximum: The BILGA index is calculated by taking the maximum value of all its sub-indices. The pollutant with highest toxicity exposure is the only one taken in account to assess IAQ.
- Specific formula: Some indices are not based on a concentration divided by an ELV but on a specific formula that returns a value per pollutant, which can be summed up to all pollutants to obtain a global health risk assessment level.
- Score using breakpoint concentration: the IEI Taiwan is based on the attribution of a score for each pollutant using 4 ranges of concentrations between breakpoints. Scores are summed in the category except if one score of the category is below 60, in which case the minimum score of the category is chosen. Scores of respective categories are then summed and weighted by a category coefficient.

Table 2 summarizes the main pros and cons of the published indices.

Table 2: Main pros and cons for IAQ indices and types of formula.

Type of aggregation	**Corresponding indices**	**Main pros**	**Main cons**
Sum-average	IEI, CLIM2000, LHVP, Quad-BBC	IEI values are limited between 0 and 10. Quad-BBC has an adaptive formula depending on the type of room.	Loss of information by ambiguity or eclipsing (Ministry of Environment, Forests and Climate Change, 2014): importance of a high value can be reduced in a mass of low values even if it exceeds hazardous threshold level.
Maximum	BILGA	Based on the most unfavourable pollutant level. Take into account both limited risks and important risks.	ELVs used are old and need to be updated
Specific formula	GAPI, DALY	GAPI has a flexible formula that can be readapted to any pollutants and many studies criteria. DALY is based exclusively on health impacts.	GAPI value has no real signification. DALY approach is very approximate and many pollutants lack of available data to be used efficiently.
Score by breakpoint concentration	IEI Taiwan	IEI Taiwan gathers both Sum-average and Maximum type advantages.	In practice, it is almost equal to Maximum type. Breakpoint concentrations and categories weights are defined subjectively without a related health correlation

2.2 Target pollutants

The pollutants used in the calculation of each index are listed in Table 3.

Table 3: Pollutants used in the calculation of each index.

Indices	**Pollutants**
IAPI	Formaldehyde, Benzene, Acrolein, Carbon monoxide, Carbon dioxide, PM_{10}, $PM_{2.5}$
LHVP	Carbon monoxide, Carbon dioxide

CLIM 2000	Carbon monoxide, Carbon dioxide, Formaldehyde
BILGA	Carbon monoxide (1h), Carbon monoxide(8h), Carbon dioxide, Formaldehyde, Radon
GAPI	Formaldehyde, Acetaldehyde, Acrolein, Hexaldehyde, Benzene, 1-Methoxy-2-propanol, Trichloroethylen, Toluene, Tetrachloroethylene, 1-Metoxy-2-Propyl, Acetate, Ethylbenzene, m,p-xylenes, styrene, o-xylene, 2-Butoxyethanol, 124-Trimethylbenzene, 1,4-dichlorobenzene, n-decane, 2-Butoxy ethyl acetate, n-undecane
IEI Taïwan	Carbon monoxide, Formaldehyde, Carbon dioxide, $PM_{2.5}$ and Total volatile organic compounds (TVOC)
Quad-BBC	Carbon monoxide, Formaldehyde, $PM_{2.5}$, Radon, Toluene, o-xylene, Acetone, PM_{10}
DALY	$PM_{2.5}$, Carbon monoxide, Acrolein, Formaldehyde, Benzene

2.3 Exposure Limit Values (ELV)

Almost every index use Exposure Limit Value (ELV) to quantify the exposure level to a pollutant. Among the studied indices, 4 different types of ELV are used:

- Limited Risk Value (LRV): For exposure below LRV, health impacts are limited, null, or unknown.
- Important Risk Value (IRV): If exposure is above IRV, health impacts are proven, corresponding to irreversible lesions, chronic diseases, or even death.
- Toxicological Reference value (TRV): Based on animal toxicological studies by applying a conversion factor, or sometimes based on human epidemiologic studies.
- Indoor Air Guideline Values (IAGV): Threshold values defined by national or international organizations, e.g. the French Agency of Health and Environment Security (ANSES). According to the definition, there is no known health impact for the selected period below the threshold concentration.

Note that, among the 4 main ELV used, TRV are not accurate and may differ from one study to another; LRV and IRV are too old and too lax. IAGV seems to be the most relevant one, because it is current, accurate, and based on known health impacts.

2.4 Comparison procedure

In order to proceed with the comparison of IAQ indices, a common set of inputs is necessary. Most studied IAQ indices require both pollutants concentration levels and Exposure Limit Values (ELVs). Regarding the first kind of inputs, the French dwellings survey conducted from 2003 to 2005 by OQAI (French Indoor Air Quality Observatory) on 567 housings (Kirchner et al., 2007) was chosen as a reference for IAQ assessment in residential buildings. In this survey, only long-term effects were taken in account. NO_2, SO_2, O_3, mold and bacteria were not measured. Whenever a pollutant concentration is not available but is needed in the calculation, the index formula was readapted so that it does not bias the results. As much as possible, all indices were calculated the same way as it was firstly described in the literature. Most indices need ELVs for considered pollutants. If the ELV was not clearly defined, the French Indoor Air Guideline Value (IAGV) was chosen (ANSES, 2011). If not available, international reference values were used instead e.g. WHO (WHO 2010), OEHHA (2016)...

The following procedure is applied to compare the indices. A first graph presents the distribution of the studied index according to its original scale considering the 567 dwellings (Figure 1, left). A second one is produced to transform the results using a common 3 level-scale with the following interpretation: good, intermediate or bad IAQ (Figure 1, right). All indices have an interpretation to determine if IAQ is good or bad in a dwelling in their original definition except for DALY and GAPI. The first approach quantifies DALY lost per year per 100,000 persons due to exposure to indoor air pollutants but there is no indication on how many DALYs should be lost per year to consider IAQ as good or bad. The GAPI index returns a value that relies on the weight of the selected criteria without any scientific signification.

A last graph (Figure 2) intends to detect eclipsing as defined by Sharma and Bhattacharya (2012) and inconsistencies. Most of IAQ indices employ aggregation (maximum, sum, weighted averages, root-mean-square formulation…) of sub-indices at some point so that information for a particular pollutant can be hidden by the weight of the other pollutants. In this analysis, the studied indices are plotted against the maximum value of the concentration of each pollutant to its ELV ratio (MAX) in order to identify whether the indices are not hiding critical cases or not. In Figure 2, some points are encircled in red, they are associated with dwellings that have a bad IAQ according to IAPI value whereas it has an excellent IAQ according to MAX index (<0.5). On the contrary, points encircled in blue correspond to dwellings with an intermediate IAQ whereas MAX (>1) characterizes a very bad IAQ (one pollutant at least is above short-term IAGV). In this example the dispersion is so high that IAPI is not able to distinguish the level of IAQ as shown by the green region of equal MAX and IAPI ranging from 4 to 10 and the orange region where IAPI predicts the same level of IAQ with a MAX ranging from 0.2 to 3.5. Short term IAGV was used as ELV to detect bad IAQ with certainty.

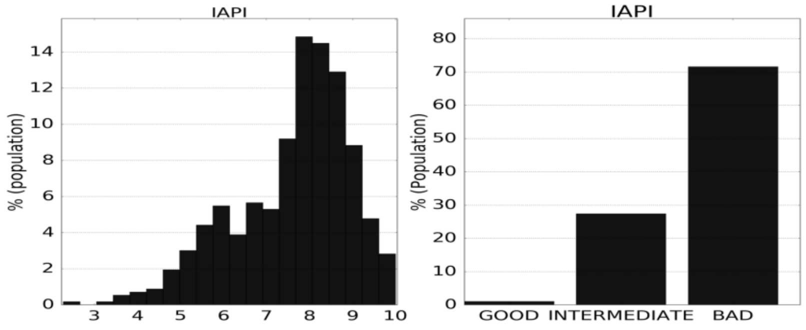

Figure 1: Representation of indices (left: original scale; right: common scale) – Example for IAPI.

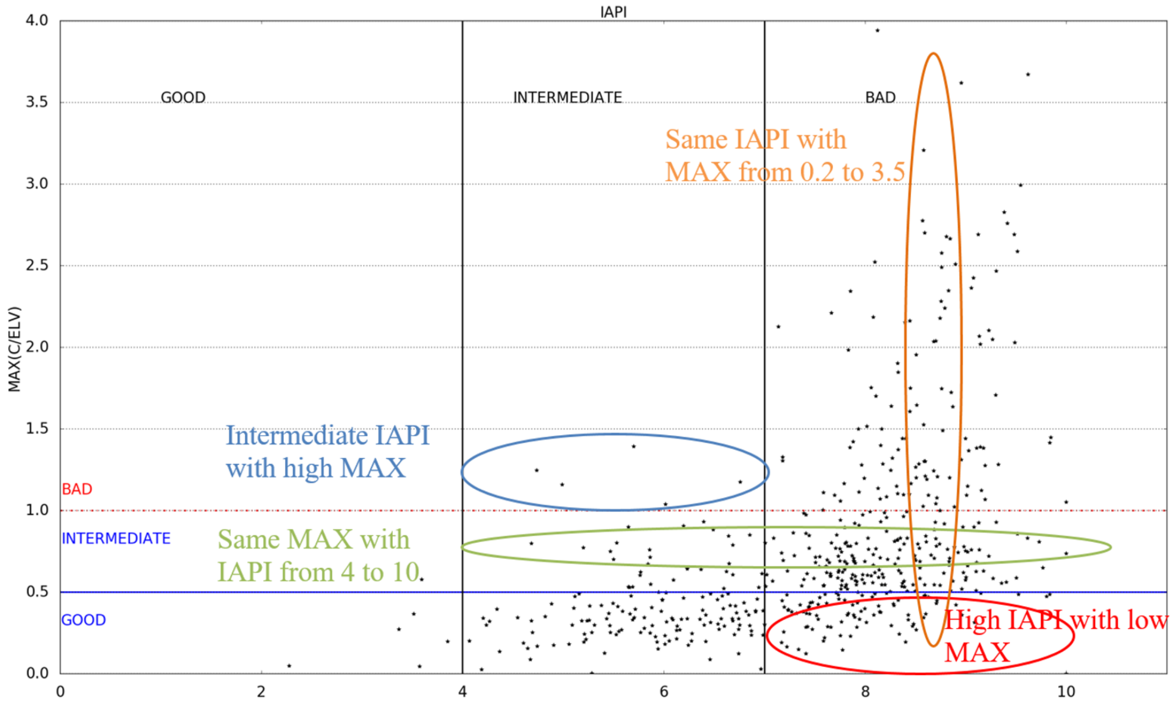

Figure 2: Detection of hidden information – Example for IAPI.

3 RESULTS AND DISCUSSION

3.1 IAQ indices comparison

All results obtained by calculating the 8 IAQ indices are compiled in Figure 3 to 5. Since $PM_{2.5}$ weights about 90% of DALYs lost and was not measured in every dwelling, we decided to considerer only the dwellings where $PM_{2.5}$ was measured (noted as "DALY (with $PM_{2.5}$)" hereafter). Figure 3 shows that some indices do not distinguish well the differences among the buildings (LHVP, GAPI, IEI Taiwan) whereas the others do. Figure 4 strengthens this observation. In particular, only two indices clearly classify the building population according to the interpretation scale: IAPI and DALY. However, they interpret the IAQ in opposite way with 70% and 20% of bad IAQ for IAPI and DALY, respectively. Figure 5 highlights the lack of correlation between the indices and the MAX except for DALY and, to a lower extent, BILGA and IAPI.

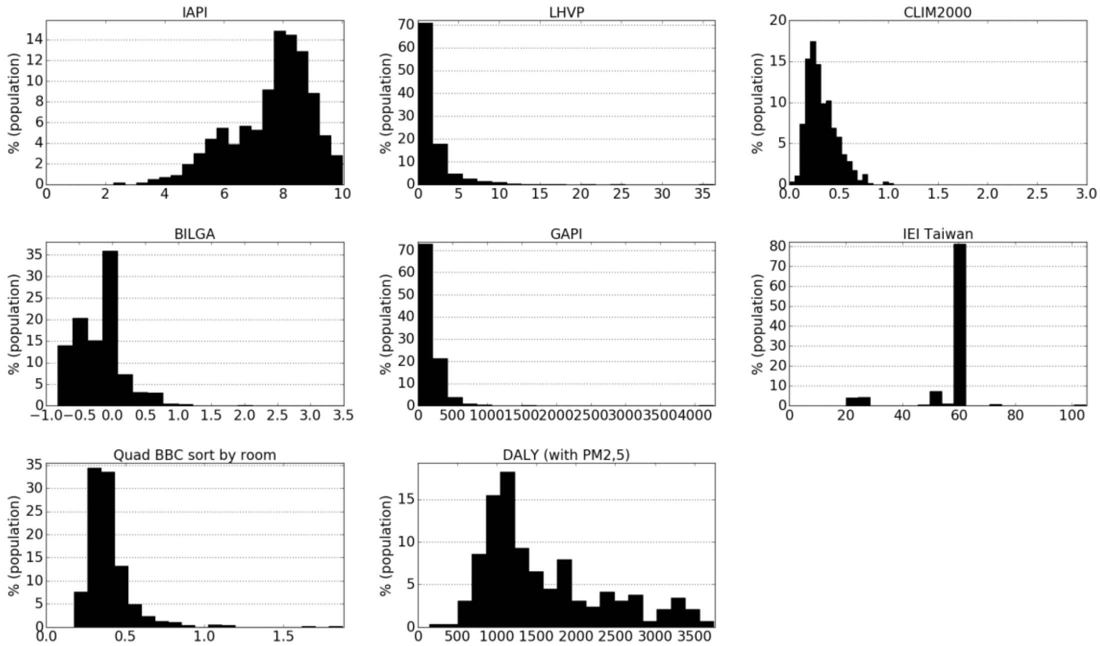

Figure 3: Representation of indices according to their original scale.

3.2 Proposal of a new index

Since there is no current consensus about the definition of good or bad IAQ, we propose a few statements that IAQ should reflect in our opinion:

- IAQ is good if there is no known health impact in a long-term perspective. Long-term (usually 1 year period) IAGV can be seen as the minimum threshold to be considered.
- IAQ is bad when the long-term (annual) average concentration is above short-term exposure maximum threshold. Short-term IAGV represents the maximal threshold for a long-term (annual) average concentration.
- Since the comparison is made with a critical threshold, if only one pollutant reaches this threshold, it is sufficient to affirm that IAQ is bad with certainty, no matter how low the concentration of the other pollutants are. The most unfavourable situation is relevant to define an IAQ index.

- There is no point in letting IAQ index values range from]-∞; +∞[. If the long-term (annual) average concentration of one pollutant is above critical threshold, no matter how high the concentration, IAQ remains bad; a maximum value for the index can be then defined. In the same way, concentration below the minimum ELV threshold refers to good IAQ so that an index minimum value can be proposed.

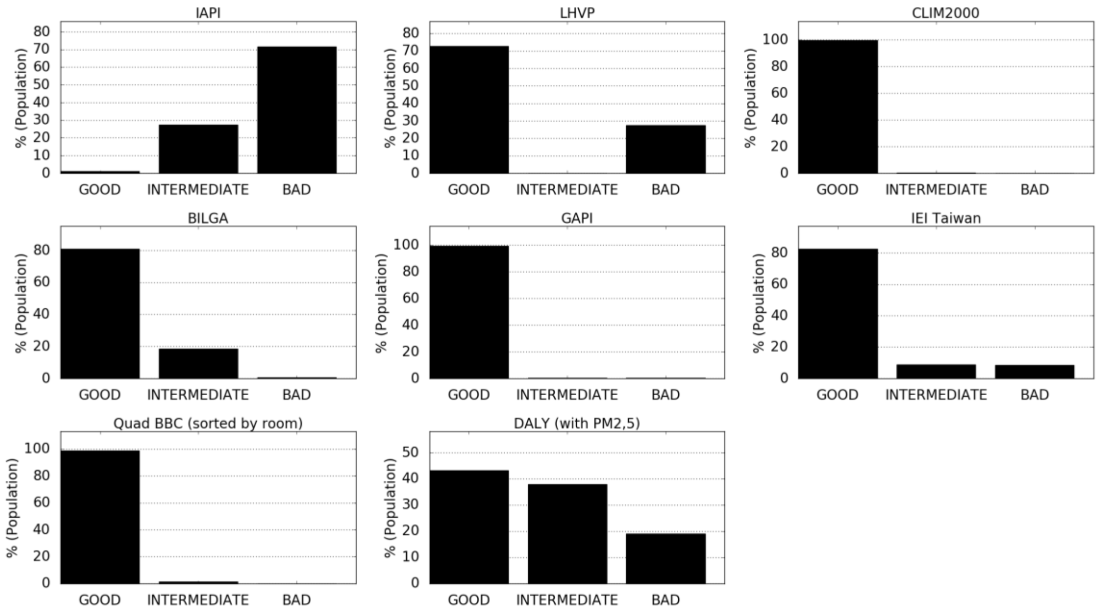

Figure 4: Representation of indices according to their interpretation scale.

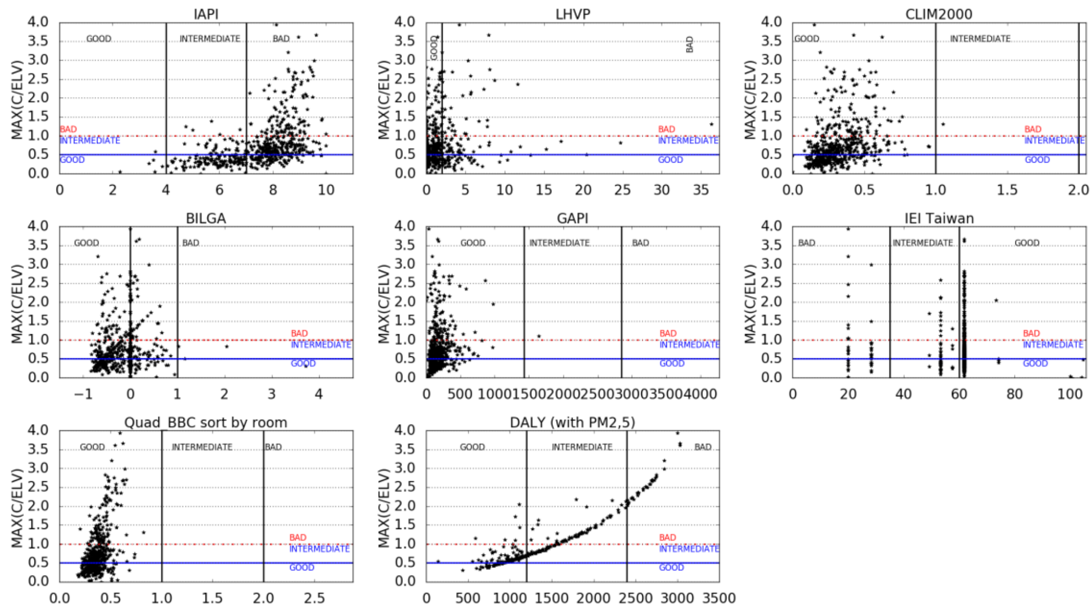

Figure 5: Comparison of indices with the MAX index.

Based on the previous points, the proposed formula for a new index, called ULR-IAQ, is the following:

$$I_{ULR-IAQ} = max\left(\frac{10\left(C_{ind,i} - IAGV_{LT,i}\right)}{IAGV_{ST,i} - IAGV_{LT,i}}\right) \tag{9}$$

$IAGV_{LT,i}$ is the indoor air guideline value for long-term exposure (usually 1 year) to a pollutant, $IAGV_{ST,i}$ is the indoor air guideline value for short-term exposure (shortest available) and $C_{ind,i}$ is the indoor concentration of pollutant *i*. If $C_{ind,I} > IAGV_{ST,I}$ then $C_{ind,I} = IAGV_{ST,I}$ and if $C_{ind,I} < IAGV_{LT,I}$ then $C_{ind} = IAGV_{LT,i}$.

This index varies from 0 to 10. A value of 0 means that IAQ is good; there is no known health impact due to the target indoor air pollutants. Index equals to 10 means a very bad IAQ; it is dangerous for human health even on short-term exposure and something must be done to improve IAQ. Between those two boundaries, a linear trend is used for sake of simplicity as we cannot currently define intermediate situations between good and bad IAQ.

The pollutants accounted for this new index have been selected according to the existence of a long- and short-term exposure IAGV and concentration level availability in the OQAI campaign (OQAI, 2007). They are[1]: formaldehyde [10; 50], acetaldehyde [160; 3000], acrolein [0.8; 6.9], benzene [2; 30], trichloroethylene [20; 800], toluene [70; 15000], tetrachloroethylene [250; 1380], styrene [250; 21000], o-xylene [200; 22000], PM_{10} [20; 50], $PM_{2,5}$ [10; 25] and carbon monoxide [10; 100].

3.3 Evaluation of the proposed index

As for the previous indices, ULR-IAQ was calculated over the whole French dwellings measurement campaign of 567 housings. Results are presented in Figure 6. The new index shows another picture of the IAQ in French buildings: about 28% bad, 10% good and the remaining 62% with intermediate IAQ. This picture is close to the finding of Wei et al. (2016), using a more complex combination of index classification: 34% bad, 6% good and 60% intermediate IAQ. The third graph confirms the capability of detecting bad IAQ; this result is obvious as it is part of the definition of ULR-IAQ.

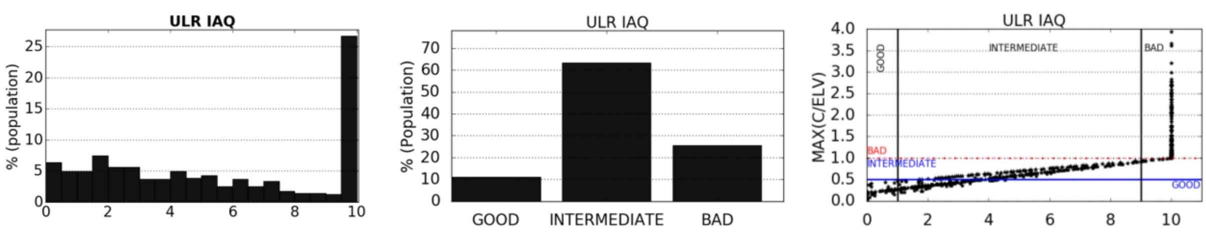

Figure 6: Results of ULR-IAQ, original scale (left), interpretation scale (middle) and comparison with max (right).

One key element to evaluate the IAQ is the list of target pollutants to be considered. A total of 12 pollutants have been used to evaluate the new index. However, not all pollutants have the

[1] All pollutants are presented as follows: name [long-term ELV; short-term ELV]. All units are in $\mu g.m^{-3}$ except for carbon monoxide which is in $mg.m^{-3}$

same importance on the ULR-IAQ final value. Figure 7 reports how frequent each pollutant has the first, second and third highest sub-index, respectively noted “pollutant 1, 2 and 3”. The result clearly points formaldehyde, acrolein, benzene, PM_{10}, $PM_{2.5}$ and carbon monoxide as unavoidable when evaluating IAQ in dwellings. However, from literature, at least three more pollutants of interest should be added to the list i.e. radon, nitrogen dioxide and mould. Their harmful effects are known but there was no available data in the French survey to take them into account.

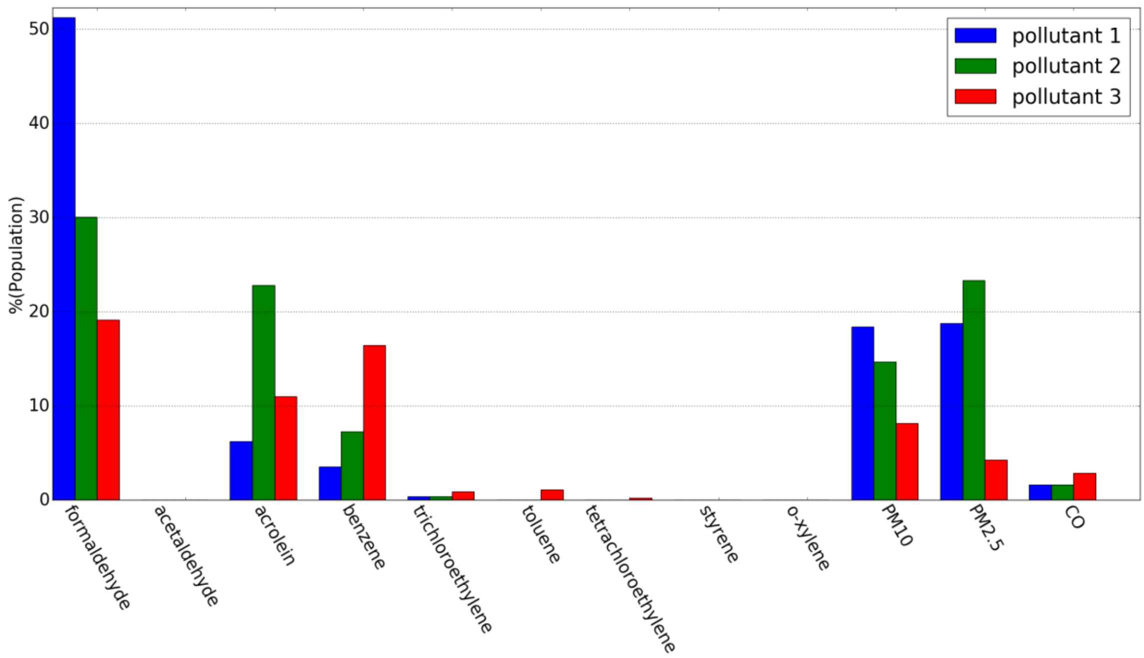

Figure 7: Frequency of pollutants corresponding to the 3 most unfavourable on the whole dwelling measurement campaign.

4 CONCLUSION

This work is based on the comparison of IAQ indices. Eight indices found in the literature were calculated and compared using the data of the French dwelling measurement campaign (567 housings) as inputs. By analysing the outputs and indices’ original definitions, the advantages and drawbacks have been listed and the definition of a new index called ULR-IAQ has been proposed. The new index seems to give a better representation of the IAQ of the studied dwellings. In particular, the index allows the detection of bad IAQ caused by one (or more) pollutants, ability not included in the existing indices. The new index permits to limit the list of pollutants of interest to a minimum, a list in agreement with previous prioritization studies (INDEX, 2005; Kirchner et al., 2007).

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