

Article

Combined Model for IAQ Assessment: Part 1—Morphology of the Model and Selection of Substantial Air Quality Impact Sub-Models

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Abstract: Indoor air quality (IAQ) is one of the most important elements affecting a building user's comfort and satisfaction. Currently, many methods of assessing the quality of indoor air have been described in the literature. In the authors' opinion, the methods presented have not been collected, systematized, and organized into one multi-component model. The application purpose of the assessment is extremely important when choosing IAQ model. This article provides the state-of-the-art overview on IAQ methodology and attempts to systematize approach. Sub-models of the processes that impact indoor air quality, which can be distinguished as components of the IAQ model, are selected and presented based on sensory satisfaction functions. Subcomponents of three potential IAQ models were classified according to their application potential: IAQ quality index, IAQ comfort index, and an overall health and comfort index. The authors provide a method for using the combined IAQ index to determine the indoor environmental quality index, IEQ. In addition, the article presents a method for adjusting the weights of particular subcomponents and a practical case study which provides IAQ and IEQ model implementation for a large office building assessment (with a BREEAM rating of excellent).

Keywords: indoor environment quality; IEQ; PPD; IAQ; TVOC; BREEAM assessment; occupant satisfaction

1. Introduction

1.1. State-of-the-Art Indoor Air Quality Measurement Systems

Approximately 30 years ago, people began to realize that buildings not only provide them with a sense of security, but can also significantly affect their health and well-being. This is particularly important due to the fact that people spend an increasing amount of time in closed indoor environment. Air quality and ventilation approaches were initially based on the users' dissatisfaction with the scent of the human body and, as such, the understanding of indoor air quality (IAQ) had serious limitations. Large quantities of pollutants and their sources clearly influence the indoor comfort of building inhabitants, as well as their health. In 1998, Fanger [1] presented an approach to the quantitative determination of perceived IAQ based on the level of dissatisfaction of residents caused by bad odors and irritants, smoke, and other sources of pollution. This approach provided two new measures of IAQ: the olf, which quantifies the pollution generated from a strong source of human bio-pollutant in the range of the impact of emitted odors on perceived air quality, and the decipol, measuring the perceived air quality in an indoor space with a source of pollution of one olf at a ventilation rate of 10 l/s. The number of emitted olfs per floor unit in different types of buildings and the amounts of pollutants from tobacco smoking (in olfs) can then be determined. Consideration of only the odour of the human body, without taking into account the influence of pollutants from various other sources (for example

emissions from construction products), was very limited. At this stage, the determination of IAQ did not take into account the significant differences among contaminants and did not distinguish their specific impacts on health or comfort. The study of emissions undetectable by the senses (such as carbon monoxide and other pollutants that affect health at concentrations below their odor threshold), together with health-effects thresholds, has become particularly important. The range of air pollutants that should be considered as IAQ components is very difficult to determine, because the composition of pollutants constantly changes due to the fact of their dynamic nature, secondary reactions, sorption processes, and other physical and chemical phenomena occurring in indoor environments, thus it cannot be inherently determined, as illustrated in Figure 1.

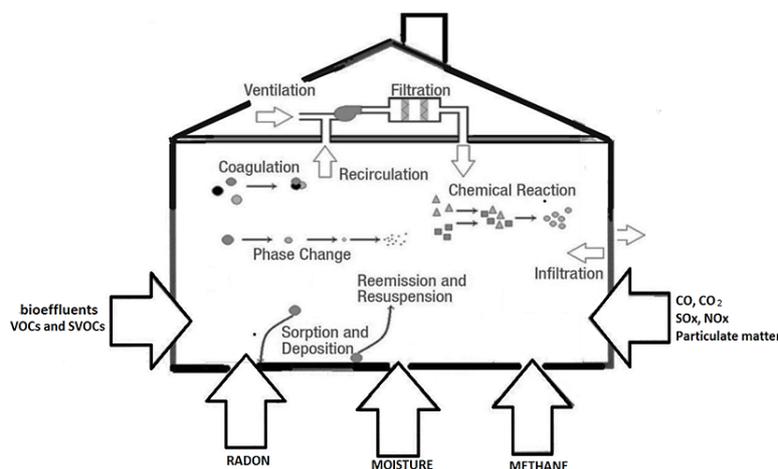


Figure 1. Overview of the physical and chemical processes of potential pollution sources in the indoor environment of a building. (VOCs—Volatile Organic Compounds, SVOCs—semi Volatile Organic Compounds).

Smoking alone emits more than 7000 different compounds, many of which are harmful [2] for humans and animals and may transport biological pollutants that can act as allergens. People and household animals emit gases which are unpleasant, transfer pathogens, and cause diseases. These examples show that there are many paths for penetration of and exposure to the sources of pollution in indoor environments.

In connection with the growing need to determine levels of indoor air pollution, new centers performing tests and new methods have been created considering the ability to analyze an increasing number of harmful substances. Measurement of pollutant concentrations in the air is generally a task performed by experts mainly in accredited laboratories and the results are published in scientific journals, technical reports, and, eventually, in guidelines, e.g., those of American Society of Heating Refrigerating and Air Conditioning Engineers ASHRAE [3]. The presence and concentrations of pollutants are often detected and measured without careful consideration of the significance of these measurements, and the pollutants measured may not be the most widespread or the most harmful. Some emissions are incorrectly grouped together; for example, more than one million volatile organic compounds (VOCs) are known and their toxicities are generally unknown, but they are often reported as a single value and referred to as the total VOCs (TVOCs) component. Frequently, carbon dioxide is used as an indicator of IAQ, although it does not have such a negative effect on the health of residents in the concentrations in which it is usually found in buildings. In our opinion, CO₂ is rather a marker of human bioeffluents. Examples of different understandings of the set of typical pollutants in an indoor environment are shown in Table 1 [4]. This table provides recommended values from the results of the European project HealthVent [5], which aimed to develop health-based ventilation guidelines. Table 1 also includes recommendations provided by the World Health Organization (WHO) on the acceptable levels of pollutant concentrations [6,7], as well as recommendations from other organizations, such as China's IAQ standard values [8]. Different approaches to the IAQ issue mean that the exposure limits assumed in the various source materials differ.

Table 1. Acceptable levels of pollutant concentrations occurring in indoor air, according to World Health Organization (WHO) recommendations supported by the results of the EU research program HealthVent, values recommended by the standard EN 16798-1:2019 (replacing EN 15251:2007), values recommended by the Chinese indoor air quality (IAQ) standard GB/T 18883-2002 and for acceptable levels of pollution for the certification of office buildings in Hong Kong.

Pollutant	WHO Guidelines for IAQ with Updates [6,7]	HealthVent Project [5,9]	EN 16798-1:2019 [10]	IAQ Standards for China [8,11,12]	IAQ Certification Hong Kong [13]
CO ₂			<500 ppm beyond outdoor level	485 ppm	<1000 ppmv 1800 mg/m ³ (8 h)
CO	100 mg/m ³ (15') 35 mg/m ³ (1 h) 10 mg/m ³ (8 h) 7 mg/m ³ (24 h)	19 mg/m ³ (8 h)	100 mg/m ³ (15') 35 mg/m ³ (1 h) 7 mg/m ³ (24 h)	1 mg/m ³	10 mg/m ³ 7000 µg/m ³ (8 h)
Formaldehyde HCHO	0.1 mg/m ³ (30')	0.03 mg/m ³ (30')	0.1 mg/m ³ (30')	10 µg/m ³	<0.1 mg/m ³ (8 h)
Benzene	>0.17 mg/m ³	<outdoor concentration	No safe level can be determined	0.11 mg/m ³	17 µg/m ³
NO ₂	40 µg/m ³ (1 year) 200 µg/m ³ (1 h)	40 µg/m ³ (1 week)	40 µg/m ³ (1 year) 200 µg/m ³ (1 h)	10 µg/m ³	150 µg/m ³ (8 h)
SO ₂	20 µg/m ³ (24 h)		20 µg/m ³ (24 h)	20µg/m ³ (24 h)	
Naphthalene	0.01 mg/m ³ 0.02 (1 year)	0.01 mg/m ³ (1 year)	0.01 mg/m ³ (1 year)		0.01 mg/m ³ (8 h)
Trichloroethene	>2.3 µg/m ³				230 µg/m ³ (8 h)
Tetrachloroethene	0.25 mg/m ³ (1 year)	0.25 mg/m ³ (1 year)	0.25 mg/m ³ (1 year)		0.25 mg/m ³ (8 h)
Respirable particulate matter PM _{2.5}	10.0 µg/m ³ (1 year)		10 µg/m ³ (1 year)	15 µg/m ³ (1 year) 35 µg/m ³ (24 h)	100 µg/m ³ (8 h)
PAH *	>0.012 ng/m ³		No safe level can be determined		1.2 ng/m ³ (8 h)
TVOC **			1000 µg/m ³	600 µg/m ³	600 µg/m ³ (8 h)

* PAH Para-Aminohippuric Acid—cyclic aromatic hydrocarbons; ** TVOC Total Volatile Organic Compounds; Reference [13] provides additional TVOC certification tests for new office buildings by determining (at the ppbv level) the content of carbon tetrachloride, chloroform, 1,2- and 1,4-dichlorobenzene, ethylbenzene, toluene, and o-, m- and, p-xylene.

Theoretical work on a combined IAQ model allowing aggregation of the results of the assessment of components affecting humans [14] is not yet well recognized in the literature. However, studies on IAQ indicators, which aim to provide a quantitative description of indoor air pollution, have been conducted since the nineties. In 2003, a significant study by Sekhar et al. [15] was published related to the standard indoor pollutant index (IPSI), the disease symptom index in the building symptom index (BSI), and to the often-cited works by Moschandres and Sofuoglu [16,17] on the indoor environmental index (IEI), indoor air pollution index (IAPI), and the indoor pollutant standard index (IPSI). The IAPI characterizes air pollution in an office with a single number: the index. The index value ranges between zero (lowest pollution level, i.e., best indoor air quality) and 10 (highest pollution level i.e., worst indoor air quality). The IAPI is a composite index; sub-indices are aggregated using the arithmetic mean in conjunction with a tree-structured calculation scheme. This scheme gives rise to some reservations, because at the top of the tree-structured calculation scheme is the IEI (calculated as the arithmetic mean of the IAPI and the IDI (indoor air discomfort index), and the combination of IAQ sensation and thermal conditions does not appear until later.

While considering the indicators for the quantitative description of pollution, the proposal of the IEA Working Group named “Defining the Metrics of IAQ” should also be mentioned. This group prepared, in 2017, the document entitled “In the Search of Indices to Evaluate the Indoor Air Quality of Low-Energy Residential Buildings” [18]. The group made the following assumption for the categorization of various indicators: there should be one index per individual pollutant and a dimensionless coefficient should be specified to evaluate the IAQ, provided that the current (observed) concentrations of a given pollutant c_j are related to the ELVs (exposure limit values) concentration $c_{j,ELV}$.

$$IAQ_{index}(j) = I_j = \frac{c_j}{c_{j,ELV}} \quad (1)$$

The index is calculated for each individual pollutant [18], which is specific only for this exact pollutant. The report showed that aggregation can be performed by addition, by taking the maximum value or by other methods, in an attempt to define metrics that can be used to evaluate IAQ. The assumption was that the reference value usually refers to health risks (accounting for chronic or acute effects), but other metrics can also be used, (e.g., odor or irritation threshold). There are two important properties to be considered when aggregating sub-indices: ambiguity and eclipsing. As a result of the analysis, the authors concluded “that there are problems with model aggregation methods. In the aggregation model $I_{agg} = I_1 + I_2$, ambiguity creates a false alarm and in the aggregation model $I_{agg} = 1/2(I_1 + I_2)$, eclipsing underestimates the effect” [18]. Therefore, the discussion remains open [18]. The report also showed how there are large spreads of concentrations of individual pollutants (up to seven rows), even in the group of pollutants for which sub-indices were built. It determined the difficulties of building a weighted scheme based on the simplest percentage adjustment of the concentration shares and, thus, the share of the mass of pollutants to be removed by ventilation.

The current state of knowledge does not provide information authorizing the omission of certain pollutants. Hence, taking into account the lack of data on the characteristics of each chemical compound and consideration of the “removal efficiency” [19] requires us to abandon thinking about the adjustment of many individual pollutants, and to focus only on the creation of a model based on the representative and target components. In this state of knowledge, there are hopeful studies and proposals with a grey combined $\sum IAQ_{index}$ model and the grey clustering model for IAQ indicators proposed by Zhu and Li in 2017 [20] is particularly interesting, especially when the relationships between system factors and the system’s IAQ behavior and the interrelationships among the factors are uncertain. At first, all specific indoor air pollutants and related parameters should be measured. However, this is a very complex and time-consuming process. On the basis of the characteristics and correlations of the pollutants, the indoor air quality can be characterized by representative indicators. Studies [20] have pointed out that respirable particulates, CO₂ and TVOCs, were the three most representative and independent environmental parameters which can be used as an evaluation index of indoor air

quality in office buildings. Since each indicator represents a class of pollutants with similar sources and dissemination characteristics, this index group avoids unreliability due to the fact that these indicators are “too small” because of critical concentration depression. A data pretreatment method must be used in the calculation procedure, reflecting the differences in concentration levels among different pollutants, but also expressing their influence on the comfort and health of the indoor occupants. Moreover, the measured pollutant concentrations can be used to predict the probable levels of other parameters, and good agreement was found between the predictions and measured values.

1.2. The Research Questions

The main research question contained in the paper concerned whether it was possible with the current state of knowledge to create and use in practice an IAQ model that was based on a unified and coherent approach for input indoor air parameters (such as pollutant concentrations, odor levels, and moisture content) and provided one output parameter (we proposed occupant satisfaction, IAQ_{index} (in %)). The authors looked for physical equations for the IAQ_{index} 's subcomponents and dependencies for their predicted occupant satisfaction functions with a pollutant concentration c_j ($PD = f(c_j)$ in %) which could be used as a model for subcomponents.

This paper's intention was to provide an IAQ model with a step-by-step process which can be used to determine the value of the overall indoor environmental quality index (in %) including another three components: thermal comfort, acoustic comfort, and lighting quality. The innovative approach and added value of this article is in the use of the proposed IAQ model in practice and the relatively simple calculation of the overall IEQ value (with an uncertainty estimation) using the actual results of measurements in the Building Research Establishment Environmental Assessment Method BREEAM certified case study office building. The authors also provided occupant satisfaction functions for CO_2 , TVOCs, and formaldehyde HCHO in two variants: with experimental %PD values taken from the literature and for these pollutants' %PD values converted from an Air Quality Index system (see Section 2.2.).

2. Methods

2.1. Research Content and Strategy

The proposed IAQ model is presented in Sections 2.2–2.7. The model is later used to analyze the case study of an office building described in Section 2.9. Figure 2 presents the subsequent research steps from theory to practical application. Section 2.8 shows the method for determining indoor environmental quality IEQ_{index} where IAQ index is a subcomponent/part of the IEQ_{index} model. In order to determine the IAQ and IEQ, physical measurements of the indoor environment in the building were conducted using the experimental approach provided in Section 2.10. Based on these physical indoor measurements the IAQ and IEQ indexes (number of occupants satisfied with the indoor air and overall indoor quality, respectively) were assessed (see Section 3) and discussed (see Section 4).

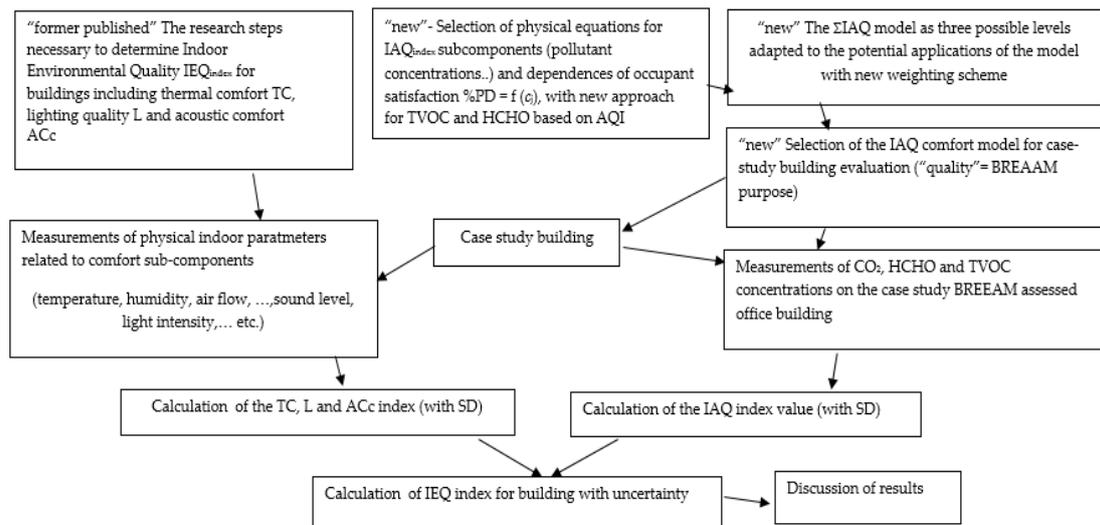


Figure 2. To determine the indoor air quality and indoor environmental quality (IEQ) indexes for the case study. (TC—thermal comfort, L—light quality, ACC—acoustic comfort).

2.2. The IAQ Model Proposal—Basic Assumptions

In the IAQ model construction process (our proposal), the commonly accepted approach is to transform individual concentrations of pollutants into subcomponents before they are aggregated into a single index (occupant satisfaction in %). However, summation of sub-indices can lead to situations in which all are under individual health thresholds, but the final indicator shows when the threshold has been exceeded. Conversely, the averaging of partial sub-indices can lead to an overall indicator showing an acceptable IAQ, even though one or more partial indicators are larger than their individual thresholds. One solution is to use the maximum value of all sub-indices to create the final form of the ΣIAQ_{index} . Taking these issues into consideration, the authors created the ΣIAQ model with three complication levels adapted to the purposes of potential applications of the model, as presented in Figure 3;

- i. Certification of a building, e.g., via the BREEAM system using (three sub-indices), called “quality”;
- ii. Design, including perceptible contaminants affecting comfort and using the IAQ index when calculating the IEQ (five sub-indices), called “comfort”;
- iii. Complex design, with the ΣIAQ_{index} representing both comfort and health (seven sub-indices) called “comfort/health”.

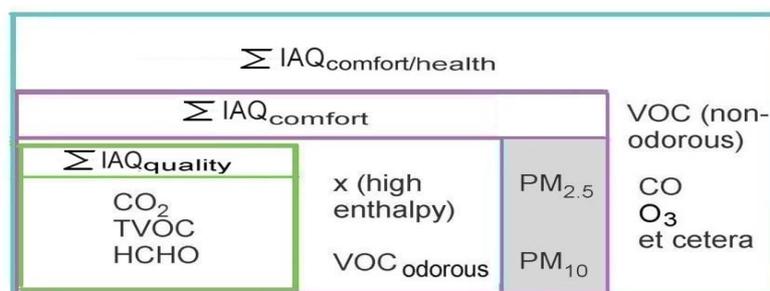


Figure 3. ΣIAQ model has three possible levels (i.e., similar to a Russian doll structure) adapted to the potential applications of the model.

The simplest one, “quality”, is an inner part of the $\Sigma IAQ_{comfort}$ model and can be used separately for simple applications with the main purpose of supporting a green building certification, e.g., via the

BREEAM system using three components, i.e., CO₂, HCHO, and TVOC. This model is used later on the case study of a BREEAM building.

Figure 1 shows the processes influencing the morphology of the Σ IAQ model and Figure 3 provides a list of the pollutants for which three IAQ submodels were built, containing human-perceived contaminants (IAQ_{quality} and IAQ_{comfort} models), but also the IAQ_{comfort/health} model for both perceptible and imperceptible pollutants, i.e., those that are not perceptible by humans but affect health and require additional energy for intensive ventilation for health reasons. There are potential sub-indices, such as IAQ(VOC_{non-odorous}) or IAQ(CO) [5,7]. Dust pollutants may have their sub-index both in the comfort model (if reliable curves of human sensory perception of PM concentrations are known) or in the IAQ_{comfort/health} model if their health impact is considered to be the dominant feature. Considering the types of pollutants harmful to health assigned to the sub-indices of IAQ, we only consider the most important air pollutants (i.e., target emissions) that were given in the WHO guide in 2010 [5,7]. Submodels of processes that impact on air quality in indoor environments, which can be distinguished as components of the IAQ model, were based on sensory satisfaction functions (index of occupant dissatisfaction (PD) with the level of air pollution). Subcomponents of the three potential IAQ models were classified according to their future potential applications: in the assessment of environmental quality index IEQ (models IAQ_{quality} and IAQ_{comfort}) or in the design of ventilation taking into account all possible harmful-to-health pollutants (model IAQ_{comfort/health}). In our opinion, such systematization creates order and has a practical dimension as presented later on in the case study. The following are the target pollutant groups:

- i. In the air quality model Σ (IAQ)_{quality}, the IAQ index subcomponents were assigned to the selected three pollutants. The submodels for the IAQ were CO₂, TVOC, and formaldehyde HCHO, as recommended by References [5,10,21,22];
- ii. In the Σ (IAQ)_{comfort} model, the previously provided simplified IAQ_{quality} subcomponents for the three main pollutants were extended with a set of selected compounds VOC_{odorous}, related to the collection of IAQ sub-indices (VOC_{odorous}) with an unknown cardinality, increased appropriately for the number of dominant pollutants. In addition, we provided a conditional deluge of two more components: (1) calculated using the enthalpy of hot and humid air (high enthalpy $h > 55$ kJ/kg [23]), the percentage of persons dissatisfied with respiratory cooling with humid air at relatively high temperatures and (2) the percentage of persons dissatisfied with indoor pollution with respect to dust pollution (PM₁₀ and PM_{2.5}), measured via panel tests. The introduction of a dust-pollution subcomponent to the IAQ model may be debatable, because some experimenters [24,25] underline the unique results of sensory tests of discomfort from dust, and the influence of “emissions” of respiratory dust particles on satisfaction is still under-researched. Considering the above, we expected two variants of the comfort model: with PD (PM₁₀, PM_{2.5}) or without this factor;
- iii. In the overall Σ IAQ model, comfort (IAQ)_{comfort} and health risk (IAQ)_{health} indicators were used, and, hence, this model was called (IAQ)_{comfort/health}. Models for subcomponents of IAQ not perceived by humans but influencing health, can be borrowed from the index set in the AQI (air quality index) system [26–28], which was adapted to assess the quality of indoor air based on, and in accordance with, the concepts of the air quality assessment system used globally by the American EPA.

Values of AQI indices published on active EPA websites using the air quality index system were introduced for application in US federal regulations in 1999 [28]. Currently, the AQI system for outdoor air includes the following pollutants: ozone, particulate pollutants (PM₁₀ and PM_{2.5}), carbon monoxide CO, sulfur dioxide SO₂, and nitrogen dioxide NO₂. To convert a specific air pollutant concentration to an AQI, the EPA developed a tool called the AQI Calculator, which is an open resource [29]. This system (referring to the index from 2004 [16] and the indoor pollutant standard index (IPSI)) was further developed, and the proposed IAQI for indoor air presented by Wang et al. [30] in 2008

and a newer proposal [27] from 2017 for a similar but narrower set of indices, also for indoor air, were both modeled on it. The AQI and IAQI indicators showed an increase in the level of impact on human health with increasing concentrations of air pollution. There are some detected difficulties here, since “AQI is a piecewise linear function of the pollutant concentration” [27]. The calculated values of the AQI [31] or IAQI [30] indices, over the entire 0–500 scale calculated from the measured concentrations of selected contaminants or in the part of the scale corresponding to the IAQ rating, ranged from “good” to “unhealthy”, and can be converted to PD% for use in the model equation, $(IAQ)_{\text{comfort/health}}$. Concentrations will be significant when the uncertainties of scale conversions are estimated. Authors believe that their way of converting the AQI scale to PD% (which is similar to the method of conversion of the IEQ components’ ordinal scales from the OFFICAIR EC project [32] to PD% scale; for example, the occupant percentage dissatisfied with noise [33,34] should be accepted in light of the expected results of a metrological analysis of the reliability of the combined Σ IAQ model.

Subcomponent models (physical functions, PD%) of the IAQ model for all individual air pollutants are presented later in this section.

2.3. Σ IAQ Model Weighting Scheme Considering Air Pollution Ventilating

To obtain a comprehensive picture of IAQ in a building, it is necessary to measure the number of pollutants with different individual concentrations. There are methods that weigh sub-indices [21] but the problem is finding an effective weighting scheme and understanding how to adjust them in the overall model of all the pollutants in Σ IAQ. For this reason, we proposed an adjustment method for the weights. In our opinion, provided in detail in References [33,34], and also according to Reference [22], the best weighting scheme, which would lead to a credibly aggregated model of IAQ composed of many extractable components (sub-indices), would be a system based on concentration values (the “excess masses” of pollutants to be regarded as loadings for the ventilation system). Therefore, the we aimed to determine the individual pollutants assigned to the IAQ model, their concentrations, c_j , as the inputs of the IAQ submodels, and their “excess concentrations” originating from emissions or determined within indoor environments. Thus, it was possible to determine directly the energy requirements for ventilation purposes and the required minimum global ventilation rate. Determining the input concentration value, c_j , for each IAQ sub-index enables the determination of the total mass of pollutants in the air, which is the basis for determining the air change rate $N_{1, \dots, 7}$ (overall air change rate), assuming that the model includes all significant IAQ pollutants.

Currently, according to References [35–37], the most common assumption made is that pollution from VOC_j compounds arises only from emissions due to the presence of construction or finishing materials (for $j = 1, 2, \dots, n$) (it can be assumed that the source i of an emission is the entire indoor environment and then $i = 1$) from the zero state. The physical model for determining the ventilation rate in indoor environments polluted with VOC-type pollutants from building materials is given by EN 16798-1:2019 [10], assuming that design parameters for indoor air quality are derived using limit values for substance concentrations. In accordance with ECA Report Number 11 [36], the design ventilation rate required to dilute an individual substance emitted from building materials is calculated as:

$$Q_h = \frac{G_h}{C_{h,j} - C_{h,0}} \times \frac{1}{\varepsilon_v} \tag{2}$$

where Q_h is the ventilation rate required for dilution in m³ per second, G_h is the emission rate of the substance in micrograms per second, $C_{h,j}$ is the guideline value of the substance in micrograms per m³, $C_{h,0}$ is the concentration of the substance in the supply air in micrograms per m³, and ε_v is the ventilation effectiveness.

In fact, in a building with active “indoor chemistry” (see Figure 1), the use of this formula seems to be increasing. Taking into account the dynamic nature of the processes of generating various pollutants, the approach to IAQ and its components should be changed and subcomponents should be treated as pollution load processes, increasing in number not only due to the emission processes but also due to

the generation of bio-pollution, water evaporation, and even dust infiltration from outside. It is also possible to set steady-state (initial) concentrations of pollutants and to determine the expected time courses of removal of these pollutants by means of ventilation (curves $\sum c_j = f(\tau)$), at constant values of air change rate per hour ACH (h^{-1}). Such ventilation rate calculations for CO_2 were developed in 1997 by Persily [38] and similar ones were provided in 2017 by Gyt [39] at the Berkeley National Laboratory. These calculations are not very accurate, as shown in the general demonstration graph in Figure 4.

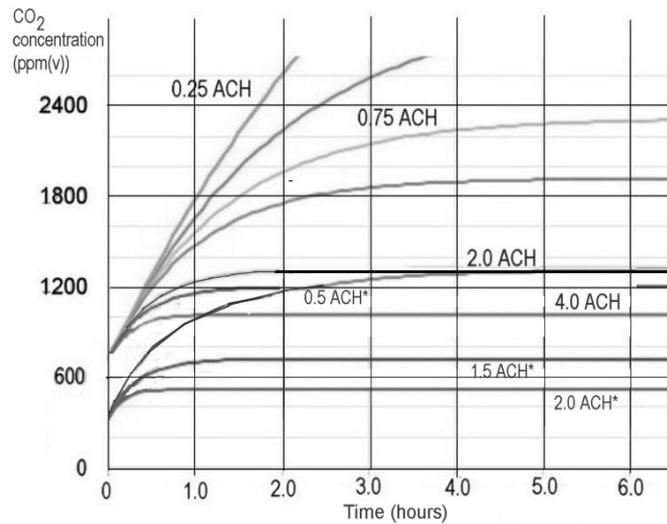


Figure 4. Of CO_2 above outdoors levels with two people in the contaminated building (ACH—air change rate) and in a typical clean office room (ACH*).

Less accurate time-dependent curves of the total minimum ventilation rate ACH needed for “contaminant exhaustion” can be determined using programs [40] based on generic engineering equations for the sum of pollutants $\sum c_j$. The generic equation for pollution concentration (the ratio of the amount of polluting product to the amount of fluid in the space (such as air in a room) can be calculated from the following equation:

$$c = q/(n \cdot V \cdot (1 - e^{-Nt})) \tag{3}$$

where c is the pollution concentration in the space (or in the room) with perfect mixing (m^3/m^3) or (kg/kg), q is the amount of pollution added to the space (m^3/h) (kg/h), N is the air change rate per hour (h^{-1}), V is the volume or mass of the space (m^3) or (kg), e is the number 2.72, and t is time (h). If the initial concentration (at $t = 0$) in the space and the concentration in the supply fluid is zero, after some time the concentration in the room will stabilize. The ventilation rate graph for an amount of pollution $q = 1$ and a volume of space $V = 1$, shows the values of $\sum c_j$, similar to Figure 4. In order to obtain more exact values of the VOC concentrations remaining in the room for the air change rate function, it is possible to use the published dependencies or for the assumed volumes V of ventilated spaces with determinate concentrations, as they can be determined experimentally. A simplified method for determining the ventilation rate N from a simple formula for the time, t , course of a trial ventilation was provided by the Japanese researchers Noguchi et al. [41] in 2016. A description of this method is worth reading. Based on the temporal changes of the TVOC concentration measured using a PID_{TVOC} meter [42], the air change rate N or the ventilation rate F was estimated using the following method. Assuming perfect mixing of the air in the room and a constant TVOC emission rate E , the concentration change of TVOC in the room can be expressed by the following equation:

$$C(t) = C_j + \left(\frac{E}{F}\right)\left(1 - e^{-\frac{F}{V}t}\right) = C_j + \left(\frac{E}{F}\right)\left(1 - e^{-Nt}\right) \tag{4}$$

Finally, Equation (5) can be expressed with one unknown parameter, the air exchange rate N as:

$$\log\left(\frac{C_{st} - C_j}{C_{st} - C(t)}\right) = Nt \quad (5)$$

The initial concentration c_j can be determined from the experimental results. After a long time, when the exponential term in Equation (5) can be assumed to be zero, the concentration $C(t)$ becomes constant. The steady-state concentration C_{st} can be determined from the temporal change in the experimental results where the concentration levels off.

The rule that the IAQ model should include a weighting scheme, referring to the variation in the share of pollutants in the IAQ, has been noted in References [35,37]. According to the first proposal, the weighting system is based on the differentiation of coefficients R_j , which are the ratios of the real concentration values (or mass of pollutants) to the values of reference concentrations, representing the so-called relative masses of non-eliminated pollutants. This can also be represented by the desirable reduction in the level of pollution by means of ventilation and, thus, also by the energy requirements. For one emission source, the proposed system with a coefficient R_j for a given pollutant C_j has the formula:

$$R_j = \frac{y_j}{I_j}, \quad j = 1, 2, \dots, m \quad (6)$$

where I_j is the ratio of the gas-phase concentration to the reference concentration value. For example, for the LCI (Lowest Concentration of Interest) value for the j th compound emitted from the building material, the factor R_j is dimensionless, since y_j is the gas-phase concentration for the j th compound in $\mu\text{g}\cdot\text{m}^{-3}$, I_j is the lowest concentration of interest (LCI) [41] for the j th compound in $\mu\text{g}\cdot\text{m}^{-3}$ and m is the number of all elected compounds. The weight coefficients W_j are used as the weights of the equations in the IAQ index, according to:

$$W_j = \frac{R_j}{\sum_{j=1}^m R_j} \quad j = 1, 2, \dots, m \quad (7)$$

The authors of Reference [35] justified adjusting the coefficients where $\sum R_j \leq 1$, but they did not explain the physical meaning of this condition. We believe that further discussion should include the issue of whether the “relative mass” of contamination expressed by Equation (6) has a proper place in the weighting scheme for the equations. The dimensionless quantity (7) does not have a sound physical meaning [37]. In our opinion, this type of calculation method is debatable.

One should strive to cover all the sub-indices of the combined IAQ_{ij} model with a weighting scheme that would give VOCs a share in the total energy requirements for ventilation. The term “relative mass” should correspond to weights rationally proportional to the energy expenditure for ventilation of individual pollutants (IAQ sub-indices). Therefore, our future work will focus on introducing weights for all expressions in the overall IAQ model equation. However, since this is currently not possible without an adjustment method adapted to weight determination for very small concentrations, it was decided to present our model as an interim solution. We proposed the use of weights based on the “excess concentration” values within the pollutant categories only with similar and comparable orders of concentration values, for example the VOC_{odorous} and $VOC_{\text{non-odorous}}$ categories. The rules of adjustment with boundary conditions will be provided and justified in the follow-up article to this report.

2.4. $\sum IAQ$ Model Scheme Morphology

According to the new proposal, for models with air quality sub-indices $IAQ(P_j)$ (developed with the standard EN 16798-1:2019 as a reference for IEQ model creation [22,33] and with assumptions

described in Reference [34]), in the case where indoor air has many pollutants, P_1, \dots, j , the combined ΣIAQ_{index} equation is:

$$\Sigma IAQ_{index} = W_{P1} \cdot IAQ(P_1)_{index} + W_{P2} IAQ(P_2)_{index}, \dots, W_{Pj} IAQ(P_j)_{index} \tag{8}$$

where the W_{P1}, \dots, P_j weighting system for IAQ components is created on the basis of the arithmetic mean and the concept of "excess concentration" is introduced only for groups of pollutants with similar concentration values. There is a difference in concentration Δc_j between the observed concentration of pollutant c_j and the reference concentration c_{ref} (c_{ELV} or c_{LCI}), which is below the current concentration in contaminated rooms. Thus, the excess concentration is:

$$\Delta c_j = c_j - c_{ref} \tag{9}$$

The weights W_1, \dots, j for all three IAQ models are determined on the basis of arithmetic means or by adjusting all the values of Δc_j in a given model using Equation (10):

$$W_j(IAQ_{comfort/health}) = \frac{\Delta c_j}{\sum_{j=1..7} \Delta c_{1..7}} \tag{10}$$

where the sum of the adjusted weights W_j of all ventilated pollutants described with sub-indices should be unity. The weight values for a given IAQ model, (e.g., $IAQ_{comfort}$) may be different, but the sum of the sub-index weights must be ≤ 1.0 .

The values of the reference concentrations are the concentration levels that are acceptable or recommended as limit values for various pollutants P_j . In the case of the $\Sigma IAQ_{quality}$ submodel as part of the IEQ_{index} model, weights should be used for the $VOC_{odorous}$ (HCHO and TVOC) reference threshold concentrations of odors. The weights in the weighting system should be adjusted to unity according to the Equation (11):

$$W_{HCHO} = \frac{\Delta c_j}{\sum_{j=2,3} \Delta c_{2,3}} = \frac{(c_j - c_{ref})}{(c_{TVOC} - c_{ref}) + (c_{HCHO} - c_{ref})} \tag{11}$$

There are, however, non-typical cases in which the scales have different values. This is the case for formaldehyde, the concentration of which is many times lower in the building than the threshold level c_{th} . According to the WHO [7], the admissible value c_{ref} is also higher than the concentration in the building. In this case, the authors recommend taking the reference value as zero. Then, the weight W_{HCHO} described by Equation (11) (for two pollutants), would not be negative ($c_{HCHO} - c_{ref}$). The ASHRAE Guideline 10 (2011) [3] recommends that the IEQ model (and appropriate weights, W_i) should contain synergy effects of environmental parameters included in the subcomponents and their sensory perceptions.

Figure 5 shows the extended IAQ_{index} model with its sub-indices treated as components of the IEQ_{index} , but also with sub-indices of the $IAQ_{comfort/health}$ type, i.e., pollutants that do not belong to the IEQ model but are important to health and the energy balance of a building with a mechanical ventilation system. The experimental dependencies of the percentage of persons dissatisfied, %PD, and the values of the concentrations of pollutants, c_j , sensed in indoor air in the appropriate ranges are of fundamental significance in the sub-indices relevant to the IEQ model [43].

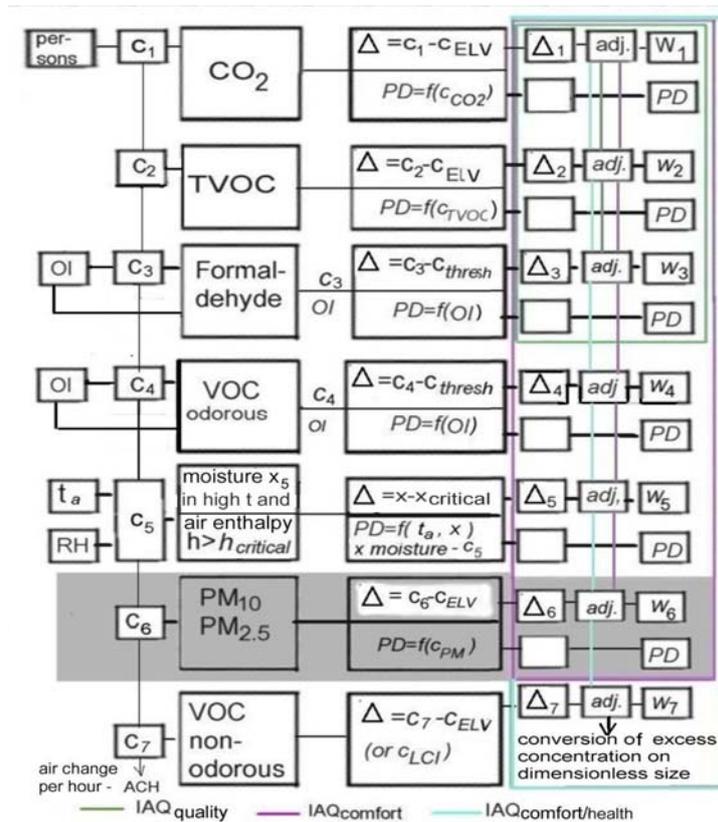


Figure 5. Σ IAQ_{index} model with weighting scheme.

From the dependencies, expressed as the curves for $PD(CO_2)$ or $PD(VOC_{\text{odorous}})$, the equations of the models are derived Equations (12)–(14):

$$\Sigma IAQ_{\text{quality}} = W_1 \cdot IAQ(CO_2) + W_2 \cdot IAQ(TVOC) + W_3 \cdot IAQ(HCHO) \quad (12)$$

$$\Sigma IAQ_{\text{comfort}} = W_1 \cdot IAQ(CO_2) + W_2 \cdot IAQ(TVOC) + W_3 \cdot IAQ(HCHO) + W_4 \cdot IAQ(VOC_{\text{odorous}}) + W_5 \cdot IAQ(h) \quad (13)$$

$$\Sigma IAQ_{\text{comfort/health}} = W_1 \cdot IAQ(CO_2) + W_2 \cdot IAQ(TVOC) + W_3 \cdot IAQ(HCHO) + W_4 \cdot IAQ(VOC_{\text{odorous}}) + W_5 \cdot IAQ(h) + W_6 \cdot IAQ(PM_{2.5}, PM_{10}) + W_{7a} \cdot IAQ(VOC_{\text{non-odorous}}) + W_{7b} \cdot IAQ(CO) + W_{7c} \cdot IAQ(NO_2) \quad (14)$$

The scheme of the $\Sigma IAQ_{\text{comfort/health}}$ model consists of seven (or more) components or IAQ submodels and these are models for the various types of pollutants: $IAQ(CO_2)$, $IAQ(TVOC)$, $IAQ(HCHO)$, $IAQ(VOC_{\text{odorous}})$, $IAQ(h)$, $IAQ(PM_{2.5}, PM_{10})$, and the selected $IAQ(VOC_{\text{non-odorous}})$. The $IAQ(VOC_{\text{odorous}})$ and $IAQ(VOC_{\text{non-odorous}})$ models should be multiplied, depending on the number of dominant VOC pollutants, and, hence, the $\Sigma IAQ_{\text{comfort/health}}$ model will, in practice, have more than seven components.

The inputs of each IAQ submodel are unit concentrations in air of a given pollutant, c_j (in the case of $IAQ(h)$). This is the moisture content x in well-known units “g of water vapor (g_w) per kg of dry air (kg_a)”, converted to a concentration of c_j in $\mu g_{\text{water}}/m^3$ (or H —absolute humidity in g_w/m^3 which is a measure of water-vapor density). In some cases, it is necessary to convert the pollution-derived parameter to VOC concentration (conversion of the odor intensity OI to VOC concentration is described later in this section).

From the concentration values, total air pollution can be calculated, and, subsequently, also the energy needed to ventilate the indoor air pollution. When the concentration levels of pollutants are variable and are increasing due to the presence of emissions, then the formulas given in Reference [36] and the amended standard EN 16798-1:2019 are used to calculate the required ACH ventilation rate. When the level of contamination is set (or quasi-fixed) and the volume and other parameters of the ventilated room are known, it is possible to calculate ventilation-time curves, i.e., maximum ventilation curves for ACH ventilation rate to reach concentration levels ELV, LCI or the olfactory threshold level, according to Reference [40] or another adequate equation.

There are two outputs of each IAQ submodel as described below:

1. The weights of the weighting system for the model $\sum \text{IAQ}_{\text{quality}}$ and hypothetically $W_1, \dots, 5$ for the model $\sum \text{IAQ}_{\text{comfort}}$ or $W_1, \dots, 7$ for the model $\sum \text{IAQ}_{\text{comfort/health}}$ (in a hypothetical model with a set adjustment method). These should reflect the energy load of the IAQ expressed by the theoretically assumed increase in the current concentration of pollutant c_j relative to the reference concentration of $c_{j,ref}$, which determines the level of this concentration intended to be obtained by ventilation.
2. The $PD\%$ with the IAQ as a function of air pollution concentration. These values, determined in panel tests, reflect the impact of the interaction of air with a given pollutant at the actual level of concentration, estimated via panelists' sensations/perceptions ($PD = f(c_j)$ in %).

Examples of measurable physical parameters for the purpose of IAQ and IEQ calculations (see case study) are given in the following section.

For the construction of the combined model $\sum \text{IAQ}_{\text{index}}$ with a weighting scheme useful for aggregating sub-indices, we proposed the model presented in Figure 5. In this scheme, the combined IAQ model is shown as the basic assumption for the aggregation of all sub-indices. First, the model was cut by a cross-connected vertical connection regarding the inputs of submodels—the calculation of the sum of the masses of all pollutants $\sum c_j$ in the ventilated space, using the values for the inputs of all submodels of IAQ concentration values of contaminants. The sum of the concentrations of all air pollutants expressed as mass units of pollution per m^3 of volume (which can be read after multiplication by V (m^3) as the mass to be displaced by ventilation), is the basis for calculating the “air change rate per hour” (ACH), the minimum air exchange rate needed to reduce the observed mass level of air pollution in a ventilated room (see Reference [40]). The second connection concerns the submodel outputs—the conversion of excess concentration to a dimensionless value, which allows for the weighting scheme of the $\sum \text{IAQ}_{\text{index}}$ combined model and the weights of individual IAQ submodels to be determined.

Additional assumptions were as follows:

- i. The sum $\sum \Delta c_1, \dots, 7$, which admittedly constitutes an excess mass increase of the sum of pollutants described by the submodels, was treated only as a “virtual energy load of the building” for ventilation conducted for the elimination of pollutants, and therefore, when adjusting the weights, the possibility of dividing the excess concentration by the sum of concentrations should be considered.
- ii. The percentage of persons dissatisfied $PD(\text{IAQ}_{\text{component}})$ determined experimentally in sensory studies using panelists' sense of air quality during their exposure to an internal environment deteriorated by a given contamination component ($PD = f(c_j)$), was derived from the literature or direct experiments.

Values of weights $W_{1, \dots, j}$ in sets of three, five or more components of the three $\sum \text{IAQ}_{\text{index}}$ models (see Equations (12)–(14), were adjusted to a value of unity by dividing $\Delta c_{1, \dots, j}$ of each component by the sum of excess concentrations $\sum \Delta c_{1, \dots, j}$ in μ/m^3 . We proposed the use of c_{ref} values, apart from the values of c_{LCI} [18], c_{ELV} , and the threshold values c_{th} for odorous compounds, were as follows.

- i. For IAQ(CO₂) and IAQ(HCHO), the c_{ELV} concentrations were derived from EN 16798-1:2019 [10];
- ii. For IAQ(TVOC) and IAQ(VOC_{odorous}), the threshold concentrations, c_{th} , for identified odorous compounds or mixtures are from Reference [44];
- iii. For the IAQ(h), the water-vapor concentration H (g_w/m^3), recalculated from the moisture content x ($\text{g}_w/\text{kg}_{\text{dry air}}$) using the gas constant for the water vapor and the actual temperature, the value of h up to the critical value for “high enthalpy of humid air” was evaluated using the formula:

$$h = 1.006t_a + x \cdot (2501 + 1.805t_a) \quad (15)$$

where h is the specific enthalpy of humid air (kJ/kg), which must be >55 kJ/kg. The EN 16798-1:2019 standard [10] recommends a limit for the dehumidification of air of $12 \text{g}_w/\text{kg}_{\text{dry air}}$ (this value must be converted to a c value in g_w/m^3).

- i. For IAQ(VOC_{non-odorous}), the c_{ELV} value in cases where no established LCI values were derived from the EN 16798-1:2019 standard.
- ii. For IAQ(PM_{2.5}, PM₁₀), the c_{ELV} values were derived from the WHO [7] or other organizations (Tables 1 and 2).

The proposed reference values of pollutants forming the sub-indices of the IAQ model are given in Table 2. With reference to the concentration values of c_{LCI} , it should be noted that according to References [18], this value is typically acquired by dividing occupational exposure limits by a safety factor (100 or 1000). Concentration c_{LCI} is taken from Lowest Concentration of Interest (EU-LCI) from European Commission lists.

However, the model values for exposure limit values (ELVs) of indoor air pollution, in accordance with the recommendations of the health-based ventilation guidelines [5], should be adopted in accordance with the current WHO guidelines given in the periodically issued *WHO Air Quality Guidelines* [7].

2.5. Selection of Submodels for Pollutant Components

Our overall selection of physical subcomponent equations and dependences for $\%PD = f(c_j)$ is presented in Table 3. The models presented were used to determine the IEQ for the sample building. The highlighted pollutants were taken into account in the case study building assessment.

Table 2. Exemplary pollution concentration reference values for low-pollution building.

Component of Pollution P _j	Reference Concentration	Reference Value	Reference/Recommendation List
CO ₂ (outdoor 350 ppm)	c _{ELV}	380 ppm	EN 16798-1:2019
TVOC	c _{ELV}	<300 µg/m ³	EN 16798-1:2019
	c _{th}	50 µg/m ³	MV. Jokl [45]
HCHO	c _{ELV}	30 µg/m ³ (30 min) 100 µg/m ³ (30 min) 9 µg/m ³ (1 year)	EN 16798-1:2019 WHO Guidelines for IAQ (2010) IEA-AIVC Report. Annex 68 (2017)
	or c _{th}	300 µg/m ³ 60 µg/m ³	AIHA Odor Thresholds for Chemicals with Established Health Standards (2013)
VOC _{odorous} (as in EN 16516)			
Naphthalene	c _{th}	10 µg/m ³ (1 year)	AIHA Odor Thresholds for Chemicals (2013)
Nitrogen dioxide	or	20 µg/m ³ (1 year)	
Ammonia	c _{ELV}	70 µg/m ³ (1 year)	EN 16798-1:2019
Ozone		100 µg/m ³ (8 h)	
Carcinogenic VOCs		5 µg/m ³	
Moisture content x in indoor air (enthalpy >55 kJ/kg, t _a = 23 °C and 60% RH) x [g _{water} /kg _{dry air}] ⇒ H [g _{water} /m ³]	> unacceptable value of moisture content x at 23 °C.	x > 12 g/kg RH > 60%	EN 16798-1:2019
PM ₁₀	c _{ELV}	20 µg/m ³	WHO Air Quality Guidelines (2010) EU Directive 2008/50/EC introduced additional
PM _{2.5}	c _{ELV}	10 µg/m ³	PM _{2.5} objectives targeting the exposure of the
	c _{DIRECTIVE}	2 25 µg/m ³ (1 year)	population to fine particles.
VOC _{non-odorous} (EN 16516 includes pollutants with limit values on concentration that have been identified):	c _{ELV} or c _{LCI}		EN 16798-1:2019 EN 16516;
Carbon monoxide		7 mg/m ³ (24 h)	
Carcinogenic ¹ VOCs		5 mg/m ³	WHO Guidelines for IAQ (2010)

¹ Limit values and carcinogenic effect: the level of PAHs, particles, benzene, and trichloroethylene should always be kept as low as possible.

Table 3. Selection of physical equations for IAQ_{index} components and dependences for $PD = f(c_i)$.

Sub Component	Input Parameters	Sensory Equations to Calculate the %PD Value	References
CO ₂	$c(\text{CO}_2)$ (in ppm)	$PD_{IAQ(\text{CO}_2)} = 395 \cdot \exp(-15.15 \cdot C_{\text{CO}_2}^{-0.25})$	[36]
		$c_{IAQ(\text{CO}_2)} = 55\,833 \cdot (\ln(PD) - 5.98)^{-4}$	[45]
		$IAQ = 6 \times 10^{-0.07} c_{\text{CO}_2}^2 - 0.0025 \times c_{\text{CO}_2} + 1.9416$	[46]
		$PMV_{\text{CO}_2} = 6.364 \times \log \frac{c_{\text{CO}_2}}{485}$	[47]
		$PD = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)$	[48]
TVOC ¹	$c(\text{TVOC})$ \Rightarrow PD	$c_{\text{TVOC}} = 16,000(\ln(PD) - 5.988)^{-4};$ $c_{\text{TVOC}}(\mu\text{g}/\text{m}^3)$	[49]
	$IAQI \Rightarrow$ PD^*	$PD_{(IAQ)TVOC} = 405 \cdot \exp(-11.3 \cdot c_{\text{TVOC}}^{-0.25})$ In Taiwan EPA Indoor Air Quality Index System (IAQI). Nine major indoor air pollutants are included: PM10, PM2.5, CO ₂ , CO, O ₃ , HCHO, TVOC, bacteria, and fungi. We proposed the use of a calibration curve $IAQI = f(c_{\text{TVOC}})$ for conversion to PD^* %	[22,45]
			[30]
HCHO	$c(\text{HCHO})$		[47]
	$(\text{pi})^2 \Rightarrow$ $OI^3 \Rightarrow$ PD	$PMV_{\text{HCHO}} = 2 \log \frac{c_{\text{HCHO}}}{0.01}, \quad c_{\text{HCHO}}(\text{mg}/\text{m}^3)$ $PD = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)$ $PD_{IAQ(OI)} = \frac{1}{1 + \frac{1}{\exp(2.14 \cdot OI - 3.81)}}$	[48]
			[50,51]
	$c(\text{HCHO})$ \Rightarrow $IAQI \Rightarrow$ PD^*	In the Taiwan EPA Indoor Air Quality Index ⁶ System (IAQI). Nine major indoor air pollutants are included: PM10, PM2.5, CO ₂ , CO, O ₃ , HCHO, TVOC, bacteria and fungi. We proposed the use of the calibration curve $IAQI = f(c_{\text{HCHO}})$ for conversion ⁷ to PD^* %	[30]

Table 3. Cont.

Sub Component	Input Parameters	Sensory Equations to Calculate the %PD Value	References
SVOC and VOC _{odoros}	$c_{VOC} \Rightarrow OI^4$	Formulae for the conversion of odorant concentration c_j to odor intensity OI for recalculation ⁽⁴⁾ of the conversion of odor intensity to odorant concentration.	[52]
	$c_{VOC} \Rightarrow OI^3$	Conversion of the chemical concentrations c_j (mg m ⁻³) into odor concentrations c_{OD} (ou _E m ⁻³) and odor intensities OI ; $c_{OD,0}$ – unity of odor concentration ($c_{OD,0} = 1\text{ou}_E \text{ m}^{-3}$) $OI_j = k_j \log c_{OD,j} + 0.5$	[53]
	$OI^3 \Rightarrow ACC_{VOC} \Rightarrow PD$	The mean of acceptability votes as a function of the mean of intensity votes. $ACC = -0.45 OI + 0.93, R^2 = 0.979$ ACC in scale: from -1 to +1 OI odor intensity in scale: from 0 to 5 $PD_{IAQ(OI)} = \left(\frac{\exp(-0.18-5.283ACC)}{1+\exp(-0.18-5.283ACC)} \right) 3100$	[54]
	OI^2 in scale (pi) recalculation to $\Rightarrow OI^3$	The perceived intensity in pi units is determined by comparing the intensity of the sample with different specified intensities of the reference substance, (e.g., acetone). Concentrations for 1 to n (pi) follow a linear gradation of the acetone concentration. Confidence intervals should be within ± 2 pi. Recalculation (pi) to OI	[55]
			[34]

odors from the distribution of food. These 22 odorants can be divided into five chemical groups: (1) reduced sulfur compounds, (2) carbonyls, (3) nitrogenous compounds, (4) VOCs, and (5) volatile fatty acids. For example, for the group of reduced sulfur compounds for compound number 1, the conversion equation for H_2S is $Y = 0.950\log X + 4.14$, for the carbonyl compounds group for compound number 10, ammonium NH_3 , it is $Y = 670\log X + 2.38$, and for the VOC group for styrene it is $Y = 1.420\log X + 3.10$.⁵ If one considers a cooling system that removes heat from a space but does not remove moisture unless condensation occurs, such as radiant cooling without dehumidification in a ventilation system, the importance of humidity is very clear. The sensible cooling of air in a room (no change in absolute humidity) from 25 °C and 60% RH to 20 °C (process a–b for $x = 0.012 \text{ kg}_w/\text{kg}_a$). This value, coupled with a high temperature, $t_a = 25 \text{ °C}$, is accepted as the critical limit value for dehumidification by EN16798-1:2019 [10] and can be converted into an absolute humidity H (g_w/m^3). These processes are expected to significantly increase thermal comfort and air quality. Nevertheless, the same change in enthalpy of the air h can be achieved by simply reducing the humidity by 10% RH and keeping the temperature constant (processes a–c). Since IAQ is a function of enthalpy, these are expected to be the same. Here, a change in humidity of 10% RH at constant temperature is equivalent to a change in temperature of 5 or 6 °C at constant moisture content in air x ($\text{kg}_w/\text{kg}_{\text{dry air}}$).⁶ The IAQI system [30] adopts the methodology of AQI to set up the range of IAQI values from zero to 500, including 50, 100, 150, 200, 300, and 500. The IAQI values of 100 and 150 correspond to the concentrations in the Taiwan IAQG standard. Other IAQI values between 50 and 200 correspond to the concentration rankings given by several reference resources including the US EPA AQI system [31]. All on-site concentrations of indoor air pollutants (HCHO, TVOC, PM10, PM2.5, CO, CO₂, O₃, bacteria, fungi, SO₂, and NO₂) are combined using the IAQI system. The IAQI values are calculated on the basis of the concentration value c using the interpolation method for each air pollutant. In the IAQI system, the index range 0–50 is “good” with a significance level of “little or no risk”, 51–100 is “moderate” where “sensitive persons or those with respiratory symptoms are concerned”, 101–150 is “unhealthy for sensitive groups”, 151–200 is “unhealthy for all individuals”, 201–300 is “very unhealthy—more serious health effects for everyone for short-term exposure”, and 301–500 is “hazardous” with “health warning of emergency conditions for everyone”. Therefore, the comfort scale for IAQI is adequate for index values from zero to 200 and our proposal is to use the “hypothetical” scale of PD^* of 0–100% in this range, converted from IAQI.⁷ The method of conversion of the IAQI scale to the PD^* scale is based on experiences gained during research [27]. The IAQI values in a health-risk scale can be given in % for persons giving a verbal answer of “no risk”, “moderate”, and “unhealthy” as their health risk evaluation. Therefore, when determining, for instance, the concentration function values of the $\%PD_{IAQI}(\text{TVOC})$ and $\%PD_{IAQI}(\text{HCHO})$ components, it is necessary to recalculate the scale $IAQI = f(c)$ in the range from zero to 200 to the scale PD^* from 0 to 100%. There are break points in the new $PD^*\%$ scale: for IAQI values 0–50, $PD^*\%$ is 0–25, for IAQI values 51–100, $PD^*\%$ is 26–50, for IAQI values 101–150, $PD^*\%$ is 51–75, and for IAQI values 151–200, $PD^*\%$ is 76–100.

The air quality indexes (i.e., AQI [31] and IAQI [30]) are piecewise linear functions of the pollutant concentrations. At the boundary between AQI categories, there is a discontinuous jump of one AQI unit. To convert from concentration c_j to I_j (in the converted scale index I_j will be PD_j , Equation (16) is used.

$$I_j = ((I_{high} - I_{low}) / (c_{high} - c_{low})) \cdot (c_p - c_{low}) + I_{low} \quad (16)$$

where I_j is the air quality index I in the PD^* scale, c_{low} is the pollutant concentration break point, which is $\leq c_j$, c_{high} is the pollutant concentration break point, which is $\geq c_j$, I_{low} is the index break point corresponding to c_{low} , I_{high} is the index break point corresponding to c_{high} and c_p is the truncated (to an integer) actual concentration for the pollutant. Little data exist on the AQI's metrological reliability for AQI and IAQI. Only in the EPA Air Program undertaken at Cornell University [26] is there a previous review of the quality assurance requirements for AQI.

2.6. The Representative VOCs for Indoor Environment

The time when IAQ studies focused on a class of contaminants referred to as volatile organic compounds (VOCs) is bygone. The analytical methodology available was the primary basis for this focus, but the recent broadening of analytical methods has led to growing realization that other compounds (i.e., SVOCs) beyond traditional VOCs are implicated in IAQ problems. The choice of VOCs remains a challenge in IAQ assessment. Moreover, VOCs is somewhat vague term, the definition of which is not universally agreed upon. It has been defined in terms of vapor pressures and boiling points, as well as molecular chain lengths detectable by chromatographic techniques. Due to the complexity of VOC emission profiles, it is tempting to simplify the analysis and reporting of emissions by grouping all detected compounds together. The first problem with this approach is that individual compounds have highly variable health and/or comfort effects, the result being that concentration alone is not predictive of IAQ effects. Levels of concern vary by orders of magnitude, so a collective concentration will not correlate with IAQ. Second, VOC detection and quantification are highly method dependent. A given sampling and analysis system cannot capture or respond to all the VOCs present in any indoor environment or in the test chamber for a given emitting material. Thus, the term "total" is misleading. The important aspect of IAQ submodel selection is the strategy defined by the US EPA as "VOCs—Total versus Target: Irritancy, Odor and Health Impact". The representative 90 target VOCs were presented by Canada's National Research Council's Institute for Research in Construction (NRG-IRC) in collaboration with several academic and governmental partners, including Health Canada. The compounds were selected based on health impact, occurrence in indoor air, known emission from building materials, as well as suitability for detection and quantification by gas chromatography-mass spectrometry (GC-MS) or high-performance liquid chromatography (HPLC). Our list of target VOCs was actually representative for indoor environment and recommended by the HealthVent project and is provided in Table 1.

2.7. Steps of ΣIAQ_{index} Calculation

After selection of the IAQ model type ($\Sigma IAQ_{quality}$ or $\Sigma IAQ_{comfort}$), the IAQ_{index} evaluation was carried out using the complex model ΣIAQ from Figure 5, which should contain the following stages.

- (a) Calculation of the total concentration of pollutants in the ventilated space or the total mass of air pollutants per m^3 , the level of which is to be reduced by the ventilation process (taking into account the ventilated volume of the room and the emissions present).
- (b) Selection of the IAQ_{index} model shape from the models defined by Equations (12)–(14), with the provision that due to the multiplication of the submodels for $IAQ(VOC_{odorous})$, the number of subcomponents of the $IAQ_{comfort}$ model will be more than five.
- (c) Processing the input data of the submodels to obtain the concentration value c_j , e.g., converting the measured OI value into a concentration value for a given pollutant c_j in $\mu g/m^3$.

- (d) Calculation of the excess concentration values for each identified contaminant (Table 2)
 $\Delta c_j = c_j - c_{ref}$.
- (e) Calculation of the sum of excess concentrations (see Table 2), $\sum \Delta c_j$.
- (f) Calculation of adjusted weights W_j for the selected model equations. $IAQ_{quality}$ and $IAQ_{comfort}$ are determined on the basis of arithmetic means or by adjusting all the values of Δc_j in a given model using Equation (10), only for groups of pollutants with similar concentration values.
- (g) Calculation of the value of the ventilating air flow for the environment described in the IAQ_{index} model in accordance with the requirements of the standard EN 16798-1:2019 (a method using the criteria for the ventilation required for the individual substance emitted) [10].
- (h) Calculation of given IAQ environmental input parameters, including concentrations of pollutants c_j assigned to submodels. The PD values from their sensory equations (Table 3) are presented as the dependence of the percentage of persons dissatisfied $PD = f(c_j, \dots)$, from one of the formulas from Table 3, in order to determine this function.
- (i) Selection of the $\sum IAQ_{quality}$ model equation (with weights $W_1, W_2,$ and W_3) or the $IAQ_{comfort}$ model equation (with weights W_1, \dots, W_5 or more) and calculation from Equation (13) of the value with adjusted weights, followed by multiplication of IAQ submodels (Equation (8)) and insertion as a term of the IEQ_{index} in Equation (18) [34].

When selecting the $\sum IAQ_{comfort/health}$ model type, an IAQ_{index} evaluation is carried out using the combined model $\sum IAQ$ from Figure 5, which should contain the following steps.

- (a) Calculation of the total concentration of pollutants $\sum c_j$ in the ventilated space or the total mass of air pollutants per m^3 , the level of which is to be reduced by the ventilation process (taking into account the ventilated volume of the room and the emissions present).
- (b) Choosing the IAQ_{index} model (12) from among the models defined by Equations (12)–(14), with the provision that by multiplying the $IAQ(VOC_{non-odorous})$ submodels, the number of subcomponents of the $IAQ_{comfort/health}$ model will be more than seven.
- (c) Processing of submodel input data to obtain concentration values c_j in $\mu g/m^{-3}$.
- (d) Calculation of excess concentration values for each pollutant identified (Table 2) using $\Delta c_j = c_j - c_{ref}$.
- (e) Calculation of the sum of excess concentration values for submodels 1–7 via $\sum \Delta c_{1 \dots 7}$.
- (f) Determination of the adjusted weights $W_{1, \dots, 7}$ for the equation of the $IAQ_{comfort/health}$ model on the basis of arithmetic means or by adjusting all the values of Δc_j in a given model using Equation (10), only for groups of pollutants with similar concentration values.
- (g) Calculation of the values of the ventilating air stream from the total concentration of indoor air pollutants $\sum c_j$ (for instance, Reference [42]), for the environment described by the $\sum IAQ_{index}$ model (Figure 5) in accordance with the requirements of the EN 16798-1:2019 standard for the individual substances emitted and using an alternative method when the concentration in the room has stabilized.
- (h) Calculation of the given IAQ input parameters, including concentrations of all pollutants, c_j , assigned to the submodels. The PD values are taken from their sensory equations (Table 3) depending on the percentage of persons dissatisfied, $PD = f(c_j, \dots)$, or selected from the formulas for determining this function given in Table 3.
- (i) Development of $IAQ_{PM2.5}$, IAQ_{PM10} , and $IAQ_{non-odorous}$ submodels. When it is planned to use the indoor air quality index scale IAQI or a similar scale, it is necessary to convert these to PD^* values in %, in two steps: (1) by reading from the standard curves of the $IAQI = f(c_j)$ all IAQI values for the determined (measured) $VOC_{non-odorous}$ concentration values and using the converted scale calibration curve, $PD = f(IAQI)$, by reading from the recalibration curve (Equation (16)), the $PD = f(c_j)$ values on the dissatisfaction rating scale from zero to 100 in %, according to Footnote 7 in Table 3.

- (j) Calculation of IAQ values for P_j pollutant submodels from Equation (8) and insertion into the model equation $\sum IAQ_{\text{comfort/health}}$ (14) (with weights W_1, W_2, \dots, W_7 or more).

2.8. The IEQ Assessment Equation with $\sum IAQ$ As a Subcomponent

The proposed IAQ model can be a substantial component of the IEQ model; for example, in the case study shown later in the article. The indoor environmental quality index refers to the quality of a building’s environment with respect to the occupants’ satisfaction in %. The morphology of the IEQ_{index} model used to assess buildings, to determine as an IEQ component the IAQ_{index} and to determine other subcomponents TC_{index}—thermal comfort, ACC_{index}—acoustic comfort and L_{index}—light quality based on measurements of physical properties in each of the submodels—in accordance with the scheme of the Piasecki–Kostyrko model, is presented in Figure 6 [22].

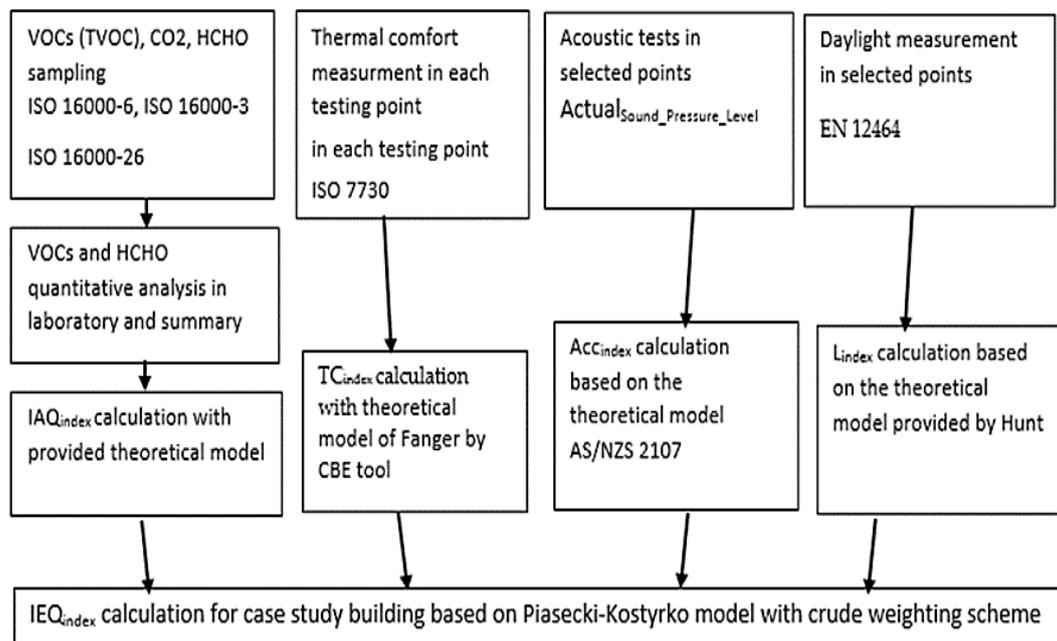


Figure 6. The research steps necessary to determine the IEQ_{index} for buildings, including physical and design parameters of buildings and subcomponent models.

The EN 16798-1:2019 is the reference for IEQ model creation [22,33]. The standard allows complex indoor information to be presented as one overall indicator of indoor environmental quality of the building—IEQ_{index}. The model reliability, including the uncertainties of measurements and data for this model, was discussed clearly in Reference [34], where the authors also presented the internal incongruity in the IEQ model structure and the justification for using the crude weights method for each subcomponent. Originally, the IEQ model was expressed as a polynomial equation consisting of four terms by Wong [43]. The IEQ_{index} is composed of the following subcomponents (SI_i): thermal comfort (TC_{index}), indoor air quality (IAQ_{index}), acoustics (ACC_{index}), and lighting quality (L_{index}). Multiplying their weights, W_i , leads to Equation (17).

$$IEQ_{index} = \sum W_i \cdot SI_i \tag{17}$$

The authors adopted the crude weighting system, where all elements are weighted in the same way (0.25 for W_1 – W_4), as shown in Equation (18).

$$IEQ_{index} = 0.25 \cdot TC_{index} + 0.25 \cdot \sum IAQ_{index} + 0.25 \cdot ACC_{index} + 0.25 \cdot L_{index} \tag{18}$$

As a consequence of the equation, the subcomponents SI_i (the predicted percentage of those satisfied) can be calculated using Equation (19).

$$SI_i = 100 - PD(SI_i) \tag{19}$$

where PD is the predicted percentage dissatisfied (PPD) and $PD(SI_i)$ is the percentage of persons dissatisfied with the IEQ subcomponent (SI_i) level. The authors' simulations for IEQ_{index} sub-indices and preliminary metrological analysis of the overall IEQ model fitting were performed with Monte Carlo tests.

It is easy to show that the standard deviations of these values are equal:

$$SD(SI_i) = SD(PD(SI_i)) \tag{20}$$

2.9. A Case Study of a Building

The experimental part of this study was performed simultaneously with the BREEAM certification process, including determination of the three primary IAQ pollutants: formaldehyde concentration, CO₂, and VOCs in the indoor air [22]. The building is a high tower, made of a convex concrete–steel structure with a glass facade. The basic information on the assessed building is presented in Table 4. At the time of the test, the building had a standard empty office without furniture (so-called pre-occupancy stage). The walls were plastered and painted, the suspended ceilings were in place, and the floors were finished with synthetic carpets. All building installations were active, including the mechanical ventilation controlled by the Building Management System BMS system with zonal CO₂ concentration sensors. The building was tested a few days after the formal end of finishing works. The tests were made on the 55th and 47th floor.

Table 4. Information on the building in the case study.

Office Building Certificate	Facade View	Indoor View	Life-Stage	Number of Floors	Net Area (m ²)	IAQ Assessed	
						Area (m ²)	Number of Floors
BREEA Mexcellent			pre-occupant	49	59,000	3000	2

Measurement points in the building were determined based on the analysis of frequencies of designed occupancies of the room and interior finish standards (open spaces). The sampling plan was prepared with the BREEAM assessors conducting the certification process of the facility. The main focus was on the IAQ index of open spaces in which the largest number of people may reside, and these represent the largest occupied usable floor space. According to the detailed design project documents, the building emphasizes the use of materials with known and low emission levels (BREEAM certified).

2.10. The Equipment, Measurements, and Experimental Approach

Standardized CEN and ISO analytical methods were used to determine the VOC concentrations and CO₂ and formaldehyde concentrations in the indoor air of the building. Selection of the sampling points was made with the BREEAM assessor in two representative office zones per tested floor and a minimum of two floors. The building was tested three days after formal final finishing works at the pre-occupancy stage with no users inside. For this office building, the tests were conducted on the 55th and 47th floors. Air samples were collected using an active sampling procedure with an electronic mass flow controller, which controlled the air flow (10 dm³/h for VOC tests and up to 30 dm³/h for formaldehyde tests). Indoor samples were set up in selected representative office locations, approximately 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 and ISO 16000-3:2011 standards. The VOCs were assessed using tubes filled with Tenax adsorbent. Then, they were thermally desorbed using a thermal desorption apparatus (TD-20, Shimadzu, Tokyo, Japan). The process of separation and analysis of volatile compounds was achieved using a gas chromatograph equipped with a mass spectrometer (GC/MS) (model: GCMS-QP2010, Shimadzu, Tokyo, Japan). The following GC oven temperature program was applied: initial temperature 40 °C for five min, 10 °C per min to 260 °C, and the final temperature of 260 °C for 1 min. The 1:10 split ratio injection mode was applied. The method used has a limit of quantification of 2 µg/m³. The volatile compounds were identified by comparing the retention times of chromatographic peaks with the retention times of reference compounds and by searching the NIST data base (National Institute of Standards and Technology, Gaithersburg, MD, USA) mass spectral database. Identified compounds were quantified using a relative identification factor obtained from standard solution calibration curves. 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 via cassettes using a solid absorbent silica gel coated with 2,4-dinitrophenyl hydrazine (2,4-DNPH), and then subjected to a laboratory test using high-performance liquid chromatography (HPLC) with UV-Vis detection (Dionex 170S, Dionex, Sunnyvale, CA, USA) and an isocratic pump (Dionex P580A, Dionex, Sunnyvale, CA, USA). The described method has a limit of quantification at 2 µg/m³.

Other IEQ_{index} components were tested as follows. The acoustic tests confirming the designed values were carried out by the measurement of the equivalent sound levels, LA_{eq}, in the selected locations. The measurements were carried out during the daytime (starting at 11:00). The following equipment was used for the measurements: Brüel&Kjær 4231 acoustic calibrator (Brüel&Kjær, Nærum, Denmark), Nor-121 analyzer (Norsonic, Tranby, Norway), Brüel&Kjær 4165 measuring microphones (Brüel&Kjær, Nærum, Denmark), analyzer with microphone Norsonic-140 (Norsonic, Tranby, Norway). Before the tests were carried out, the calibration of the measuring path was conducted in accordance with the instructions to “check the acoustic measurement channel”. The test results were evaluated in relation to the requirements considering permissible sound levels A in rooms intended for human dwellings. Thermal environmental measurements were provided using the microclimate multifunctional instrument HD32.1 and the tests were in accordance with ISO 7726 and ISO 7730. VOCs were tested simultaneously at all points. Visual comfort (Hea 01) was confirmed by using a MAVOLUX 5032C instrument (USB version) with a 3C15683 detector (Gossen, Nürnberg, Germany), in accordance with EN 12464 provisions.

2.11. Additional Explanations

The adaptation of the IAQ model to a practical casestudy was mainly for illustrative purposes in the context of the presented IAQ calculation/aggregation method. We did not focus deeply on discussing the technical or environmental issues of the presented building. Other IEQ subcomponents, such as thermal, acoustic, and visual satisfaction (in %), used to determine the IEQ index, were experimentally determined and partly presented in References [22,33]. Authors do not focus on these results in this article, as they have already been discussed in other papers [22].

3. Results

3.1. Results for the IAQ_{index} and IEQ_{index} Prediction

A previous publication of ours [22] reported on IEQ and IAQ building assessments for a larger number of BREEAM buildings, where IEQ was assessed without calculating the combined \sum IAQ index. The combined model of the \sum IAQ_{index} presented in this paper had not yet been previously developed, and we were limited in determining the IEQ_{index}, thus we only took into account two of the most well-known pollutants (i.e., CO₂ and TVOC) separately. The assessment of the IEQ index was made by adaptation of the measured parameters (complying with the draft EN 16798-1:2019 standard for indoor

environments) as the input values for the submodels of the IEQ_{index}. The input values for the case study are presented in Table 5, which provides the input data for determining the IEQ_{index} sub-indices of thermal comfort (TC_{index}), indoor air quality (IAQ_{index}), acoustics (AC_{index}), and lighting quality (L_{index}) for an office building (47th floor) three days after completion of the finishing work before users were allowed in the building (i.e., pre-occupancy stage).

Table 5. Physical parameters ¹ and IEQ_{index} results calculated using Equation (9) separately for an IAQ_{index} with internal air pollution of CO₂ and an IAQ_{index} with internal TVOC air pollution, assuming a realistic uncertainty of parameter measurement for the case study of a building (47th floor; open space) three days after the completion of finishing works.

Sub-Index	Sub-Index PD(SI _i) Models	Input Values	Sub-Index (Satisfied) and ±SD
TC _{index}	PMV (Fanger-CBE-ISO 7730) PMV = f(t _a , t _r , v _a , p _a , M, I _{cl}) PD _{TC} = f(PMV)	I _{cl} 0.55 clo t _a 24.0 °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·exp(-15.15·C _{CO2} ^{-0.25})	450 ppm	85.2% ± 0.6%
	PD _{IAQ(TVOC)} = 405·exp(-11.3·C _{TVOC} ^{-0.25})	787 µg/m ³	52.0% ± 18.0%
AC _{index}	PD _{ACc} = 2·(Actual _{Sound_Pressure_Level} (dB(A)) -Design _{Sound_Pressure_Level} (dB(A))) Actual (background) noise level 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 variant with c _{CO2} as an IAQ _{index} parameter IEQ _{CO₂} = 92.2% ± 5.8% ¹			
IEQ _{TVOC}	Second variant with c _{TVOC} as an IAQ _{index} parameter		IEQ _{TVOC} = 80.1% ± 10.7%

¹ The IEQ and its measurement's uncertainty (with subcomponent standard deviation values) were calculated for IEQ physical parameter values, where 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} is the clothing insulation (clo). In addition, c_{CO2} is the concentration in ppm, c_{TVOC} is the highest observed TVOC concentration in µg/m³, actual noise is in dB(A), and E_{min} is the minimum daylight illuminance (lux).

3.2. Results for the ΣIAQ_{index} and IEQ_{index} Assessment Including Identified Pollutants (CO₂, TVOC, and HCHO)

The example of a modified calculation of the collective submodel ΣIAQ_{quality} for three basic pollutants, as a component of the IEQ model for determining one project value for this indicator, is provided in two variants. The first variant uses sub-indices of IAQ for two pollutants, CO₂ and TVOC, which are described in Table 5, as well the sub-index of the third pollutant, HCHO (according to Reference [47]), where these differences in the approaches mean one must combine them into one submodel ΣIAQ in order to be used in IEQ calculation. The second variant uses submodels of IAQ for TVOC and HCHO pollutants based on the IAQI system [30] and then converts them into percentages of persons dissatisfied PD* in %. According to the diagram of the model ΣIAQ from Figure 5 and using Equation (12) of the ΣIAQ_{quality} model, the submodel weights are calculated as follows.

W_{CO₂} for the submodel IAQ(CO₂) = 0.5 is a component of the polynomial:

$$\sum \text{IAQ}_{\text{quality}} = 0.5 \cdot \text{IAQ}(\text{CO}_2) + 0.5 \cdot \text{IAQ}(\text{VOC}) \tag{21}$$

W_{VOC} for submodel IAQ(VOC) = 0.5 is a weight for combined submodel of the polynomial:

$$IAQ(VOC) = W_{TVOC} \cdot IAQ(TVOC) + W_{HCHO} \cdot IAQ(HCHO) \tag{22}$$

with the terms W_{TVOC} and W_{HCHO} calculated from Equation (14) using the measured values c_j (actual concentration of TVOC and HCHO) and the reference values c_{ref} (Table 6).

Table 6. Calculation of the weights of the W_{TVOC} and W_{HCHO} values for the two sub-indices of the combined IAQ(VOC) model.

Sub-Index	Input Value c_j	Input ¹ Value c_{ref}	Excess Concentration Δc_j	W_j
IAQ(TVOC)	787 $\mu\text{g}/\text{m}^3$	300 $\mu\text{g}/\text{m}^3$	487 $\mu\text{g}/\text{m}^3$	0.96
IAQ(HCHO)	18 $\mu\text{g}/\text{m}^3$	0	18 $\mu\text{g}/\text{m}^3$	0.04

¹ EN 16798-1:2019 for a very low-pollution building.

In our case study, the value of the submodel IAQ weight for the model (HCHO) ought to also be calculated from the measured value and the reference value c_{ref} . However, formaldehyde is an unusual pollutant because, although it belongs to VOC_{odorous} compounds, the concentrations found in buildings are many times lower than the HCHO threshold $c_{th} = 300 \mu\text{g}/\text{m}^3$ according to the WHO [7] and lower than the threshold concentrations of HCHO from 60 $\mu\text{g}/\text{m}^3$ to 70 $\mu\text{g}/\text{m}^3$ issued in 2013 by the American Industrial Hygiene Association [44]. The permissible value of $c_{ref} = 100 \mu\text{g}/\text{m}^3$ is also higher than the formaldehyde concentration found in buildings, according to Reference [5] and the standard EN16798-1:2019 [10]. Therefore, the authors propose that in such a case (to avoid a negative value of Δc_j), the value modelling the reference should be taken as zero. Then, the form of the adjusted W_{HCHO} weight in the model described by Equation (11) for air with three pollutants, would be as follows.

$$W_{HCHO} = \frac{\Delta c_j}{\sum_{j=2..3} \Delta c_{2..3}} = \frac{(c_{HCHO} - 0)}{(c_{TVOC} - c_{ELV}) + (c_{HCHO} - 0)} \tag{23}$$

The results of the weights assessment for the two variants of the $\sum IAQ_{quality}$ model are presented in Table 6.

According to the diagram of the model $\sum IAQ$ from Figure 5 and Equation (8), we proposed sensory equations for the percentage of persons dissatisfied %PD* in two variants.

The submodel $\sum IAQ$'s first variant includes the following:

1. The IAQ submodels used so far in References [22,33] for CO₂ and TVOC pollutants, as shown in Table 5;
2. The IAQ submodel for formaldehyde, using two types of equations depending on the range of HCHO concentrations measured in the building. Formaldehyde concentrations in the air with values above the threshold concentration, c_{th} , for its odor, i.e., above 60 or even 300 $\mu\text{g}/\text{m}^3$, can be used to create IAQ submodels for rooms with volatile and aromatic VOC compounds as well as for the HCHO equation [50].

$$PD_{HCHO} = \frac{\exp(2.14 \cdot OI - 3.81)}{\exp(2.14 \cdot OI - 3.81) + 1} \tag{24}$$

However, in the case study building, the maximum concentration of HCHO was 18 $\mu\text{g}/\text{m}^3$ and, therefore, its concentration in the air was several times lower than the concentration of the odor threshold, c_{th} [44]. The intensity of the formaldehyde odor was undetectable under these conditions, and the sensory equation $PD = f(OI)$, which is appropriate for sensory detection of IEQ, is not applicable for odors below the threshold. Therefore, for small concentrations, we proposed the use of the equation

taken from the work of Zhu and Li [47] based on the analysis of “health effects on the human body”, derived from “indoor air quality comfort evaluation experiments and the literature”.

$$PMV_{HCHO} = 2 \log \frac{c_{HCHO}}{0.01} \quad (25)$$

This equation links the value of the new unit “the effect of formaldehyde on human comfort”, called PMV_{HCHO} , with its c_{HCHO} concentration ($\mu\text{g}/\text{m}^3$) in the air. It covers the range from $10 \mu\text{g}/\text{m}^3$ to $320 \mu\text{g}/\text{m}^3$ and, as declared by the authors, this value has the same nature as PMV thermal comfort, which can be converted into a $PD\%$ unit according to the formula in Reference [48], experimentally confirmed for nearly zero energy buildings (NZEBS) by Reference [58].

$$PD_{HCHO} = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2) \quad (26)$$

The submodel Σ IAQ’s second variant includes the following.

- i. The IAQ(CO_2) submodel used so far for CO_2 pollution, as shown in Table 5.
- ii. The IAQ submodels for TVOC and HCHO types of pollution used as indoor air quality index ratio values borrowed from the IAQI system [30], which are then converted into percentages of persons dissatisfied (PD^* in %) in the following way
 - (a) The reference curves of $IAQI = f(c_j)$ [30] for two dependencies of the IAQI index on TVOC and HCHO contamination values must be reconstructed. On the y -axis are the IAQI index values from zero to 200 in the range from “no risk” to “unhealthy” and on the x -axis, the c_j values are presented.
 - (b) In accordance with the measured values of c_{TVOC} and c_{HCHO} , the values $IAQI_{TVOC}$ and $IAQI_{HCHO}$ are determined from the functions $IAQI_{TVOC} = f(c)$ and $IAQI_{HCHO} = f(c)$.
 - (c) Based on the IAQI system parameters [30] given in Footnote 6 of Table 3, which are presented as data for the functions for indexes, the $IAQI_{TVOC}$ and $IAQI_{HCHO}$ values appropriate for the break points in perceived pollution concentration values are calculated in a range from zero (good) to 200 (unhealthy) using the ordinal scale $IAQI = f(c)$ [27]. This function was converted to $IAQI_{TVOC}$ and $IAQI_{HCHO}$ scales using the concentration function scales $PD^*(TVOC)$ and $PD^*(HCHO)$ in the PD^* range from 0 to 100% (Figure 8).
 - (d) The data used for calculation and conversion of IAQI and PD^* scales are presented in Table 7.
 - (e) Based on data determined for the new converted scales (Table 7) for the percentage of persons dissatisfied ($PD^*(TVOC)$ and $PD^*(HCHO)$ concentration functions), the $PD^*(c)$ working graphs were drawn (Figure 7). (To harmonize the concentration scale of pollutants on the y -axis, c_{HCHO} values multiplied by 10 were applied.)
 - (f) The interpolation of the percentage of persons dissatisfied ($PD^*(TVOC)$ and $PD^*(HCHO)$) in % for the measured values of pollution concentrations in the air must be made using the graph from Figure 7 or using Equation (16) [31].

Table 7. Recalculation and conversion of IAQI value scales.

PD* Value	IAQI Value	Evaluation	c_{TVOC} -TVOC (1 h)		c_{HCHO} -HCHO (1 h)	
			ppm	$\mu\text{g}/\text{m}^3$	ppm	$\mu\text{g}/\text{m}^3$
0	0	No risk	0	0	0	0
25	50	Good	0.3 ¹	300	0.01 ²	12.3
50	100	Moderate	0.9	900	0.04	49.1
75	150	Unhealthy for sensitive	3.0	3000	0.10	122.8
100	200	Unhealthy	4.6	4600	0.75	921.0

¹ Conversion factors TVOC: 0.3 ppm corresponds to 300 $\mu\text{g}/\text{m}^3$ [44]. ² Conversion factors HCHO: 1 ppm corresponds to 1228 $\mu\text{g}/\text{m}^3$ [44].

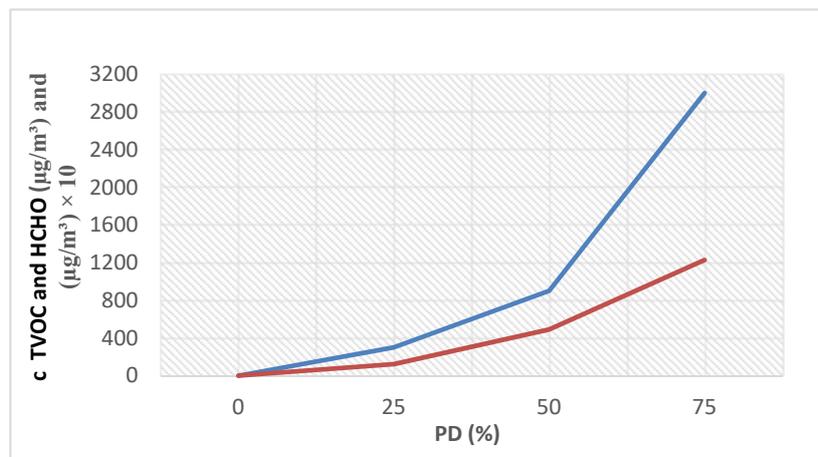


Figure 7. The percentage of persons dissatisfied function of TVOC (blue line) and HCHO (brown line) versus concentration.

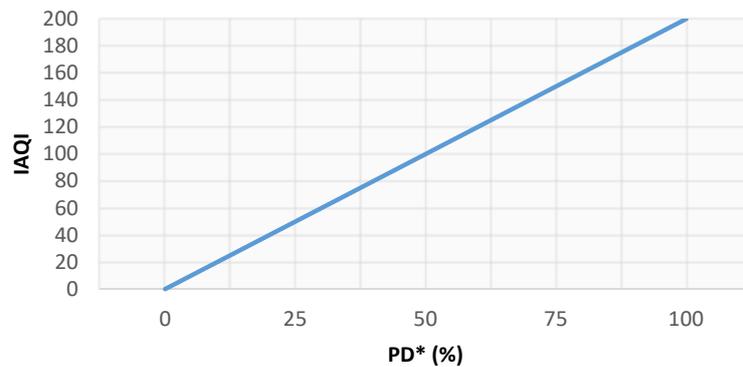


Figure 8. Percentage of persons dissatisfied, %PD*, in relation to IAQI values.

In the context of the results for the overall IEQ model index when treating both the main pollutants CO₂ and TVOC separately, we present in Table 8a the transformed IEQ calculations with the sub-indices \sum IAQ. The results for the individual case study building IAQ subcomponents are taken from Table 5 (for $c_{TVOC} = 787 \mu\text{g}/\text{m}^3$ and $c_{HCHO} = 18 \mu\text{g}/\text{m}^3$ [22]). The IEQ index with \sum IAQ_{quality} values was calculated using two variants—the first conventional and the second borrowed from the IAQI scale [30] (Table 8a).

Standard deviations for each concentration are provided in Table 8b.

Table 8. (a) Physical parameters (Footnote ¹ in Table 5) and IEQ results calculated from Equation (9) with Σ IAQ; assuming realistic uncertainty of parameter measurements for the case study building (47th floor; open space) a few days after completion of the finishing works. (b) Measured pollutant concentrations *c* and standard deviations SD(*c*).

(a)			
Sub-Index	Sub-Index PD(S ₁) Models	Input Values	Sub-Index (Satisfied) and ±SD
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	90.0% ± 3.2%
Σ IAQ _{index} (1) Sub-indices First variant	$PD_{IAQ(CO_2)} = 395 \cdot \exp(-15.15 \cdot C_{CO_2}^{-0.25})$	$c = 450$ ppm	85.2% ± 0.6%
	$PD_{IAQ(TVOC)} = 405 \cdot \exp(-11.3 \cdot C_{TVOC}^{-0.25})$ $PMV_{HCHO} = 2 \log \frac{c_{HCHO}}{0.01}$	$c = 787$ µg/m ³	52.0% ± 18.0%
	$PD_{HCHO} = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)$	$c = 0.018$ mg/m ³	65.8% ± 10.7%
Σ IAQ _{index} (1)	$IAQ_{VOC} = 0.96 \cdot IAQ_{variant1}(TVOC) + 0.04 \cdot IAQ_{variant1}(HCHO)$ $\Sigma IAQ_{index}(1) = 0.5 \cdot IAQ(CO_2) + 0.5 \cdot IAQ_{variant1}(VOC)$		53.0% ± 17.3%
			69.1% ± 9.0%
Σ IAQ _{index} (2) Sub-indices ¹⁾ Second Variant	$PD_{IAQ(CO_2)} = 395 \cdot \exp(-15.15 \cdot C_{CO_2}^{-0.25})$ PD^*_{TVOC} read from the graph with $PD^*_{TVOC} = f(c_{TVOC})$ or determined from Equation (16)	$c = 450$ ppm $c = 787$ µg/m ³ ± 18%	85.2% ± 0.6%
	PD^*_{HCHO} read from the graph with $PD^*_{HCHO} = f(c_{HCHO})$ or determined from Equation (16)		54% ± 13.8%
	SD for c_{TVOC} and c_{HCHO} at “break points” ± 12%	$c = 18$ µg/m ³ ± 12%	71.1% ± 11.0%
Σ IAQ _{index} (2)	$IAQ_{VOC} = 0.96 \cdot IAQ_{variant2}(TVOC)$ $+ 0.04 \cdot IAQ_{variant2}(HCHO)$ $\Sigma IAQ_{index}(2) = 0.5 \cdot IAQ(CO_2)$ $+ 0.5 \cdot IAQ_{variant2}(VOC)$		54.7% ± 13%
			70.0% ± 6.5%
ACC _{index}	$PD_{ACC} = 2 \cdot (\text{Actual}_{\text{Sound_Pressure_Level}}(\text{dB(A)}) - \text{Design}_{\text{Sound_Pressure_Level}}(\text{dB(A)}))$ Actual (background) noise Design sound level	55 dB(A) 45 dB(A)	80.0% ± 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% ± 9.0%

Table 8. Cont.

Sub-Index	Sub-Index $PD(S_i)$ Models	Input Values	Sub-Index (Satisfied) and $\pm SD$							
IEQ _{index(1)} with $\sum IAQ_{index(1)}$ meas. IEQ _{index(1)} $\pm SD$	$IEQ_{index} \pm SD = W_1 \cdot TC_{index} + W_2 \cdot \sum IAQ_{index(1)} + W_3 \cdot AC_{c_{index}} + W_4 \cdot L_{index}$		84.4% \pm 3.7% $u_{meas} = 2 \cdot 3.7 = \pm 7.4\%$							
overall IEQ _{index(1)} $\pm u_{overall}$ ²⁾	$\pm u_{overall}(IEQ) = \frac{(\sum (SD_{real}(PD(S_i))^2 + \sum (SD_{vote}(PD(S_i))^2))^{-2}}{IEQ_{index(1)} \pm u_{overall}}$		$u_{overall} = \pm 16.24\%$ 84.4% \pm 16.24%							
IEQ _{index(2)} with $\sum IAQ_{index(2)}$ meas IEQ _{index(2)} $\pm SD$	$IEQ_{index} \pm SD = W_1 \cdot TC_{index} + W_2 \cdot \sum IAQ_{index(2)} + W_3 \cdot AC_{c_{index}} + W_4 \cdot L_{index}$		84.6% \pm 3.3% $u_{meas} = 2 \cdot 3.3 = \pm 6.6\%$							
overall IEQ _{index(2)} $\pm u_{overall}$ ²⁾	$\pm u_{overall}(IEQ) = \frac{(\sum (SD_{real}(PD(S_i))^2 + \sum (SD_{vote}(PD(S_i))^2))^{-2}}{IEQ_{index(2)} \pm u_{overall}}$		$u_{overall} = \pm 16.15\%$ 84.6% \pm 16.15%							
(b)										
	c_{mes}	SD(c_{mes})	c_H	SD(c_H)	c_L	SD(c_L)	PD*_H	SD	PD*_L	SD
TVOC	787	18% \Rightarrow 141.7	900	12% \Rightarrow 108	300	12% \Rightarrow 36	50	12%	25	12%
HCHO	18	12% \Rightarrow 2.16	49.1	12% \Rightarrow 5.89	12.3	12 \Rightarrow 1.48	50	12%	25	12%

¹⁾ The method of calculation of mean values PD^* and $\pm SD(PD^*)$ for TVOC and HCHO is based on Equation (16) and takes the form (27).

$$PD^* = \frac{(PD^*_H - PD^*_L)}{(c_H - c_L)} \times (c_{meas} - c_L) + PD^*_H \tag{27}$$

Concentrations c and $SD(c)$ are in $\mu g/m^3$; PD^*_H , PD^*_L , and $SD(PD^*)$ are in %, and standard deviations of the HCHO concentration of 12% was adopted on the basis of reports from IAQ research conducted as part of BREEAM in 2016 [22]. The assumptions were that c_H and PD^*_H are the coordinates of the upper break point (i.e., high break point) of the converted scale $PD^* = f(c)$, and c_L and PD^*_L are the coordinates of the lower break point (i.e., low break point) of the converted scale $PD^* = f(c)$. Standard deviations were assumed for c_{meas} , c_{TVOC} , and c_{HCHO} as well as for $PD^* = \pm 12\%$, as this is half of the transformed segment of the scale, which according to Table 7 covers a range of 25% of PD^* , with one perceived category of air quality, e.g., “no risk” or “moderate”. Therefore, the maximum standard deviation was 12.5% and, according to the literature on AQI and IAQI values, it should be rounded to a total value. ²⁾ $SD_{vote}(PD(S_i))$ from the $\pm u_{overall}(IEQ)$ equation was the standard deviation of a probability distribution of an each. $(S_i)_{vote}$ and was calculated primary using the $PD(S_i)$ equation calibration curve [34].

4. Discussion

4.1. Discussion of the $\sum IAQ_{index}$ Theoretical Model

For years, the authors, as accredited laboratory personnel, have conducted IAQ pollution tests in indoor environments for various applications. Based on our experience, it was concluded that the general approach to assessing combined IAQ has not yet been systematized and that there is a global tendency to assess individual IAQ parameters separately or to group them without a justified aggregation method. This is not a good situation from the point of view of building users' needs. This, in our opinion, may lead to incorrect IAQ interpretations in specific building situations. In the context of analyzing the problem in this paper, authors presented a summary of the state-of-the-art methods and also provided a new approach for solving some of these problems. As presented, it is possible to create a $\sum IAQ$ index aggregating the results of indoor air analyses, taking into account various representative pollutants. Three levels of comprehensive air quality assessments (with three, five or seven subcomponents), depending on the application of the assessment, were proposed, together with step-by-step procedures. This may be practical, as shown in the evaluation of a case study on a building. We originally selected the main IAQ subcomponent equations and user satisfaction dependences, $\%PD = f(c_j)$, and provided them all in one place (Table 3). We then proposed and justified the weighting schemes for the IAQ total equation. In most of the studies in the literature, the weighting schemes used for IEQ or IAQ assessments are not physically justified or explained. There are known methods of weighting sub-indices, but the problem that was solved in this paper was an effective system for weight adjustments. For the construction of the combined model IAQ_{index} , with a weighting scheme useful for aggregating sub-indices, we proposed the model scheme presented in Figure 5. According to the results, the advantage of the complex model $\sum IAQ_{index}$, in which the input quantities always constitute concentrations of given pollutants, is the ability to use these concentrations to calculate excess pollution concentrations from Equation (10) and generate weighting schemes W_1, \dots, n for all three models by adjusting the weights based on the concentration values of excess air pollutants to a value ≤ 1.0 for each IAQ_{index} model. The Δc_j values determine the masses of pollutants that must be removed by ventilation to eliminate the target pollutant effect. They can be determined as differences between the current concentrations of pollutants and the concentration of pollutants at the reference or standard level (e.g., c_{ELV} or c_{LCI}), and in the case of $VOC_{odorous}$, the odor threshold c_{th} . The presented approach may allow planning of air quality for the building.

As discussed, it is important to identify those VOCs with comfort, health, and impacts and focus on the IAQ sub-model choice aspect, briefly defined as the strategy "VOCs—Total vs. Target: Comfort, Irritancy, Odor, and Health Impact". The model from Figure 5 has uniform inputs, i.e., concentration levels c_j and two outputs: (1) weighed (adjusted) and (2) sensory equations, $PD^* = f(c_{TVOC})$, constituting the IAQ submodel equations. These second outputs of submodels (PD^* values) are coefficients of satisfaction from the comfort sensation or lack of "health risk". These are the terms of the equation describing "combined $\sum IAQ$ ", which meets the requirements of the abovementioned strategy of selecting IAQ sub-models related to IAQ components that have the most impact on the resulting IEQ perception.

Models for subcomponents of IAQ not perceived by humans but influencing health are recommended to be used from the index set in the AQI system [26–28], which was adapted by the authors to assess the quality of indoor air based on, and in accordance with, the concepts of the air quality assessment system used globally by the American EPA. In the context of the subcomponent of the TVOC concentration in Figure 7, the authors provided the relationships of $PD^* = f(c_{TVOC})$ based on Jokl research [49] and resulting from the IAQI scale [30] as converted by the authors. The relationship between PD^* and TVOC concentration in both approaches is strongly correlated, as shown in Figure 9.

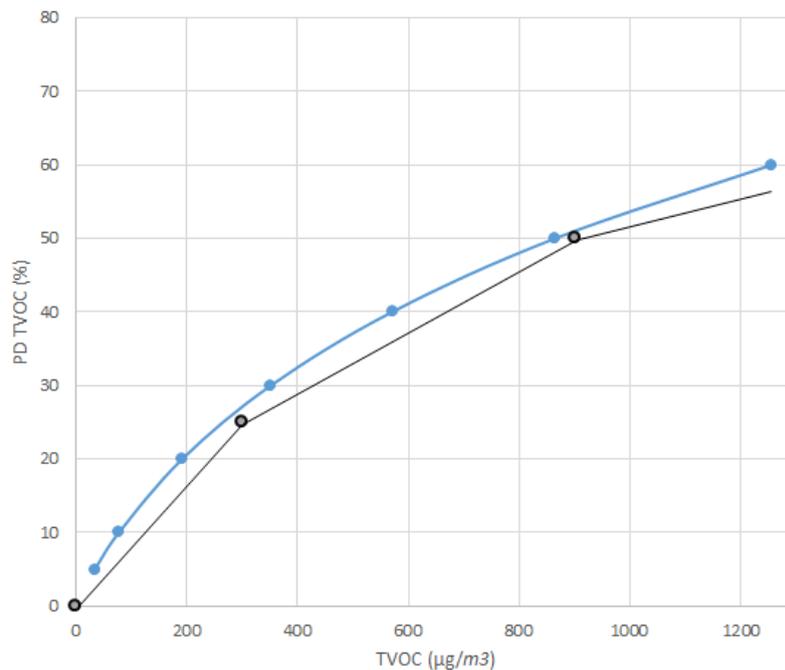


Figure 9. PD_{TVOC} based on conversion from IAQI to the PD^* scale and study of Weber-Fechner theory.

The curves obtained from the conversion confirm Jokl's predictions provided in [49] and previously accepted idea. However, the final confirmation of these curves will be done experimentally as panel tests, as planned by the authors for the near future.

4.2. Discussion of Results for the Case Study on a Building

The experimental study was performed in a BREEAM certified building, and included the determination of formaldehyde concentration, CO_2 , and VOCs in the indoor air. The example calculation of the combined $\sum IAQ$ model for three basic pollutants, as components of the IEQ_{index} model, is presented in two variants but the calculated PD^*_{TVOC} values obtained with both calculation methods were very similar. The first variant of $\sum IAQ$ calculation used $\%PD = f(c_j)$ curves in $\%$ sub-indices of IAQ for three pollutants, and the differences in approach in Tables 5 and 8a meant combining them into one IEQ submodel: the $\sum IAQ$ model intended for the IEQ calculation. The second variant used submodels of IAQ for TVOC and HCHO pollutants based on the IAQI system [30] which were then converted into percentages of persons dissatisfied (PD^* in $\%$).

The first conclusion is that CO_2 concentration cannot be used separately for the IAQ_{index} assessment, especially at the pre-occupancy stage (Table 5). The building was polluted with VOC emissions and HCHO from the construction products directly after finishing works were completed.

The authors confirmed that all three pollutions should be a simultaneously integrated part of the IAQ model, because the importance of TVOC is much greater, representing the main source of pollution—the construction and finishing materials.

According to the results, we recognized two variants of the combined $\sum IAQ_{index}$ calculation. For the first variant [22], the combined $\sum IAQ$ index of satisfied users was 69.1% and, for the second variant (new approach with converted AQI index), the $\sum IAQ$ index was 70.0% satisfied. The results of the $IEQ_{index}(1)$ (for Variant 1) were within the interval of combined overall uncertainty, $\pm 16.24\%$, and the results of the $IEQ_{index}(2)$ (for Variant 2) were that the overall uncertainty was $\pm 16.15\%$. Therefore, the result was convergent, which confirms the credibility of the proposed approach.

The results obtained also showed that, in the period immediately after completion of finishing works in indoor spaces, there may be a temporarily increased concentration of TVOC, which systematically decreases over time, as we have shown in other papers. In the case of a building, the research showed that

tests carried out immediately after finishing works gave results that significantly exceeded the BREEAM limits for TVOC at $300 \mu\text{g}/\text{m}^3$ (twice as high). It should be expected that an acceptable level should be reached after a minimum of one month from the completion of the work.

For correctness of the obtained calculations, the authors are conducting a model credibility analysis that will be provided in the next article—Indoor Air Quality Model Part II: The Combined Model $\Sigma\text{IAQ}_{\text{index}}$ Reliability Analysis. The model uncertainty estimate may be compromised because the model reproduces the discomfort level associated with the dominant component.

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