DEFINITION AND ASSESSMENT OF INDOOR AIR QUALITY CLASSES: SOURCES OF UNCERTAINTIES AND RATING IMPLICATIONS

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ABSTRACT

This paper describes the method, in which human observers assess indoor air quality. This method is at present necessary to determine actual levels of air quality indoors in non-industrial buildings to fulfil comfort requirements specified by the standards. The paper attempts to identify the potential drawbacks of the method, its limitations and the factors influencing these measurements. Examples are given illustrating, how the measurement uncertainty influences the estimated level of indoor air quality. Implications are discussed for the indoor air quality levels and the categories of emissions from building recommended by the current standards. Suggestions for modifications are given and an alternate approach outlined, which both ensure that the intended indoor air quality levels can reduce health risks and can additionally be verifiable in practice.

KEYWORDS

Indoor Air Quality; Sensory Assessments; Measuring Errors; Building emissions; Non-Industrial Environments

1 INTRODUCTION

Humans are constantly exposed in residential and non-residential (public) buildings to varying number and concentrations of particulate, gaseous and biological contaminants, which have both an outdoor and indoor origin. For example, a typical mixture of gaseous contaminants measured indoors can contain several thousand compounds, few hundreds stemming from human bioeffluents, few hundreds from building materials and equipment and few thousand from tobacco smoke, if smoking is allowed. These contaminants affect the quality of air indoors.

The quality of air indoors may be expressed as the extent to which human requirements are met. There are, however, quite large differences between the requirements of individuals. Some people are rather sensitive to air quality and are difficult to satisfy, while others are less sensitive, and are easier to satisfy.

One way to characterize indoor air quality is by performing physical and chemical measurements. The results of these measurements can then be compared with the guideline values set by the cognizant authorities.

In case of industrial environments, occupational safety and health guidelines are used to regulate the quality of quality. They define maximum concentrations, to which people working in these environments can be exposed for a certain duration; usually the averaging times are 8 hours/day in a 40 hours week for a long duration (TLV-TWA, Threshold Limit Value-Time Weighted Average), and 15 min no more than 4 times a day for a short duration (TLV-STEL, Threshold Limit Value – Short-term Exposure Limit). They also define ceiling limits, i.e. exposures that cannot be surpassed ever (TLV-C). These limit values are usually defined by the concentrations, above which serious health risks will occur, e.g., irritation and/or other chronic diseases. They are defined for individual contaminants, since occupational exposure are predominantly governed by the exposure to a single or maximum few contaminants at elevated concentrations, all other contaminants being at background or negligible level. In case when there are few dominant contaminants, the sum of ratios of their concentration to their threshold limit cannot be higher than one.

With the exception of few compounds such as e.g., radon and formaldehyde, the approach used to reduce occupational hazards cannot be directly adopted to set limits in non-industrial environments. This is because in non-industrial environments people are exposed to hundreds and/or thousands of contaminants occurring in different combinations and at very low concentrations, frequently orders of magnitude lower than TLVs used to set occupational exposure limits; often these concentrations are even lower than their odour detection thresholds. For many of these contaminants, there is additionally very limited toxicological data in the present literature, which completely precludes using TLVs or any other guideline values. These contaminants under certain conditions can moreover interact with one another and can undergo chemical reactions with other contaminants changing thus their concentration in indoor air and creating new contaminants, which are not normally present taking into account typical sources of pollution. The exposures in non-industrial buildings are thus very dynamic, which sets an additional challenge not only for setting the exposure limits but also for monitoring and quantification of the potential risks for people exposed to them. Consequently, a complex compound-by-compound approach may not always be applicable and sufficient to define indoor air quality levels. It may not provide complete, adequate and credible information, as to what the true level of indoor air quality is. Regulating indoor air quality by defining guideline values for all compounds in non-industrial environments seems thus nearly unrealistic, considering additionally that every day many new contaminants are introduced into environment. The limits can still be effectively applied for those compounds that can be measured and quantified, and are known to be hazardous for humans; this approach should not be dismissed.

Because detailed chemical characterization provides incomplete evidence that is necessary to regulate and set classes of indoor air quality based on the negative effects on humans, it has become frequent practice to supplement it with the method that characterizes indoor air quality by asking people to judge whether the quality of indoor air is good or poor (certain harmful pollutants such as radon and carbon monoxide are not sensed by humans at all, so sensory evaluations of humans cannot be used to quantify their effects). Human senses are stimulated during breathing: the olfactory sense, situated in a small area of the nasal cavity, which is sensitive to around half a million odours, the general chemical sense, situated all over the mucous membrane of the nose, which is sensitive to more than one hundred thousand irritants, and the thermal sense located in the nasal cavity, which is sensitive to varying levels of air temperature and relative humidity, providing that the air temperature is different from the mucosal temperature which is ~30-32^{o}C. This stimulation can be used to determine whether air quality is good or poor.

Several measuring approaches can be used when people are asked to judge indoor air quality (ECA, 1999). The two have been used most prevalently, i.e. assessments of odour intensity and acceptability of air quality. The former method was first thoroughly documented and applied for setting the air quality criteria indoors in the classical studies of Yaglou et al. (1936). In the method it has to be arbitrarily decided which level of odour intensity is to be set as the air quality guideline. The latter method propagated by Fanger and his colleagues (e.g., Fanger et al., 1988) have an advantage that individual occupants of indoor spaces are the final arbiters of whether the indoor air quality is acceptable or not. The level of air quality can then be set by selecting the percentage of people finding the air quality acceptable, as used by ASHRAE Standard 62.1 (2013) or the maximum percentage of dissatisfied with air quality, as used by the European Standard EN15251 (2007). The method also assumes that the assessments of acceptability of air quality does not only take into account odour intensity but also integrates other sensory stimulations such as air pleasantness or freshness.

EN15251 (2007) defines four categories of indoor environmental quality, Category I representing high level of expectation, Category II providing normal level of expectation, Category III and acceptable moderate level of expectation and Category IV the environments, which does not meet the above categories; this category should be avoided or accepted only for a limited period of time during the year. For each of the categories, the range of conditions is defined securing that the requirements of the category can be satisfied. This applies to the thermal environment, acoustical environment and illuminance, as well as to the indoor air quality. For indoor air quality the four categories of indoor environment quality correspond to four levels defining the percentage dissatisfied persons with the air quality, namely 15%, 20%, 30%, and more than 30% dissatisfied. Thus, they need to be determined through the assessments made by the human observers. For each category of indoor air quality, the required level of ventilation rate is provided taking into account the person component, i.e. ventilation rate needed to dilute human bioeffluents, and the building component needed to dilute and remove contaminants emanating from other sources than humans; both components are eventually added to determine the total ventilation rate for a given space. The person component depends on carbon dioxide (CO_2) the well-established indicator of human bioeffluents being also the main product of human metabolism. In case of building component three classes of emissions are defined: non-low-polluting building, low-polluting building, and very low-polluting building; for each of the classes the ventilation rate is defined. EN 15251 gives examples on how the emission classes can be determined where among defining the acceptable emissions of certain gaseous contaminants such as ammonia and formaldehyde, the permissible levels of volatile organic compounds (VOCs) expressed as TVOC (total VOCs) and carcinogenic compounds are indicated, as well as permissible dissatisfaction with odour resulting from the emissions.

The purpose of the present paper is to identify and review the methods used to determine the levels of indoor air quality, to identify possible sources of errors and to discuss their impact on classification of indoor air quality based on comfort (perceived air quality), as proposed by EN15251. Effects on health, work performance and learning are outside the scope of the present paper.

2 INDOOR AIR QUALITY EVALUATIONS BY SENSORY PANELS

Different methods for sensory evaluations of indoor air quality exist with no consensus in the literature as to which method is best suited for practical applications (ECA, 1999). A method using sensory panels assessing odour intensity and/or acceptability of air quality used to estimate the % dissatisfies with air quality have been predominantly used for this purpose in the past and are described in the following.

2.1 Percentage dissatisfied with air quality: measurements, precision, influencing factors and implications

The percentage of persons dissatisfied with air quality cannot yet be measured directly with an instrument although there have been attempts to construct such instruments (e.g., Wenger et al., 1993; Müller at al., 2007). Human observers judging the air quality are the only feasible way at present. Air quality evaluations can be carried out using dichotomous yes/no scale (Fanger and Berg-Munch, 1983) or a continuous acceptability scale (Gunnarsen and Fanger, 1992; Clausen, 2000). The assessments of acceptability are then used to predict the percentage dissatisfied with air quality.

In case of dichotomous acceptability scale, the percentage dissatisfied with air quality is calculated as the ratio of the votes indicating the air quality to be "not acceptable" to all votes of made by all observers. In case of continuous acceptability scale, the percentage dissatisfied is usually estimated using the relation established by Gunnarsen and Fanger (1992). However, there are also other relations, which are different from this relation especially at the levels corresponding to high indoor air quality, i.e. low percentage dissatisfied (Figure 1). The reasons for the discrepancy between the different relationships have not been examined in detail, and neither it was established which of the three relationships provides the best estimate of the percentage of dissatisfied. The differences between the relationships may cause inaccurate prediction of the level of percentage dissatisfied with air quality. Assuming that the ratings of acceptability of air quality correspond to 20% dissatisfied (Category II in EN 15251 (2007)) then according to the relationship developed by Gunnarsen and Fanger (1992), the actual level of % dissatisfied can be up to 35% dissatisfied if the other two relationships are considered; this is actually outside the Category III described in EN 15251 (2007).

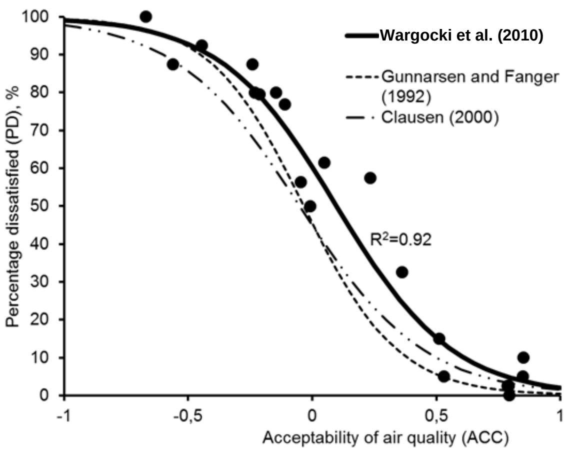

Figure 1: Percentage dissatisfied with air quality as a function of acceptability of air quality

The number of observers evaluating the air quality has significant influence on the accuracy of measurements. This is due to considerable variation in ratings of acceptability of air quality among individuals because of variation in chemosensory sensitivity in combination with variables such as personality, preference, mood and prior experience. In case of the dichotomous acceptability scale, the margin of error for assessments made by 20 observers is 20%, can be halved if 65 observers are used and to 1% for ca. 6,000 observers; 20 observers are recommended by ASHRAE Standard 62.1 (2013). The number of observers has to be thus considerably increased to improve considerably accuracy of measurements. This may not always be feasible and can cause logistic problems, as well as will increase the costs of performing the measurements. In case of the continuous acceptability scale, increasing number of observers above 30-50, which is a typical number of observers performing assessments, will actually have very little effect on accuracy (Figure 2). This is because of the quite large standard deviation of the acceptability ratings on a continuous scale, which is usually between 0.25 and 0.6 (12-30% full scale), and is on average 0.45 (22% full scale) (Gunnarsen and Bluyssen, 1994; Knudsen et al., 1998; Wargocki et al., 2010). The uncertainty of estimating whether the air quality meets Category II in EN 15251 (2007) corresponding to 20% dissatisfied will consequently be 5% to10% dissatisfied for a typical number of 40 observers and the average standard deviation, for which the standard error of acceptability rating will be 0.08 (Figure 2). This means that with the margin of error, the actual air quality level can range from 15% and 30% dissatisfied, which is actually the whole range defining different categories of air quality in the standard.

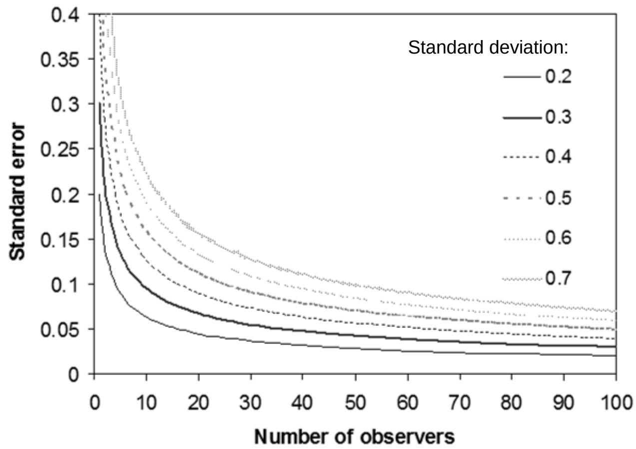

Figure 2: Standard error of the acceptability rating as a function of number of observers and standard deviation of the rating of acceptability

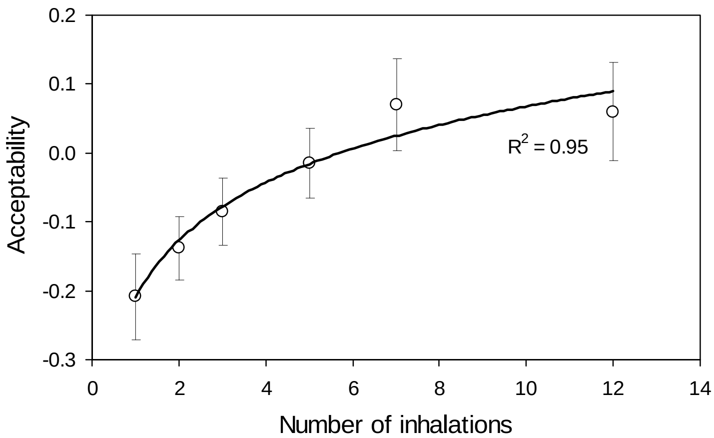

Figure 3: Assessment of air quality as a function of number of inhalations; error bars indicate standard errors

Human senses exhibit reduction in sensitivity with time of exposure, when the air is polluted by odours (adaptation). Gunnarsen and Fanger (1992) observed considerable adaptation when human bioeffluents were the pollution source, probably due to bioeffluents comprising mainly odours, moderate adaptation when tobacco smoke was the source and almost no adaptation when the air was polluted by building materials. They observed that adaptation occurred within the first 6 minutes of exposure, while in the other work the strong adaptation to indoor air polluted by typical building materials occurred already in the course of the first seven inhalations, corresponding to an exposure of about 24 seconds (Jørgensen and Vestergaard, 1998; Clausen, 2000) (Figure 3). In practical applications, it is expected that a judgment of indoor air quality be rendered immediately upon exposure and earlier than within the first 15 seconds in order to have unadapted vote; this is what is actually recommended by ASHRAE Standard 62.1 (2013). Figure 3 suggests, that there will be considerable adaptation during this time. It is thus impractical to assume in field evaluation that observers take only 1 inhalation when rendering the assessment of air quality and it should be acknowledged that some sensory adaptation will always be present: It may be thus difficult to distinguish in practical applications the unadapted assessments (of visitors to a space with very brief exposure) to the adapted assessments (of occupants staying in a space for an extended time).

The perception of air quality is also influenced by the humidity and temperature of the inhaled air even when the chemical composition of the air is constant, and the thermal sensation for the entire body is kept neutral (Berglund and Cain, 1989; Fang et al., 1998a,b; Toftum et al., 1998). Keeping the air dry and cool reduces the percentage dissatisfied with the air quality (Figure 4), and causes the air to be perceived as fresh and pleasant. Consequently, when the air quality is measured using sensory assessments of acceptability, the thermal conditions of the inhaled air should be well documented, and if necessary recalculated to reference conditions (set to 23°C and 50%RH) using models developed by Fang et al. (1998a,b). The strength of the thermal effect on the assessment of indoor air quality can be observed by examining Figure 4. For example, increasing the summer temperature from the lowest to the highest level recommended by EN 15251 (2007) for Category II can increase the % dissatisfied with air quality by as much as 15% (Figure 4).

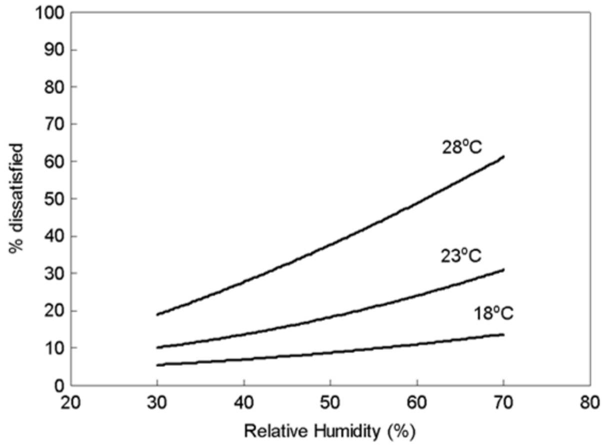

Figure 4: Percentage dissatisfied with air quality as a function of temperature and relative humidity of inhaled air

Selection of human observers evaluating the air quality can also affect the measurements of acceptability of air quality, but no systematic data exist to estimate the size of this effect on the predicted percentage dissatisfied persons. At best, the observers from the relevant population for which the measurements are addressed should be selected; this may however be difficult to achieve in practice. A rational compromise is to select at least observers of a similar age for the target population, as age has been shown to have a major impact on sensitivity, while gender and smoking status are of a slightly less importance. To minimize the errors that can result from the selection of observers, standardized methods quantifying their sensitivity should be used during recruitment and if possible observers performing similarly on these tests should be used. The screening tests comprising a ranking test used to evaluate the ability of observers to classify different odour intensities and the matching test used to assess their ability to identify several stimuli of odour (ISO 8587, 1988; ISO 8586-1, 1993) can be used for this purpose, as well as Chemical Sensitivity Scale (CSS), which examines experience with and exposure to odours and sensory irritants (Nordin et al., 2003; 2004).

2.2 Odour intensity

Measurements of odour intensity have also been used as a metric for defining the air quality levels, but to a much lesser extent than the assessments of acceptability of air quality. Measuring odour intensity requires the same experimental rigour as in case of performing assessments of acceptability of air quality, especially regarding the length of exposure and adaptation, because olfactory sense, which in this case is a main trigger of a response, exhibits very strong reduction in sensitivity with the time of exposure.

2.3 Acceptability, odour intensity and % dissatisfied

Although measurements of acceptability of air quality have been assumed to integrate different sensory attributes, it seems that they are primarily influenced by odour intensity (Wargocki et al., 2010): acceptability and odour intensity ratings of the same exposures exhibit strong correlation (Figure 5). Thus it can be stipulated that the measurements of acceptability can be substituted by the measurements of odour intensity, which are more straightforward and to a lesser extent influenced by the preferences and the experience.

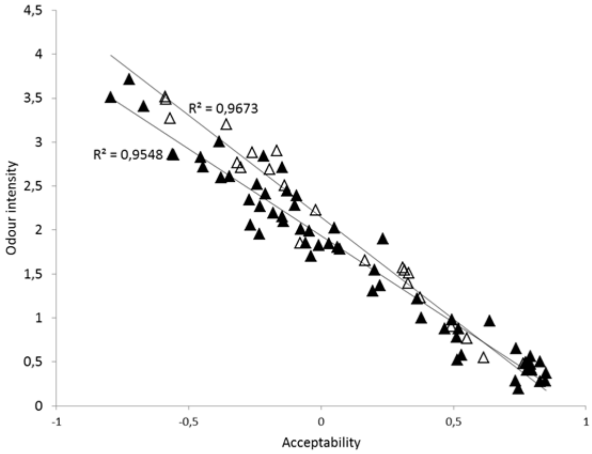

Figure 5: Correlation between ratings of acceptability of air quality and assessments of odour intensity

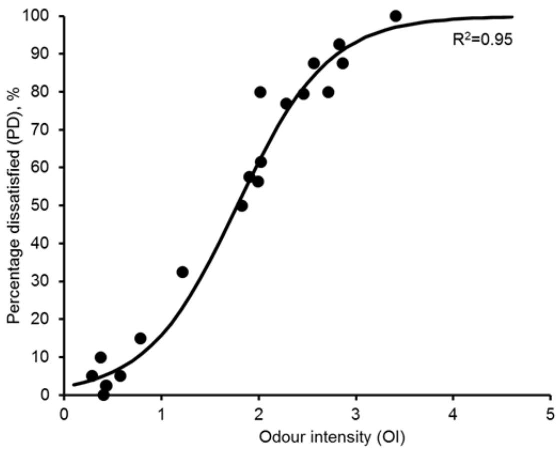

Figure 6: Percentage dissatisfied with air quality as a function of odour intensity

Assuming that odour intensity is strongly correlated with the ratings of acceptability (assuming that the exposures evoke unpleasant responses), the relationship between the percentage dissatisfied and odour intensity has been created (Figure 6). This relationship can be used to interpret and analyse the results from the experiments, in which only odour intensity has been measured. For example, Yaglou et al. (1936) in their classical studies assumed that moderate level of odour intensity should determine ventilation requirements for controlling body odour. With the relationship shown in Figure 6, the moderate odour intensity corresponding to 2 on a scale results in as many as 50% dissatisfied with the air quality; this is much higher than what is recommended by the present standards (ASHRAE, 2013; EN15251, 2007). To match the requirements of present standards, i.e. to bring the level of dissatisfaction down to e.g. 20%, the ventilation rate to control body odour should have been determined for the weak level of odour intensity (about 1 on the scale) and should correspond to about 15-20 L/s per person rather than about 7 L/s per person as proposed by Yaglou et al. (1936).

2.4 Carbon dioxide and percentage dissatisfied

The measurements of carbon dioxide are frequently used to control ventilation rates that need to be delivered to a space. Because there exists relationship between carbon dioxide concentration and the percentage dissatisfied with air quality (Fanger and Berg-Munch, 1983; ECA, 1992) (Figure 7), the concentration of carbon dioxide can be considered as the proxy for the level of indoor air quality. The limitation of this approach is that it can only be used when spaces are occupied by people (carbon dioxide is in this context a proxy for human bioeffluents as this is main human metabolite) and it may not take into account other contaminants that can potentially influence the actual level of air quality. Furthermore the levels of carbon dioxide indoor exhibit quite dynamic changes and not always reach and/or remain at the steady state level for the extended periods. The control would have to take into account these variations. Finally the sensors used to measure carbon dioxide may exhibit quite large inaccuracies. For example a study of Fisk (2007) examined 44 sensors used in nine Californian buildings and showed that their accuracy was quite low, the errors ranging from 378 to 1013 ppm. The reasons for this poor performance were not examined but certainly lack of frequent maintenance and calibration check as well as improper location of sensors are likely factors that cannot be disregarded in this context.

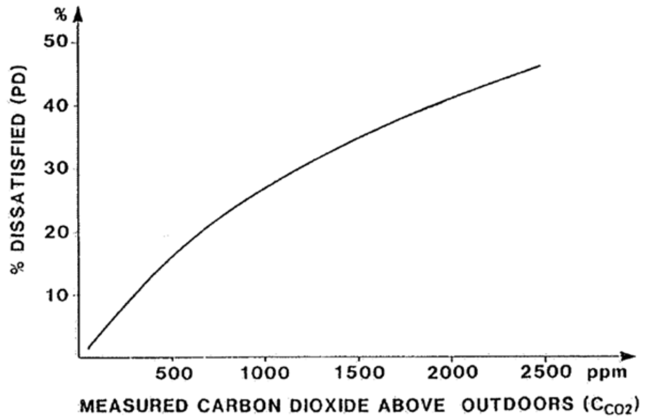

Figure 7: Percentage dissatisfied with air quality as a function of measured carbon dioxide level above outdoors

3 ODOUR INDEX

Sometimes odour index is used to examine, whether chemical compounds measured indoors would be causing odour nuisance. Odour index is defined as the ratio of the concentration of a compound to its odour threshold. Usually odour detection thresholds are used. The odour detection threshold is the lowest concentration of an individually occurring compound that can be detected by 50% of human observers (Cain, 1988; WHO, 1987). If odour index is ≥1 it is expected that the odour produced by the compound can be detected by majority of people. If an odour index is <1, the concentration is lower than the threshold and the odour produced by the compound will probably be not detected by people. Although the use of odour indices seems reasonable, the approach has several limitations. The most obvious is that chemical analysis unable to detect all compounds especially those causing sensory effects (e.g., Wolkoff et al., 1997). Another limitation is the reliability of odour detection thresholds, which can vary sometimes several orders of magnitudes for a single compound (Devos et al., 1990). The reason for this can among others be different methods of estimation of odour detection thresholds and insufficient scientific rigour when they are determined. Finally, perhaps even more important limitation of using odour indices is, that it is often observed that even when odour indices are <1, it is when it is expected that people cannot detect odour, the quality of air is still assessed as not acceptable (e.g., Wargocki et al., 1999).

4 EMISSION CATEGORIES

Standard EN 15251 (2007) defines three classes of emissions from building and for each class defines ventilation requirements. As shown in Table 1, the proposed classes represent well the variety and distribution of the potential emission rates of pollutants in non-industrial buildings related to building materials and furnishing, the HVAC system including the dust collected on the particle ventilation filters, and office equipment including personal computers (Wargocki 2004); the building components were defined based on ventilation rates required to handle emissions from building in order to reach certain level of air quality defined by the % of dissatisfied. The classes of emissions were estimated based on assessments made by human observers in different buildings (summarized by Wargocki et al., 2004). They can thus potentially be subject to inaccurate estimation considering the imprecisions related to assessments of air quality made by human observers and the factors influencing these assessments described in the preceding sections. Emission classes proposed by EN 15251 (2007) are useful when the ventilation requirements are roughly estimated. However, it can be quite challenging to predict beforehand, whether building and furnishing materials, which are going to be used in a building, meet specific postulated emission class. If material emissions are not known the designer may want to high ventilation rates according to the non-low polluting class to make sure that the air quality levels in the completed building will be met. Verification of the assumed class can be attempted, when the building is completed and put into use. Even then, the task is quite complicated. Remediation to bring the indoor air quality to the expected level, as specified during design, in case the class was improperly assumed, can be costly and demanding.

Table 1: Emission categories in EN 15251 (2007) compared to measured strength of pollution sources in buildings; the compnents provide ventilation requirements in Category II of indoor environment quality and air quality level corresponding to 20% dissatisfied

Building type	**Source strength (olf/m^{2}floor)**	**Estimated ventilation rate (L/sm^{2}floor)**	**Emission class (EN15251)**	**Source strength (olf/m^{2}floor)**	**Building component (L/sm^{2}floor)**
97 office buildings and assemby halls (where tobacco smoking occurred)	0.23±0.06	1.7±0.5	Non-low polluting	0.2	1.4
1 department store	0.15	1.1			
6 office buildings (no tobacco smoking)	0.11±0.09	0.8±0.6	Low-polluting	0.1	0.7
10 kindergartens	0.06±0.04	0.4±0.3			
6 schools	0.06±0.06	0.4±0.6			
3 office buildings (no tobacco smoking)	<0.05	<0.37	Very low-polluting	0.05	0.35

5 CONCLUSIONS AND IMPLICATIONS FOR FUTURE WORK

- Assessments of indoor air quality made by human observers can be largely influenced by the measuring errors and inaccuracies. These imprecisions can cause incorrect estimation of the indoor air quality expressed by the percentages dissatisfied with air quality. Consequently, using percentage dissatisfied to set the indoor air quality requirements can be regarded as somewhat challenging also because of the difficulties to ensure compliance. Improvements of current measuring methods using human observers are needed in order to continue application of this approach for setting indoor air quality levels.

- Other approaches for setting indoor air quality levels need to be explored. The approach proposed by the recently developed guidelines for health-based ventilation in Europe can be followed (Wargocki et al., 2013). The guidelines propose the strategy to control indoor air quality based on health end-points, in which source control is a primary method and the ventilation is used when all source control options are exploited. The World Health Organization (WHO) air quality guidelines are used to set the exposure limits (WHO, 1987; 2000; 2005; 2009; 2010). Ventilation rates are considered health-based when WHO air quality guidelines are met and the base rate is defined to control primarily human bioeffluents; the base rate must always be provided. Following WHO air quality guidelines and/or any other amenable exposure limits, e.g. EU-INDEX guidelines (Kotzias et al., 2005), for which general consensus has been reached as regards their applicability, validity and uncompromised scientific merit and completeness, may create more tangible and harmonized approach for setting indoor air quality levels. Inclusion of requirements on indoor air quality in the national regulations would be necessary to back-up and underpin this process.

- The harmonized regulation of product labelling and ventilation would be necessary to improve characterization of emissions and secure more accurate, manageable and verifiable use of emission classes. Two recently completed harmonization efforts can be used for this purpose, one for indoor products labelling (ECA, 2005; 2012) and one on health-based evaluation of indoor emissions from construction products (ECA, 2013). The first one proposes framework, which could assist in making informed choices about the new or existing products used in indoor environments. It also defines core and transitional criteria with an attempt to facilitate the convergence of existing mandatory and voluntary labelling schemes. The second one provides an approach for establishing harmonised lowest concentration of interest (LCI) values for 177 organic compounds detected in emission tests of construction materials and additionally a list of 82 compounds with interim LCI values. Integrating these frameworks with the ventilation rate design specification is likely to have a noticeable effect on improving the compliance and securing that the prospected indoor air quality levels are attained.

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