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The Approach of Including TVOCs Concentration in the Indoor Environmental Quality Model (IEQ)—Case Studies of BREEAM Certified Office Buildings

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Abstract: The article analyzes the impact of measured concentrations of Total Volatile Organic Compounds (TVOC) emissions determined for four BREEAM certified buildings on the Indoor Air Quality Index (IAQ_{index}) and the overall Indoor Environment Quality index (IEQ_{index}). The IEQ_{index} indicates the percentage of building users who are satisfied from the indoor environment. In existing IEQ models, currently the concentration of CO_2 is mostly used to evaluate the IAQ_{index} sub-component. Authors point out that it is recommended to use TVOC instead CO_2 at pre-occupant stage where building is mainly polluted by emission from finishing products. The research provides the approach where the component related to the emission of TVOCs is implemented to IEQ model. The first stage of assessment was a test of the volatile organic compounds concentrations in case study buildings. Secondly, the analysis results were assigned into the number of dissatisfied users ($PD_{(IAQ)}$) from the theoretical function given by Jokl-Fanger resulting from the Weber-Fechner equation. Finally, the overall IEQ_{index} was calculated. The IEQ approach proposed in this paper is mainly based on a consideration of EN 15251 and scientifically accepted models.

Keywords: Indoor environment quality; IEQ; IAQ; TVOC; BREEAM assessment

1. Introduction

Employees often spend eight–10 h daily in the offices. The working environment affects their health and productivity. Recent studies show that the costs incurred by the employer, owner of building and society, caused by poor indoor environment conditions in office buildings, may be higher than the energy consumption cost in a building [1,2]. A relevant quality of the indoor environment can improve the productivity of a work and reduce the number of health exemptions for employees [3]. The authors promote the use of simplified methods to assess the indoor environmental quality (IEQ). Very useful summary for IEQ literature was done by Al Horr [3]. The research of authors [4–12], influencing the presented study, indicates that the IEQ_{index} is accepted and recognized tool for assessing the comfort of building users (in design, pre-occupant stage and post-occupant stage of buildings), however, sub-models of IEQ model elements still require analysis and a global harmonization for a wider practical use (e.g., Building Research Establishment Environmental Assessment Method—BREEAM scheme [13]) and acceptance [14]. The IEQ_{index} indicates the percentage of building users who are satisfied with the indoor environment, taking into consideration air quality, visual comfort, acoustic comfort, and thermal comfort (or other) [15]. Each IEQ sub-component is based on the theoretical sub-model, presented by authors in this study (see Section 2.2). In existing IEQ models, currently the concentration of CO_2 is mainly used to evaluate the IAQ_{index} but this requires a deeper discussion. The authors in a paper undertook the research to include in the practical IEQ assessment (simultaneously with BREEAM assessment) the element related to the emission of total volatile organic compounds (TVOCs). The analysis of the literature on volatile organic compounds (VOCs) testing [16–23] and own tests of new office buildings shows that the TVOC concentration range may vary depending on the construction and finishing materials, temperature, and ventilation rate. It may change in the range 20–3000 $\mu g/m^3$, where the value "pass" required in the BREEAM system is 300 $\mu g/m^3$. The weakest odor that can be detected by the human smell sensors has TVOC threshold concentration of 50 $\mu g/m^3$ [24]. Over 1000 $\mu g/m^3$ the human sensory effects may appear. The sensory effects may include dryness, irritation, weak inflammatory irritation in nose, eyes, skin, and air ways At TVOC concentrations level above 2500 $\mu g/m^3$, other types of effects may become of greater concern [25].

Presented research intention was not to solve the problem of TVOC using to assess the indoor air quality but to provide a method and analyze a possible impact of TVOCs on the IEQ model, having in mind that TVOC approach would find wider acceptance in future (e.g., BREEAM). The main need for VOC element implementation into IEQ model is that CO_2 emissions are representative for the air pollution associated with the presence of a significant number of occupants. The VOCs emissions represent pollution caused mainly by emissions from the construction products inside the building. Having years of experience in testing building contamination with detailed VOC compounds, the authors are willing to suggest using the TVOC approach presented later for determining the IEQ_{index} but considering the fact that it is not a tool to solve the air pollution problems in a building. The authors are aware of TVOC approach criticism on international level, for example, one of main academic research center in this area stated in a scientific letter that "TVOC measurements may be grossly inaccurate and therefore the TVOC concept is unsuitable as a PASS/FAIL metric" [26].

The choice of internal environment parameters of IEQ model is regulated by EN 15251 [27] concerning the classification of the indoor environment of buildings. Individual elements of the IEQ model along with references to literature have been presented in Section 2 on methods.

A main recommendation to include information on the indoor environment in the building for the energy certificate of the building is given in Article 7 of Directive 2010/31/EU (EPBD) [28]. It was stated there that for the purposes of energy certification it may be necessary to convert complex information about the indoor environment into one simple generalized indicator of the quality of the indoor environment in the building. This generalized indicator is, according to the current analysis and research, on a global scale is IEQ_{index}, containing four components of the internal environment quality: thermal comfort, indoor air quality, acoustic comfort, and visual comfort [29,30]. Recently, among many conscious participants of the construction process, there is a consensus that energy characteristic without a part concerning the internal environment does not make any sense. In new buildings with low energy demand, nearly zero-energy buildings (NZEB), there are investigated problems with ensuring adequate air quality and comfort [31]. According to the author's experience, this problem concerns a minimum 30% of new buildings. Nowadays, the methods of commercial environmental assessment of buildings are becoming popular, taking into account the comfort of use, however, in the country of the authors, the number of facilities implemented according to the criteria of these methods is still relatively small—only dozens of buildings (mainly office buildings) for thousands of new buildings constructed each year. Fulfilling the requirements of national regulations—e.g., contained in the regulation on the technical building code to be met by buildings and their location—also does not guarantee that the building will be healthy and user-friendly. The demand for the methods of assessing building comfort available to every engineer was reflected in other CEN TC 350 standardization work. In 2014, a standard was published indicating the methodology for determining the parameters of the indoor environment, e.g., EN 16309 [32]. Standards provides the methodology of the building's social assessment, indicating the elements that affect the comfort of use of the building. Currently, various research centers world-wide are working on the IEQ model, with the assumption of building a simplified model to predict the design values of the input parameters of the internal environment or to assess the existing buildings, including thermal environment, air quality, lighting, and acoustics. The IEQ indicator model used by authors consists of four partial models of its components:

- anticipated satisfaction with TC_{index} thermal comfort,
- satisfaction with IAQ_{index} air quality,
- satisfaction with acoustic comfort ACc_{index},
- satisfaction with the quality of lighting L_{index}.

It is a physical model describing four physical processes affecting the internal environment, in which the input data are measurable environmental parameters (e.g., temperature, TVOCs, etc.), and the initial data—the percentage of people satisfied with the indoor environment. The models for components of the comfort for assessment of case study office building are briefly described later.

The authors, as part of presented research, performed measurements of internal air quality (VOCs) in new four office buildings BREEAM certified [33]. BREEAM is the international assessment method based on scientifically based sustainable metrics and indicators that covers a range of environmental aspects and issues. Its categories consider health and wellbeing (also TVOC), the energy consumption, pollution, transport, water use, materials, ecology, and management processes and waste processing. Buildings are rated using a scale of "Pass", "Good", "Very Good", "Excellent", and "Outstanding".

The concentration of TVOC and Formaldehyde were determined including other environmental parameters. The research intention was to show the potential influence of TVOC concentrations and contribution into the result of IAQ_{index} and the value of overall IEQ_{index} of the building. Until now, most authors in the IAQ_{index} analysis have been focused on the concentration of CO_2 and less common on the intensity of the odour in the indoor spaces [1]. The use of TVOC impact in the IEQ model is an issue taken up by the authors, a new element is the implementation of the function that allows the conversion of concentrations to the number of dissatisfied users (PD). Analysis of the significance of TVOC inclusion into IAQ and then IEQ models carried out by the authors gives the possibility to determine from the values of concentration of TVOC, the PD values. Obtained converted TVOC emission concentration results were used for the case study buildings IEQ assessment and the results are presented in the study. Thanks to the tests performed on the BREEAM certified buildings, it was possible to determine and validate the impact of building TVOC air pollution on the overall IEQ_{index}.

In our experience, the IEQ model (together with its sub-component models) was created mainly for the purpose of predicting user reactions/satisfaction based on the project/design values. Taking into account the building design solutions, there is an option to predict user future satisfaction. IEQ model is theoretical but resulting from the large scale practical assessments made by the authors of the sub-models. Assessment/measurements in the BREEAM system for new buildings are usually made when finishing works are completed at pre-occupant stage. The assessment on this stage is to ensure that the building occupied later will be comfortable, healthy, and safe for users (BREEAM Excellent). This is a kind of pre-verification of real performance/wellbeing. When building is already occupied, there might be no option for any high level improvements. Of course the authors are aware that real user satisfaction surveys offer a real satisfaction values and are the best option, but at pre-occupant stage presented model is satisfactory enough and technically useful. Therefore, we assess the theoretical index of the predicted/expected user response to the presence of TVOC in the office indoor air. The research cited later provides a significant correlation factor between the results predicted and the results carried later with users when building is occupied. In our future work, we will focus on this element and we are constantly investigating new buildings.

The quality of indoor air in the context of VOC pollution is significantly affected by emissions from the construction products. Therefore, before occupation stage, VOC tests carried out are a main option to detect any air problems in building. This investigation allows us to make good decisions (like postponed occupation) and the building later may be safe for users (in the case of BREEAM, recommended level of TVOC is 300 µg/m^3).

2. Materials and Methods

2.1. General Information on Methods Used

The following models and methods were used in the research:

- building assessment criteria acc. to BREEAM system [13,34]
- methods of air sampling in buildings (for VOC tests)
- methods for determining environmental conditions in in-situ buildings
- chromatographic VOC analysis methods (GC/MS) [35]
- IAQ model including TVOC impact (conversion form VOC concentration to PD) [36]
- 4 sub-component models for determining IEQ with the crude weight system [5,9]
- measurement uncertainty scheme for IEQ [37]

The authors put the main attention on the evaluation of TVOC emission and its impact on IAQ_{index} and finally on IEQ_{index}. The description of methods for estimating other 3 IEQ sub-components for case studies in the article has been partly simplified however, scientifically accepted models and results are presented below. The BREEAM guidelines and common ISO/CEN standards for measuring the parameters of the internal environment were used to determine the values of thermal and acoustic comfort in buildings. VOC measurements were the basis to calculate the sum of TVOC. The sum of VOCs was used to determine the IAQ_{index} and then to determine the total IEQ_{index} for four office buildings. Table 1 shows the most commonly used approaches for calculating the IEQ_{index} for existing and designed buildings due to the use of actual (real) and theoretical data resulting from the design and theoretical models of comfort.

Table 1. Types of possible approaches for calculating IEQ_{index} due to the use of actual and predicted data.

No	Types of IEQ Assessment	Design Stage of Building	Existing Building Pre-Occupancy	Existing Building Post-Occupancy
1	Predicted IEQ: The design values of building technical parameters + theoretical models of indoor comfort	Yes (prediction)	Yes (not recommended)	Yes (not recommended)
2	Actual IEQ: The measurement of physical parameters and real satisfaction answers (survey) from occupants	N/A	N/A	Yes (recommended) (very complex, high level of statistic accuracy is required)
3a	Semi-actual IEQ: The measurement of physical parameters and theoretical models of comfort	N/A	Yes (prediction) (recommended)	Yes (recommended)
3b	Semi-actual IEQ: The measurement of physical parameters mixed with the design values of building technical parameters and theoretical models of comfort	N/A	Yes (common approach)	Yes (common approach)

For the purposes of this study, the authors used semi-actual approach (No 3b, Table 1) including measurements (VOC and other environmental parameters) and partly use the parameters from the documentation of building design project. The theoretical models of comfort were used by authors without conducting the surveys of building users' satisfaction (buildings were not yet used/occupied). The TVOC assessment was done at the pre-occupant in accordance to agreement with Investor to ensure that the building occupied will be comfortable, healthy, and safe for users (at BREEAM Excellent level). The tests goal was a pre-verification of expected offices performance/wellbeing mainly IAQ. The authors had the only option to use the semi-actual IEQ approach mainly because: Authors were asked to provide tests only at pre-occupant stage, authors were able to do the measurement of physical parameters of TVOC and thermal indoor thermal parameters, but were not able to provide full tests on other parameters. Design data on the acoustic performance and visual comfort were verified by accredited laboratory, but is partly used from the design data of expected performance and we used such data for a case studies assessment. The selected approach uses different types of data because so this type is a mixed approach (3b).

2.2. The Equipment and Experimental Tests Methodology

The standardized analytical methods were used to determine the VOCs concentration and Formaldehyde in the indoor air of case study buildings. Selection of sampling points for each building was adopted with BREEAM assessor (two representative office zones per tested floor, minimum 2 floors per building). Building No 2 was tested 3 days and 3 weeks after formal final finishing works and other 3 buildings were tested after 2 months after the all works were finished (at pre-occupancy stage–no users inside). In every building minimum 2 representative floors were assessed. In the building No 1 measurements were carried out on 1st, 4th, 6th, 7th, and 8th floor in selected two zones of office space. In the case of office building No 2, the test was made on the 55th and 47th floor, for two office zones. For building No 3, the measurements were carried out on 1st, 2nd, 6th, 7th, and 8th also in two office areas. In the case of office building No 4, a ground floor and 1st floor were tested.

Indoor samples were set up in selected representative office locations, approx. 1.5 m above the floor, away from windows, doors, potential emission sources and direct sunlight. Air samples were tested in accordance with the ISO 16000-6: 2011 [35] and ISO 16000-3: 2011 [38]. Air samples were collected with active sampling procedure by using electronic mass flow controllers, which were produced by Aparatura Pomiarowa Ochrony Środowiska (local manufacturer). Mass flow controllers are periodically calibrated by accredited calibration laboratories.

Indoor air samples were collected in Tenax TA tubes at a flow rate of 10 dm^3/h for 1 h while through a prepacked cartridge coated with acidified dinitrophenylhydrazine (DNPH) at a sampling rate of 30 dm^3/h for 90 min. Schematic representation of experimental sampling setup was presented at Figure 1. For each tested point, double sampling was performed. The results present in Section 3.1 show average values for two parallel measurements.

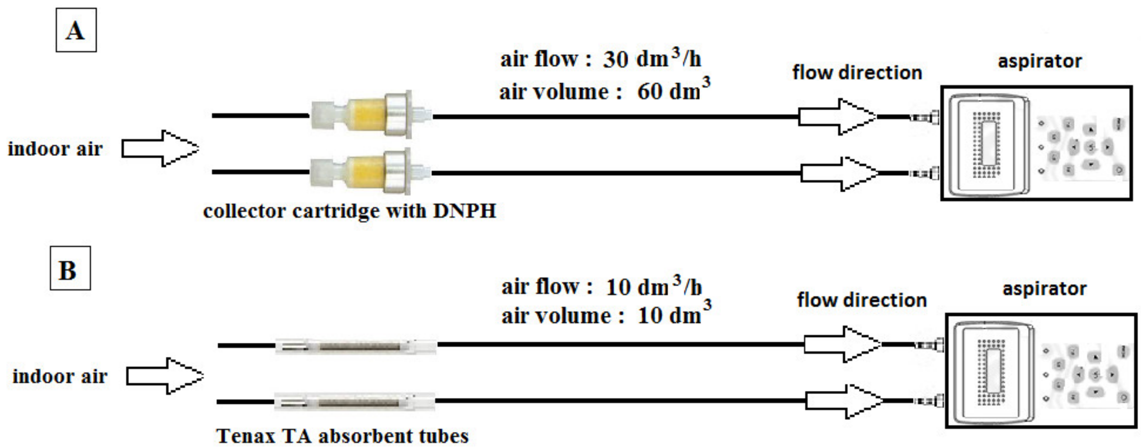


Figure 1. Schematic representation of experimental sampling setup for (**A**) Formaldehyde and (**B**) VOCs.

VOCs were taken on tubes filled with Tenax TA adsorbent. Then they were thermally desorbed by using a thermal desorption (TD 20, Shimadzu, Kyoto, Japan). The process of separation and analysis of volatile compounds was achieved using a gas chromatograph equipped with mass spectrometer GC/MS (Model: GCMS-QP2010, Shimadzu, Kyoto, Japan). The following GC oven temperature program was applied: initial temperature 40 °C for 5 min, 10 °C per min to 260 °C, final temperature 260 °C for 1 min. The 1:10 split ratio injection mode has been applied. The method used has a limit of quantification of 2 $\mu g/m^3$. The volatile compounds were identified by comparing the retention times of chromatographic peaks with the retention times of reference compounds and by searching the mass spectral database–NIST 2011. Identification compounds were quantified using relative identification factor obtain from calibration curve standards solutions. TVOC was calculated by summing identified and unidentified compounds eluting between n-Hexane and n-Hexadecane. In order to determine volatile aldehydes, air samples were taken to the collector cartridges with a solid absorbent, silica gel coated with 2,4-dinitrilophenyl hydrazine (2,4-DNPH), and then subjected to a laboratory test by HPLC-high-performance liquid chromatography with UV-VIS detection (Dionex 170S, Dionex, Sunnyvale, California, US) and isocratic pomp (Dionex P580A, Dionex, Sunnyvale, California, US). The described method has a limit of quantification of 2 $\mu g/m^3$. Standard deviation of all TVOC concentration results is ±18% [39] and the expanded uncertainty representing the 95% confidence interval is 35%.

The acoustic tests of building external walls confirming the designed values were carried out by accredited laboratory in accordance with ISO 140-5: 1999. The parameter describing the acoustic insulation of the façade is the reference difference in sound pressure levels, $D_{tr,2m,nT,w}$. The sound pressure level inside the office and outside the building was tested at a distance of two meters from the building external façade (2 measurement points per each building). In addition to the sound pressure level measurements, the reverberation time inside the office was also measured. The instruments used for measurements were: B&K 4165 measuring microphones, acoustic calibrator B&K 4231, Nor-121, and Nor-140 analyzer and sound source Nor-275. Thermal environmental measurements were provided using HD32.1 the microclimate multifunctional instrument and the tests were in accordance to ISO 7726 and ISO 7730 in all points where VOCs were tested simultaneously. Hea 01 Visual comfort of BREEAM system does not require measurements of daylight but the daylight illuminance level form executive project was confirmed by using the instrument MAVOLUX 5032C (USB version) with detector 3C15683 in accordance with EN 12464 by the BREEAM assessor.

2.3. IEQ Model and Sub-Components Models

EN-15251: 2014 draft is the reference for IEQ model creation [27]. The standard allows to present a complex indoor information as one overall indicator IEQ_{index} of indoor environmental quality of the building. Model reliability including uncertainty of measurement and data for this model was provided clearly in the research paper [37] where the authors also presented the justification for using the crude-weight method for each sub-component (Table 2). Originally, the IEQ model was expressed as a polynomial equation consisting of four terms by Wong [40]. The ASHRAE Guideline [41] recommended that the IEQ model should contain the synergy effect of environmental parameters included in sub-components and their sensory perception. IEQ_{index} is made of the following sub-components (SI_i): Thermal comfort (TC_{index}), indoor air quality (IAQ_{index}), acoustics (ACc_{index}), and lighting quality (L_{index}), and multiplying by their weights W_i (Table 2) gives IEQ_{index}, as follows:

$$IEQ_{index} = \Sigma\, W_i \cdot SI_i \tag{1}$$

Most recognized weighing schemes* for IEQ_{index} assessment (1) are presented in Table 2.

The authors adopted the crude weighting system, where all elements weight the same (0.25 for W_1–W_4), as follows:

$$IEQ_{index} = 0.25 \cdot TC_{index} + 0.25 \cdot IAQ_{index} + 0.25\ AC_{Cindex} + 0.25 \cdot L_{index} \tag{2}$$

Weight value (Table 2) is reported with two decimal points [42] therefore the satisfaction percentage is reported in the same way.

Table 2. Most often used weighing schemes* for IEQ_{index} assessment.

Types of *IEQ* Category Weighting Scheme	Number of Occupants	Thermal Comfort W_1	Indoor Air Quality W_2	Acoustics W_3	Lighting W_4
Wong LT [40]	293	0.31	0.25	0.24	0.19
ASHRAE. PMP [29] (weighting scheme is adapted to PN-EN 15251)	52,980	0.12	0.2	0.39	0.29
Crude weighting scheme [5]	-	0.25	0.25	0.25	0.25

The sub-model for determining TC_{index} was provided by Fanger [43] and based on the indoor thermal environmental parameters. For buildings with heating and cooling systems, predicted mean vote indicator (*PMV*; see ISO-7730 [44]) is commonly used as a reference parameter and also recommended by the standards EN-15251 [27] or ASHRAE-55: 2010 [44]. In buildings where people are the main source of pollution, it is commonly recommended to determine the IAQ_{index} by calculating the percentage of people dissatisfied with the air quality ($PD_{IAQ(CO2)}$) as a function of CO_2 concentration. According to the existing standard EN-15251: 2007, 350 ppm is typically used as the outdoor CO_2 concentration (if not measured). Useful Equation (10) was provided by the European Concerted Action (ECA, 1992) [45]:

$$PD_{IAQ(CO2)} = 395 \cdot \exp(-15.15 \cdot \mathrm{C_{CO2}}^{-0.25}) \quad (3)$$

where $\mathrm{C_{CO2}}$ is carbon concentration (ppm) above the outdoor level.

While CO_2 is a commonly used indicator for IAQ assessment, it does not represent other sources of indoor contamination, such as VOC emissions from construction materials, fittings, finishings, carpets, and floor covering materials. Some of the researchers went towards including into the IAQ analysis a component associated with the intensity of the odor, which is relatively easy to determine. If the concentration of an indoor odor may be detected and the curve of odor intensity (*OI*) may be known as function $OI = f(\log_{10} c)$ and the odorant concentration *C* in the air is dominant that the other contaminants can be omitted. It is suggested to use the relation-ship (4) as the model of the sub-model for the IAQ assessment. Fanger [46] discovered that the relation between an acceptability of IAQ and *OI* have a very similar shape for the odorants with various chemical structures. The team of Wargocki [47] obtained relationship (4) between the dissatisfied percentage ($PD_{IAQ(OI)}$) and the *OI*, expressed as a *OI* six-level scale from 0 to 5 (no odour = 0 and overpowering odour = 5). Basing on experimental data, there is the probable option to determine the *OI* value for a measured concentration (*c*) and then to determine the value of $PD_{IAQ(OI)}$ with $R^2 = 0.95$

$$PD_{IAQ(OI)} = \frac{\exp(2.14 \cdot OI - 3.81)}{\exp(2.14 \cdot OI - 3.81) + 1} \quad (4)$$

The *OI* linear relationships of common odorant concentrations can be found in Kostyrko and Wargocki monography [48].

The authors suggest an alternative approach where the main impact comes from building materials currently being analyzed is the implementation of the VOCs impact on users. TVOC is defined by organization of WHO as a set of compounds like Toluene, Xylene, Pinene, 2-(2-Ethoxyethoxy)ethanol, etc., with a melting points below room temperature and a boiling point in the range 50–260 °C. The EU-LCI ECA Report [49] provides information that TVOC is to be accepted in Europe in connection to product emission. It is justified also to use this indicator to quantify VOC emissions when assessing IAQ. When evaluating the emissions of construction products, TVOC provides specific additional data to be combined with the EU-LCI concept and CMR approach; carcinogenic, mutagenic, or toxic to reproduction compounds. The results of practical analyzes [50] showed that TVOC may exceed about

80% of the national standard. Formaldehyde health risks exceeded acceptable risk threshold for the adapted and un-adapted persons, 90% and 55% of the monitoring points were located within the long-term tolerance range of TVOC decibel application, respectively. According to Wu [39], high levels of Formaldehyde and TVOC may be a factor to asthma and rhinitis, and may even lead to skin, melanoma, lung, and endocrine-related cancers and of sick building syndrome (SBS), which have been regularly reported worldwide. In field studies and IAQ questionnaire survey results in the library rooms in the University of Science and Technology Beijing in April 2016, the authors get, in the results, the correlations between IAQ and the concentrations of pollutants as 0.88 ($PM_{2.5}$), 0.61 (TVOC), 0.58 (Formaldehyde). According to Reference [25], TVOC is sensed by means of olfactory-smell sensors, the impact of which depends on the magnitude of the stimulus [16,49] is suggested to create a standard for $C_{odour(TVOC)}$ sensory evaluation. Based on the Yaglou theory and the Weber-Fechner theory, Jokl [32] defined the $L_{odor(TVOC)}$ as TVOC evaluation index using the decibel concept. The decibel model is used to characterize a relationship between TVOC concentration and Predicted Dissatisfaction of indoor air quality in the percentage of dissatisfied occupants (PD%). Model provided in the research paper in Reference [36] is based on large scale research with measured TVOC values in various locations proposed an theoretical function of TVOC concentration in relation with the percentage dissatisfied (PD) adequately to the CO_2 function:

$$C_{TVOC} = k(\ln(PD_{TVOC}) - 5.98)^{-4} \tag{5}$$

The authors transformed this function and obtained;

$$PD_{TVOC} = 405 \cdot \exp(-11.3 \cdot C_{TVOC}{}^{0.25}) \tag{6}$$

The experimental research results presented in Figure 2 shows the relationship between occupants PD and measured TVOC concentrations.

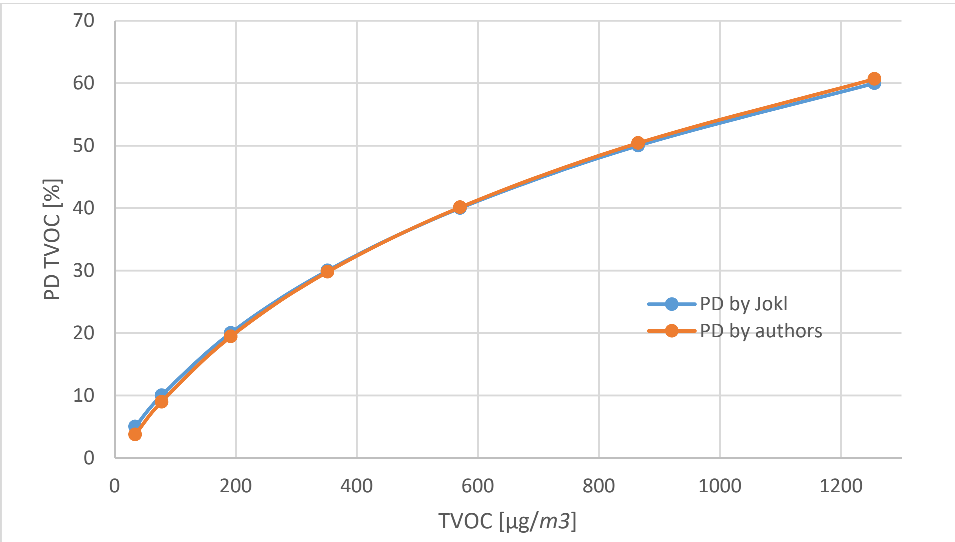


Figure 2. Relationship between TVOC concentrations and Percentage Dissatisfied (PD) for sedentary persons for results obtained by Jokl and authors.

Besides the experimental function already applied to Equations (5) and (6), a lot of individually measured TVOC levels from various locations with specific outcome from occupants were available for validation by authors. The further step of our research is the data base of PD curves for individual VOC compounds.

For the purpose of determining IEQ_{index}, a simple model of acoustic comfort evaluation was adopted. The author suggest to use the New Zealand Standard [51] that allows to calculate the increase in the percentage of people dissatisfied with noise ($PD_{(Acc)}$) with an increase in the A-weighted noise level LA_{eq}. The relationship for the increase of PD with the change in noise level from 'Design' to 'Actual' is

$$PD_{(ACc)} = 2 \cdot (ActualSound\_Pressure\_Level - DesignSound\_Pressure\_Level)\ [dB(A)] \quad (7)$$

and the calculated result is equal to the increase in percentage dissatisfied in $\%PD_{(ACc)}$. Actual sound level was measured in case study buildings by accredited laboratory and design levels that were taken from the buildings documentation.

Relationship between a daylight illuminance and probable percentage of people switching on artificial lighting calculated with Hunt's equation [52] For a purpose of this research level of daylight illuminance was measured by an un-accredited method using the MAVOLUX 5032C. L_{index} was determined by measuring [lux] results and a Hunt curve.

The sub-models presented above were used to assess the office buildings and determine the IEQ_{index} based on measurements of physical properties of the models in accordance to the scheme in Figure 3. Examples of measurable physical parameters and others from the project documentation for the purpose of IEQ calculation are given in the Results section.

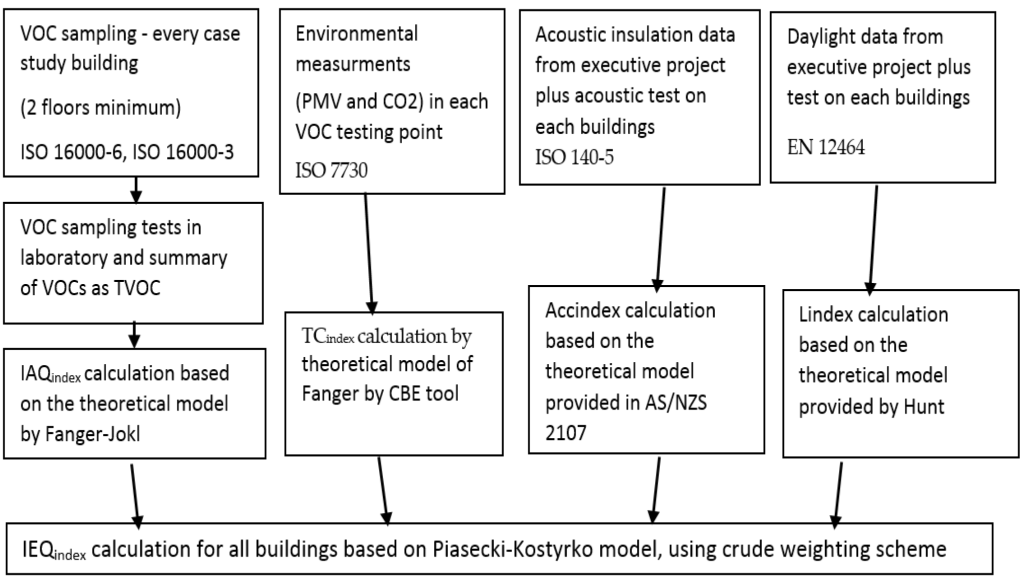
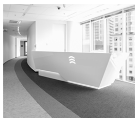


Figure 3. The research steps necessary to determine IEQ_{index} for case study buildings, including physical and design parameters of buildings and theoretical sub-components models.

2.4. Objects-Case Study Buildings

Emissions, environmental performance, and IAQ tests were carried out in four buildings constructed in the large city located in Central Europe. The study was performed mainly for the purposes of BREEAM certification including determination of Formaldehyde concentration and the sum of VOCs in the indoor air. The case study buildings are characterized by a convex concrete-steel structure with a glass façade. The basic information of assessed building is shown in Table 3. Environmental performance and IAQ tests were carried out by the authors in the years 2016–2017. At the time of the test, all buildings had the standard of an empty office without furniture. The walls had plasters and paints, suspended ceilings, the floors were finished with synthetic carpets. All building installations were active including mechanical ventilation active controlled by the BMS system with zonal CO_2 concentration sensors. Building No 2 was tested 3 days and 3 weeks after formal final finishing works and other 3 buildings were tested after 2 months after all works were finished (at pre-occupancy stage -no users inside). In every building, a minimum of 2 representative floors were assessed. In the building No 1 measurements were carried out on 1st, 4th, 6th, 7th, 8th floor in selected two zones of office space. In the case of office building No 2, the tests were made on the 55th and 47th floor, for two office zones. For building No 3, the measurements were carried out on 1st, 2nd, 6th, 7th, and 8th also in two office areas. In the case of office building No 4, the ground floor and 1st floor were tested.

Table 3. Basic information on a four case study buildings.

Office Building Number	Façade View	Indoor View	Time after Finishing Works	No of Floors	Net Area [m^2]	IAQ Assessed	
						Area [m^2]	No of Floors
No 1			2 months	8	20,000	13,000	5
No 2			3 days and 3 weeks	49	59,000	3000	2
No 3			2 months	9	27,000	19,000	5
No 4			2 months	10	34,000	9000	2

Measuring points in buildings were determined based on the analysis of frequencies of designed occupying the room, purpose rooms, interior finish standards. A sampling plan was prepared with BREEAM assessors conducting the certification process of the facility. The assessment of indoor air quality in the building did not cover rooms intended for temporary stay in them, which included: Cafes, shops, restaurants, and gyms usually located at the lowest levels of buildings. Subsequently, economic and communication rooms such as stairwells and troughs were excluded from the evaluation. The main focus was the IAQ of open spaces (28 open spaces analyzed) in which the largest number of people may reside and they are representative due to the largest usable floor space occupied. In addition, the concentrations of VOCs were checked at the reception of building and in the rooms assigned for upper management and rest rooms (kitchenettes), which were characterized by a smaller usable area and higher standard and volume of finishing materials (results not presented in a paper). According to the detailed design project documents, all buildings emphasize the use of materials with known and low VOC emission levels (BREEAM certified). All case study buildings are BREEAM excellent.

2.5. BREEAM Requirements for IAQ

According to the BREEAM schemes [13,34,53], the requirements for adequate IAQ are provided in the Health and Wellbeing category (Health and Wellbeing). This category also covers a range of issues related to broadly understood comfort, i.e., daylight and artificial lighting conditions, thermal and acoustic climate. The sub-category named Hea 02 Indoor Air Quality is aimed at providing indoor air free from harmful chemical pollutants. The initial stage includes the development of an internal air quality plan (IAQ), which aims to include specifications, installations, and activities that reduce indoor pollution. This plan has to take into account the aspects of: Air exchange in the facility mainly after completion of finishing works, the elimination of pollution sources, conducting air quality tests by an independent accredited laboratory, procedures for maintaining IAQ in the stage of building use, the building's ventilation system in accordance with the requirements of the relevant standards (mainly

EN 13779), and proper location of ventilation inlets and outlets. An essential for the elimination of the possible sources of indoor air pollution is selection of indoor finishing and construction materials, which should be characterized by low content/emission of VOCs and Formaldehyde. Emission from the construction products is the main source of indoor air pollution at the pre-occupant stage and even later. The BREEAM system has set emission requirements for the basic 8 groups of finishing materials. These requirements are presented in Table 4. According to the requirements, the permissible emission of Formaldehyde from the products is 100 $\mu g/m^3$. Use of materials with Formaldehyde emission, reduced to 60 $\mu g/m^3$ or 10 μg^3, allows us to obtain, respectively, 1 or 2 additional points in the Innovation Category.

Table 4. Formaldehyde and VOC emission requirements for construction products in the BREEAM system including approved international systems [33].

Product Group	Requirements [53]	Approved Alternative Systems [34]
Paints and varnishes	VOC according to ISO 11890-2 * Compliance with EN 13300: 2001 and EU Directive 2004/42 CE2 1 *	Indoor Advantage^{TM} Gold Building Materials (only for products certified for the European market) * EU Ecolabel for paints and varnishes * NF Environment 130 * Indoor Air Comfort©/Indoor Air Comfort Gold© *
Wood-based panels	The emission class of formaldehyde E1 or Formaldehyde emission 0.1 mg/m^3 **, Compliance with the product standard EN 13986	GREENGUARD Gold ** Indoor Advantage^{TM} Gold—Building Materials ** French VOC Regulation—Class A+/Class A/Class B * AgBB ** M1 Emission Classification of Building Materials ** Indoor Air Comfort©/Indoor Air Comfort Gold© **
Glued laminated timber	The emission class of formaldehyde E1 or Formaldehyde emission 0.1 mg/m^3, Compliance with product standard EN 14080	GREENGUARD Certified/GREENGUARD Gold - Indoor Advantage^{TM} Gold—Building Materials - French VOC Regulation—Class A+/Class A/Class B - AgBB - M1 Emission Classification of Building Materials - Indoor Air Comfort© / Indoor Air Comfort Gold©
Wooden floors	The emission class of formaldehyde E1 or Formaldehyde emission 0.1 mg/m^3, Compliance with product standard EN 14342	- GREENGUARD Certified/GREENGUARD Gold - FloorScore® - French VOC Regulation—Class A+/Class A/Class B - AgBB - M1 Emission Classification of Building Materials - Indoor Air Comfort©/Indoor Air Comfort Gold© EU Ecolabel for wooden floor coverings
Flexible, textile and laminated floor coverings	The emission class of formaldehyde E1 or Formaldehyde emission 0.1 mg/m^3, Compliance with article norm EN 14041	- GREENGUARD Certified/GREENGUARD Gold - FloorScore® - French VOC Regulation—Class A+/Class A/Class B- AgBB - M1 Emission Classification of Building Materials - Green Label Plus^{TM} - GUT - Indoor Air Comfort©/Indoor Air Comfort Gold©
Celiling panels	The emission class of formaldehyde E1 or Formaldehyde emission 0.1 mg/m^3, Compliance with product standard EN 13964	- GREENGUARD Certified/GREENGUARD Gold - Indoor AdvantageTM Gold—Building Materials - French VOC Regulation—Class A+/Class A/Class B - AgBB - M1 Emission Classification of Building Materials - Indoor Air Comfort©/Indoor Air Comfort Gold©
Adhesives for floor materials	No carcinogens or sensitizing compounds according to the Harmonized System (GHS) classification and labeling of chemical substances. Classification C1, C2 and C3 specified in Annex A of EN 13999-1: 2007. Test methods according to EN 13999, sheets, 2, 3, 4	- AgBB - M1 Emission Classification of Building Materials - EMICODE EC 1PLUS/EMICODE EC 1/EMICODE EC 2 - Indoor Air Comfort©/Indoor Air Comfort Gold©
Wallpapers	The content of vinyl chloride Formaldehyde emission Migration of heavy metals Marking in accordance with EN 12149. Compliance with product standards EN 233, EN 234, EN 259-1	N/A

* The producer must additionally confirm that the products are resistant to fungi and molds in wet rooms (kitchens, bathrooms, utility rooms); ** The producer must additionally confirm that the products do not contain forbidden biocides.

The BREEAM technical guideline set only the permissible level of emission, referring to the provisions of the harmonized product standards. This is not enough to assess actual VOC contamination. Low-emission finishing materials recommended for BREEAM should be certified by the German AgBB or the French product classification system, or voluntary systems such as Der Blue Engel, M1, or EMICODE. In 2015, the GN 22 [34], provided a list of accepted alternative systems for assessing construction products.

The IAQ plan includes the performance of indoor air quality tests confirming the fulfillment of the requirements set out in Table 5.

Table 5. Concentration allowed by BREEAM code in the office air (and also suggested by Reference [27]).

Parameter	Concentration Allowed [µg/m^3]
Formaldehyde	100
TVOC	300

The case studies tests were carried out by authors as the independent accredited laboratory. Analytical methods used were according to the ISO 16000 series standards specified in the Technical Manual.

3. Results

3.1. Results on the VOC and Formaldehyde Emission

The results of the determination of TVOCs concentration in the four case study buildings are shown in Figure 4. In office building No 2 the samples were collected three days and three weeks after finishing works finalized stage, whereas in office buildings No 1, No 3, and No 4 tests were performed two months at the pre-occupancy stage. TVOC concentrations in the building No 2 (3 days) are approximately two–three times higher than three weeks later. TVOC concentration after two months did not exceed finally the BREEAM limit of 300 µg/m^3 of air in all examined workplaces. The falling tendency of indoor air pollution levels in the workplaces is related with the aging of emission sources (like adhesives, coatings or paint) and the trend is visible in the Figure 4. TVOC level required by the BREEAM system was obtained in all the buildings (two months) and the TVOC concentration is far below the assumed threshold.

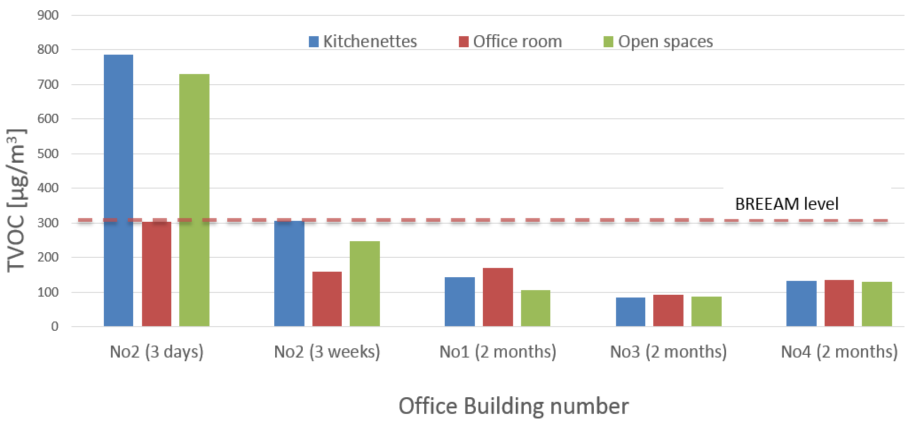


Figure 4. Mean TVOC concentrations obtained for the different types of workplace in 4 analyzed office buildings (No 2—air samples were collected 3 days and 3 weeks after finishing works; for building No 1, 3 and 4—air samples were collected 2 months after finishing works at pre-occupancy stage). Level required by BREEAM system (red dotted line).

In the case of office building No 2, the TVOC mean value for both open spaces on 46th floor after three days was equal 787 µg/m^3 (open space one had the highest concentration) and 672 µg/m^3

(open space two also had a high concentration). This exceeded the BREEAM content limit more than twice. This is related to the concentrated use (at one time) of finishing materials and furniture in the interior of the tested rooms. The measurements in building No 2 were repeated after three weeks. After this time, the concentration dropped to the acceptable BREEAM content limit. Figure 5 shows TVOC concentration results obtained for the 24 open spaces located on different floors of examined buildings No 1, 3, and 4 after two months. The mean values of TVOC concentrations ranged from 40 µg/m^3 to 185 µg/m^3. The lowest mean level (40 µg/m^3) was measured in open space two (office building No 3 on the 3rd floor). Figure 5 provides TVOC concentration results for the 24 open spaces located on different floors of examined three buildings tested two months after finishing works at the pre-occupancy stage.

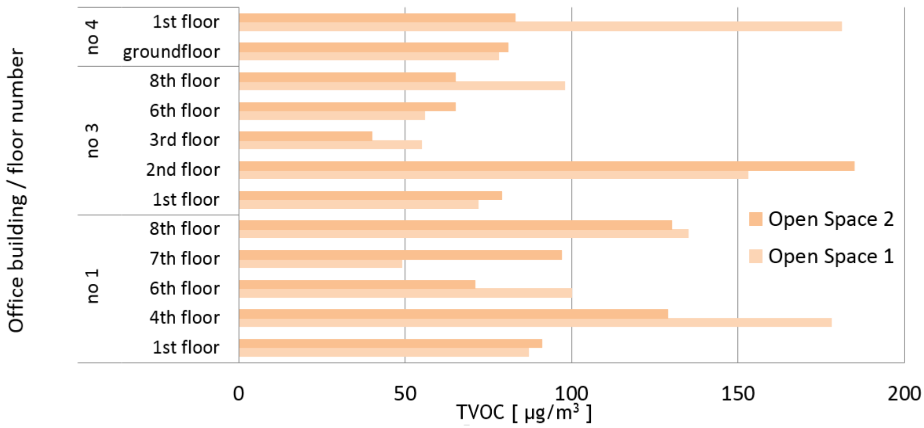


Figure 5. Mean TVOC concentration results for the 24 open spaces located on different floors of examined three buildings collected at 2 months at pre-occupancy stage. TVOC content limit (300 µg/m^3).

The results of measurements of Formaldehyde concentration (2 months) in the air of the examined office buildings are shown in Figure 6. In all the examined objects, the concentration of Formaldehyde in the indoor air of the studied office buildings was well below the limit value of 100 µg/m^3. The maximum measured concentration was 18 µg/m^3.

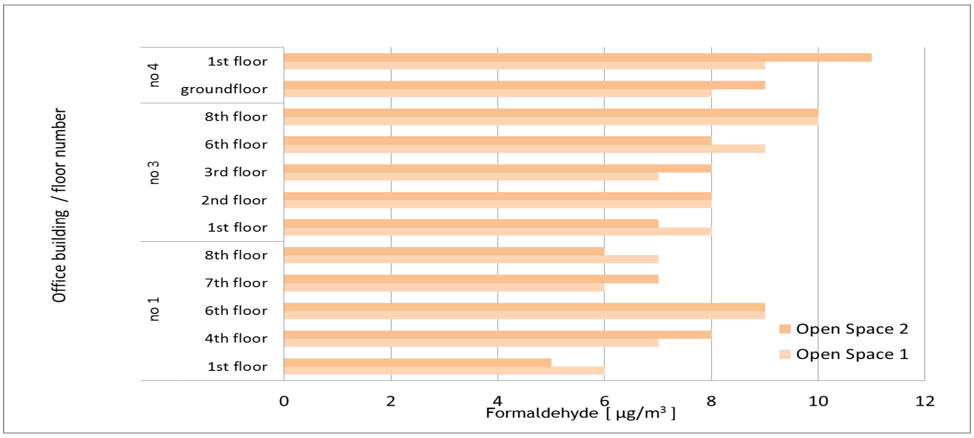


Figure 6. Mean Formaldehyde concentration results for the 24 open spaces located on different floors of examined buildings collected at 3 months at pre-occupancy stage Formaldehyde content limit for BREEAM is equal 100 µg/m^3.

It should be emphasized that due to many years of activities limiting the emission of Formaldehyde, primarily from wood-based materials, by introducing the requirements in this respect to harmonized product standards, there is currently no problem detected of indoor air pollution connected with Formaldehyde.

3.2. Results on IEQ_{index} for Open Spaces in Case Study Buildings Influenced by VOC Results

Formula (2) was a basis for IEQ_{index} calculation. The assessment was made by adaptation of the measured parameters and complying with draft EN-15251: 2014 for indoor environments as the input values for the sub-models of IEQ_{index}. The input values are presented in Table 6, which presents the measured or design input data for determining the IEQ_{index} sub-indices: Thermal TC_{index}, indoor air quality IAQ_{index}, acoustics ACc_{index}, and lighting quality L_{index} for a building No 2 (47th floor, open space one) three days after completion of finishing works (highest observed TVOC) before users were allowed to use the building. PMV was calculated in accordance with ISO 7730 [44] and important suggestions for this are reported by researchers from DTU [54,55].

Table 6. The physical parameters * and IEQ results with realistic measurement uncertainty for building No 2 (47th floor, open space 1) 3 days after completion of finishing works (highest observed TVOC).

Sub-Index	Sub-Index $PD(SI_i)$ Models	Input Values	Sub-Index (Satisfied)
TC_{index}	PMV (Fanger-CBE-ISO 7730) $PMV = f(t_a, t_r, v_a, p_a, M, I_{cl,dyn})$ $PD_{TC} = f(PMV)$	I_{cl} 0.55 clo t_a 24 °C t_r 24.5 °C v_a 0.15 m/s RH 45% M 1.1 met	90% ± 3.2%
IAQ_{index}	$PD_{IAQ(CO2)} = 395 \cdot \exp(-15.15 \cdot C_{CO2}{}^{-0.25})$ $PD_{TVOC} = 405 \cdot \exp(-11.3 \cdot C_{TVOC}{}^{-0.25})$	450 ppm 787 μg/m^3	85.2% ± 0.6% 52.0% ± 18.0%
$AC_{c\ index}$	PD_{ACc} = 2·(Actual$_{Sound_Pressure_Level}$ [dB(A)] – Design$_{Sound_Pressure_Level}$ [dB(A)]) Actual (background) noise Design sound level	55 dB(A) 45 dB(A)	80% ± 6.7%
L_{index}	$PD_L = -0.0175 + 1.0361/\{1 + \exp(+4.0835 * (\log_{10}(E_{min}) - 1.8223))\}$	450 lux	98.4% ± 9.0%
IEQ $_{(CO2)}$ First potential variant with C_{CO2} as a IAQ_{index} parameter IEQ_{CO2} = 92.2 ± 5.8%			
IEQ $_{(TVOC)}$	Second variant with C_{TVOC} as a IAQ_{index} parameter		IEQ_{TVOC} = 80.1 ± 10,7%

The IEQ and its measurement standard deviation (SD) was calculated for IEQ physical parameters values *: t_a is the air temperature [°C], t_r is the mean radiant temperature [°C], v_a is the relative air velocity [m/s], p_a is the water vapor partial pressure [Pa], M is the metabolic rate [met] and $I_{cl,dyn}$ is the clothing insulation [clo], C_{CO2} concentration above the outdoor level in ppm, OI—odour intensity is expressed on a six level scale from 0-no odour to five over-powering odors, C_{TVOC}—TVOC concentration is in μg/m^3, actual noise [dB(A)], E_{min} minimum daylight illuminance [lux].

Formula (2) was used as well as the base for the calculations for the same office space after three weeks of intensive ventilation (Table 7).

Table 7. The physical environmental parameters used for assessment and IEQ results with realistic measurement uncertainty for building No 2, 3 weeks after finishing works (building ready for use).

Sub-Index	Sub-Index $PD(SI_i)$ Models	Input Values	Sub-Index
TC_{index}	PMV (Fanger-CBE) $PMV = f(t_a, t_r, v_a, p_a, M, I_{cl,dyn})$ $PD_{TC} = f(PMV)$	I_{cl} 0.55 clo t_a 24 °C t_r 24.5 °C v_a 0.15 m/s RH 45% M 1.1 met	90% ± 3.2%
IAQ_{index}	$PD_{IAQ(CO2)} = 395 \cdot \exp(-15.15 \cdot C_{CO2}{}^{-0.25})$ $PD_{TVOC} = 405 \cdot \exp(-11.3 \cdot C_{TVOC}{}^{-0.25})$	450 ppm 234 μg/m^3	85.2% ± 0.6% 77.4% ± 18.0%
$ACc_{\ ndex}$	PD_{ACc} = 2(Actual$_{Sound_Pressure_Level}$ [dB(A)] – Design$_{Sound_Pressure_Level}$ [dB(A)]) Actual (background) noise Design sound level	55 dB(A) 45 dB(A)	80% ± 6.7%
L_{index}	$PD_L = -0.0175 + 1.0361/\{1 + \exp(+4.0835 \cdot (\log_{10}(E_{min}) - 1.8223))\}$	450 lux	98.4% ± 9%
IEQ $_{(CO2)}$ First variant with C_{CO2} as a IAQ_{index} parameter IEQ_{CO2} = 92.2 ± 5.8%			
IEQ $_{(TVOC)}$ Second variant with C_{TVOC} as a IAQ_{index} parameter IEQ_{TVOC} = 86.5 ± 10.7%			

IEQ_{index} and IAQ_{index} results for all buildings and analyzed areas are presented in Table 8.

Table 8. Results for IAQ_{index} and IEQ_{index} for four case study BREEAM certified buildings.

		IAQ_{index} (%)		IEQ_{index} (%)	
Building	**Space Assessed**	**Open Space 1**	**Open Space 2**	**Open Space 1**	**Open Space 2**
No 1	1st floor (2 months)	89.99	89.56	89.60	89.49
	4th floor (2 months)	81.64	85.83	87.51	88.56
	6th floor (2 months)	88.64	91.74	89.26	90.04
	7th floor (2 months)	94.34	88.94	90.69	89.34
	8th floor (2 months)	85.29	85.74	88.42	88.54
No 2	45th floor (3 weeks)	86.20	76.18	88.65	86.14
	46th floor (3 days)	52.04	55.99	80.11	81.10
	46th floor (3 weeks)	77.47	75.85	86.47	86.06
No 3	1st floor	91.63	90.85	90.01	89.81
	2nd floor	83.70	81.09	88.03	87.37
	3rd floor	93.61	95.47	90.50	90.97
	6th floor	93.49	92.43	90.47	90.21
	8th floor	88.84	92.43	89.31	90.21
No 4	groundfloor	90.96	90.63	89.84	89.76
	1st floor	81.40	90.42	87.45	89.70

4. Discussion of Results

4.1. VOC/TVOC

The concentration value of the VOC emitted from the construction and finishing products is not a constant value. Increased concentration of the emitted compounds in the indoor air most often occurs during the construction of the building, in particular at the stage of indoor finishing works. The results obtained in the presented studies show that in the period immediately after completion of finishing works in indoor spaces, there may be temporarily increased concentration of TVOC, which systematically decreases over time. This phenomenon should be included in the developed building air quality plan. Therefore, it would be beneficial to maintain a certain period for newly finished rooms. In the case of building No 2, the research showed that the tests carried out immediately after finishing works in this case after three days yielded results that significantly exceeded the BREEAM limit (two times higher). It should be concluded that an acceptable level should be reached after about a minimum of three weeks from the completion of the work. Generally speaking, TVOC concentration was acceptable low or very low in the open spaces in all buildings after two months, in 70% of cases did not exceed 100 $\mu g/m^3$. The similar results were reported by other authors, for example in the research paper in Reference [39].

The example (other research of authors) providing a similar trend of significant decrease in the concentration of VOCs emitted from the selected high-emissive indoor product over time is presented in Figure 7. Tests were performed using a standard chamber method with described test parameters provided in a standard [56]. Chamber tests and in-situ analyzes on the building show a highly correlated trend of TVOC emission decline over time.

As results of the conducted example test in Figure 7, the concentration of Xylene, Ethylbenzene, n-Butyl acetate, and n-Heptane emitted from the product decreases sharply in the first 10 days from the beginning of the test, from 2000 $\mu g/m^3$, in the case of n-Butyl acetate and 500 $\mu g/m^3$ for Xylene to reach the set level close to lowest measurement possibility level. Such a drop in concentration is characteristic of VOCs whose boiling point does not exceed 150 °C. Similar results were provided in the research paper in Reference [20]. However, the final concentration value is not always as low as in this example shown. In the real caste study buildings, we observed the longer-term VOC emission from products, which may be caused partly by limiting the permeation of volatile compounds through subsequent layers of overlapping coatings of construction elements. As a result of tests performed three days after the completion of finishing works in building No 2, where the wooden floor, painting the walls, suspended ceilings were installed, the value of the sum of concentrations of VOCs in 3/5 examined spaces was highly increased and ranged between 670–780 µg/m^3. After repeating the test, after three weeks from the completion of the works, TVOC concertation value in the rooms examined dropped to about half. Due to the increased value of concentrations of VOCs in the initial period from the completion of finishing works in office spaces, for the safety of workers exposed to the exposure of organic compounds, it is advisable to settle them after about a minimum of four–six or even eight weeks after the completion of construction works and interior design and control of volatile concentrations organic compounds in the room air.

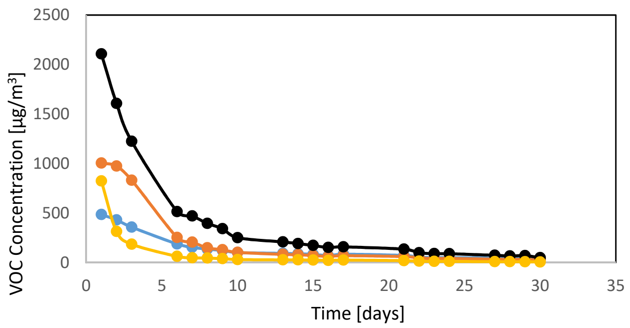


Figure 7. Change in the concentration of Xylene (blue), Ethylbenzene (red), n-Butyl acetate (black) and n-Heptane (yellow)-example construction product test performed in accordance to provisions of [56] in a laboratory emission test chamber.

The emission of VOCs depends to a large extent on the raw materials and sub products used in the production process. Metal, glass, and ceramic products are not a source of VOC emissions, provided that they do not contain organic additives: varnish for protecting surfaces, plasticizers, or fillers (synthetic resins). In contrast, indoor air pollutes construction products containing organic solvents such as Toluene and Xylene that evaporate vigorously. Polymers that do not contain individual monomers, e.g., Polyethylene or Polypropylene, will not emit VOCs as opposed to synthetic (Phenyl-Formaldehyde) resins that contain internal monomers and oligomers releasing into the air.

In the case of compounds belonging to the group of VOCs, the concentration of these compounds will decrease gradually from the product to a fixed low value. However, we didn't find VOC emissions of compounds with a boiling point above 380 °C in office rooms. Analyses of the samples of 28 open spaces also show that among all of the constituents, aromatic hydrocarbons (28%), aldehydes and ketones (23%), siloxane (14%), esters (9%), and alcohols (9%) are mainly detected (Figure 8). Only 1% of compounds were unidentified.

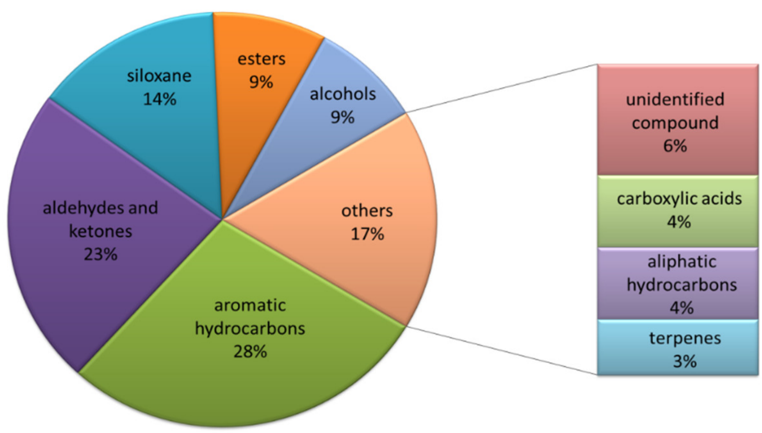


Figure 8. Percentage of VOC constituents in 28 case-study open spaces which were collected at the post construction and pre-occupancy stage.

The intensity of emissions of VOCs from construction products to indoor air is significantly affected by temperature, which is confirmed by our various studies. The increase in the concentration of VOCs may be observed with the increase of temperature in the first ten days from the start of the VOC emission form the construction products. The influence of temperature on the concentration of VOCs can be observed on hot days, in sunny places, and in the heating season, which may be signaled by the presence of chemical odor in the air. Due to the increase in VOC emissions from products built with increasing temperature, particular attention should be paid to: Office surface insolation and the quality of flooring materials. They should be characterized by the very low emissions of pollutants.

In the case of wooden products, and in particular of wood-based panels used indoor, which may be a source of Formaldehyde, an increase in temperature and humidity causes a significant increase in the concentration of this compound in the air. Changes in air humidity are negligible in the case of emissions of VOCs other than Formaldehyde. In addition to temperature and humidity, the effectiveness of ventilation, determined by the number of air changes inside the building, significantly affects the concentration of VOCs inside the office spaces. Outdoor air generally contains lower concentrations of VOCs, and causes thinning of the indoor air. The tests show that the increased air exchange has an impact on reducing the emission of VOCs in the initial period, long-term increase in air exchange per hour is negligible. The TVOC results differ for open spaces and single office rooms, which may be less ventilated and more loaded with furniture.

Bearing in mind the own experience from the presented analyzes and being aware of international air quality works and benchmarks (like BREEAM levels), we suggest using the office emission classes proposal presented in Table 9. The EU LCI Working Group is currently working on harmonization of the EU LCI values (lowest concentration of interest) across Europe to have a list which can be recommended to be used within the EU. If the calculated EU-LCI ratio is ≤ 1 for a substance, it is considered that the health risk of that specific substance is negligible. EU-LCI values are preferably derived from the data, like the DNEL (or NOAEL) generated under REACH. When TVOC concept is applicable with TVOC < 1000 $\mu g/m^3$ situation is compliant, therefore, authors consider this value as the quantification value of the significant class change (Class A to B). Class A+ is taken form BREEAM requirements. Green certification system for new buildings in Hong Kong (updated in 2018) has the upper limit value of TVOC on 600 $\mu g/m^3$ level. The same level is obligatory in Portugal. A research provided by Reference [57] shows results of TVOC emission for office buildings located in various EU countries: 179 $\mu g/m^3$, 436 $\mu g/m^3$ (DK), 495 $\mu g/m^3$ (UK), 413 (GR) $\mu g/m^3$, 518 $\mu g/m^3$ (FR), 118 $\mu g/m^3$ (SF), 528 $\mu g/m^3$ (N), and 146 $\mu g/m^3$ (D). Therefore, we assume level 600 $\mu g/m^3$ as the recommended level of TVOC class A (Table 9).

Table 9. Indoor air quality classes due to TVOC concentration suggested by authors.

Classes	TVOC 3 Days $TVOC_{D3}$	TVOC after 3 Weeks $TVOC_{W3}$	$\sum SVOC$ $SVOC_{D3}$	Not Yet Assessed Substances C_{nonLCI}
Class A++ Class A+ Class A	$\leq$10 mg/m^3	$\leq$200 $\mu g/m^3$ $\leq$300 $\mu g/m^3$ $\leq$600 $\mu g/m^3$	$\leq$0.1 mg/m^3	$\leq$0.1 mg/m^3
Class B Class C Class D	>10 mg/m^3	<1000 $\mu g/m^3$ <1500 $\mu g/m^3$ >2000 $\mu g/m^3$	>0.1 mg/m^3	>0.1 mg/m^3

Taking into consideration TVOC results obtained for office buildings certified in BREEAM in the context of assessing their air quality, according to classes suggested in Table 9 buildings No 1, No 3, and No 4 would be in the category A++ and building No 2 in category A+.

4.2. IAQ_{index} and IEQ_{index} Results

The first basic conclusion is that CO_2 cannot be used separately for IAQ_{index} assessment. As the results shows (for example for 47th floor of building No 2, three days after the completion of finishing works) the TVOC concentration measured was 787 μg/m^3 and the measured CO_2 concentration was 450 ppm which gives the IAQ_{TVOC} value of 52.04% and the IAQ_{CO2} is 85.2%. The concentrations impact directly the IEQ_{index} final value; IEQ_{TVOC} is 80.1% and CO_2 based is 88.4%. The use of CO_2 as separate component can lead to quite incorrect conclusions that the IAQ is at a good level but is not in our case because of VOCs levels. We believe that in the future both elements should be a simultaneously integrated part of the IAQ/IEQ model. In the analyzed case of "empty buildings", in which there are no users producing CO_2, the importance of TVOC is much greater, representing the main source of pollution—the construction and finishing materials. The CO_2 level of 450 ppm means that ventilation well works with the concentration of CO_2, but not necessarily in the case of the TVOC-emission.

According to the adopted model, the parameters of the indoor environment after three weeks after completion of finishing works for the assessed buildings (Table 7) should not cause significant dissatisfaction level (PD) greater than 15% in the case of the most polluted TVOC office (Table 6) and for other buildings about 10–12% (Table 8). In our case, level 10–12% of IEQ_{index} categorizes the buildings with a gold level in the BREEAM system. As has already been presented in Section 4.1, the emission of VOCs significantly decreases over time after indoor finishing works. The TVOC concentration decreased in building No 2 in three weeks by 553 μg/m^3, which affected the potential increase in user satisfaction with indoor air quality by 25.4% and increased satisfaction of users with the quality of the indoor environment by 6.4%.

For correctness of the obtained calculations, the authors suggest using the model's credibility analysis in accordance to [37]. The 'internal incongruity syndrom' condition in IEQ case study (Building No 2, three days) model may be detected. IEQ model uncertainty estimate may be adulterated because the model reproduces the discomfort level associated with the dominative component (PD(IAQ), but not the average PD, characterized by the actual value of IEQ.

Finally, it was found that in most cases the use of low-emission construction materials in BREEAM-certified buildings causes a high class of indoor air A+ or A++ in accordance to presented suggestions in Table 9. International research of IAQ satisfaction level in new office buildings (not certified) provided by a project [10] indicates that only 58% of 7178 respondents were satisfied. It seems that the BREEAM building satisfaction level, with IAQ, is about 20% higher than in the average office in Europe.

5. Summary

The article shows the impact of the TVOC concentration in four assessed BREEAM certified buildings on the value of overall Indoor Environmental Quality index. Methods allow us to present the results regarding BREEAM building assessment as a percentage of the unsatisfied occupants (PD). IEQ model (together with its sub-component models) was used mainly for the purpose of predicting of user reactions/satisfaction. Taking into account the building design solutions and measurements on the pre occupant stage there was an option to predict user satisfaction. All detected TVOC concentration in four buildings were acceptably low or very low in the all tested open spaces in all buildings after two months and in 70% of cases TVOC level did not exceed 100 μg/m^3. The predicted satisfaction IAQ_{index} in all case study buildings (two month after finishing works) is in the range of 81 to 94% while the overall IEQ_{index} is in the range 87–91%. As presented, BREEAM excellent buildings satisfaction level with IAQ is approx. 20% higher than in the average new office in the EU. Comparisons with results obtained by other citied authors shows that BREEAM excellent buildings have a higher level of indoor quality expressed as IEQ_{index}.

The model of IAQ_{TVOC} allows including TVOC concentration as sub component of IEQ model, this is a new idea. The results presented justified need to use other factors than CO_2 as sub-components in the IEQ model (to include a direct impact on the users from the indoor construction materials). $IEQ_{e(CO2)}$ indicated "a good level" of indoor air quality (85% satisfied) when one of the buildings was contaminated with VOCs emissions. Without TVOC research (52% satisfied), the interpretation of a good overall IAQ in a building would be wrong.

A way of determining indoor comfort based on measurements of TVOC influencing people's perception is a very simplified approach, but has a practical dimension for a building benchmarking. CO_2 tests should be performed only with consideration of occupants, that is, during the building operation, and TVOC may be provided at pre-occupant stage, which is an additional advantage of the presented approach.

The authors are aware on TVOC discussion on international level and do not want to present any final position on this issue, but want to show the possibilities that are behind it. The significant potential influence of TVOC concentration on IAQ_{index} results on the IEQ_{index} has been demonstrated, as an example, TVOC emission at the level of about 700 $\mu g/m^3$ decrease IAQ_{index} almost 30% and the overall IEQ_{index} by 10%.

The studies provide suggestions for the building TVOC emission classes presented in the paper (Table 9). The decreasing trend of changing in time TVOC concentration was detected, for buildings, is longer than in the laboratory chambers.

Our results show that it was possible in the case of the most polluted office space to reduce up to almost 60% of the TVOC pollution level in three weeks and further expected decrease (after two months) is half of the value after two weeks. TVOC measurement for BREEAM is suggested to be done a few days from the completion of finishing works, after a few weeks until reaching the recommended level of indoor air quality. Taking into consideration the results, there is an advice to building owners to maintain a minimum of a three week period without introducing users into the indoor offices.

The positive impact of low emission construction and finishing product on a high class of indoor office air of BREEAM buildings were proved, and thus it can indirectly promote the sustainable construction market.

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Abbreviations

The following abbreviations are used in this manuscript:

ACc_{index}	index of acoustic comfort
AC_{input}	increasing level of input noise
C_{CO2}	carbon dioxide concentration (ppm)
E_{min}	minimum daylight illuminance (lux)
IAQ_{index}	index of indoor air quality—percentage of persons satisfied with indoor air quality
$IAQ_{(CO2)index}$	index of indoor air quality—percentage of persons satisfied with CO_2 level
$IAQ_{(OI)index}$	indoor air quality index for odorous air- percentage of persons satisfied with odorous air
$I_{cl,dyn}$	clothing insulation (m^2 K/W)
IEQ_{index}	Indoor Environmental quality index—overall percentage of persons satisfied with Indoor Quality
IEQ_{crude}	IEQ with crude weighting scheme (the mean value of IEQ)—"0.25" for each of 4 components
LCI	lowest concentration interest
M	metabolic rate (W/m^2)
OI	odour intensity level (six-level scale)

pa	is the water vapour partial pressure (Pa)
PD	percentage of persons dissatisfied (percentage dissatisfied)
$PD_{(ACc)}$	percentage of persons dissatisfied with acoustic comfort level
$PD_{(IAQ(CO2))}$	percentage of persons dissatisfied with IAQ by CO_2
$PD_{(IAQ(TVOC))}$	percentage of persons dissatisfied with IAQ by TVOC concentration
$PD_{(IEQ)}$	percentage of persons dissatisfied with IEQ (indoor environmental discomfort index)
$PD_{(L)}$	percentage of persons dissatisfied with lighting quality
$PD_{(TC)}$	percentage of persons dissatisfied with thermal comfort level
PMP	ASHRAE Performance Measurement Protocols weighting scheme
PMV	Predicted Mean Vote (ISO 7730)
PMV	PMV model by ISO 7730 according to (Fanger, 1998)
PMV	value according to (Fanger, 1998) thermal comfort equations by CBE e-table
PPD	predicted percentage of persons dissatisfied
SD	standard deviation
t_a	air temperature (°C)
TC_{index}	thermal comfort index
t_g	black globe temperature (°C)
t_r	mean radiant temperature (°C)
$U_{overall}$	combined overall uncertainty of SI_i
v_a	relative air velocity (m/s)
W_1	weight for thermal comfort
W_2	weight for indoor air quality
W_3	weight for acoustic comfort
W_4	weight for lighting quality
W_i	weight for each IEQ sub-component model
VOC	volatile organic compounds

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