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Reflections on the Evidentiary Basis of Indoor Air Quality Standards

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Abstract: Buildings are expected to provide healthy and comfortable indoor environmental conditions for their users. Such conditions have diverse dimensions, including thermal, visual, air quality, auditory, and olfactory aspects. Indoor environmental quality standards, guidelines, and codes typically inform professionals in the building design and operation phase in view of procedural, contractual, and legal boundary conditions. Given this critical role of standards, it seems significant to examine the applicability and scientific validity on a regular basis. In this context, the present paper focuses on the standard-based definition of indoor air quality (IAQ) indicators and their respective values. Hence, the main aim of this effort is to study several common national and international IAQ standards in view of the scope to which they include direct or indirect evidence for the validity and applicability of their mandates and requirements. To this end, selected IAQ standards were assessed via a structured schema that includes not only basic information, quality indicators, and suggested and recommended value ranges, but also any reference to scientific studies. The findings of this effort identify certain issues with the transparency of the chain of evidence from the results of technical literature and standard-based IAQ recommendations. Moreover, recommendations are made for the development of future transparent and evidence-based IAQ standards and guidelines.

Keywords: indoor air quality; standards; scientific evidence; ventilation

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1. Introduction

1.1. On the Importance of Indoor Air Quality Conditions in View of Occupants' Requirements

The human body needs to constantly breathe in and out air for survival. The breathed air serves as a source of oxygen required to fuel life. At the same time, this air contains more elements than the required oxygen, which makes for around 21% of air. Therefore, the main interest is not related to the main part of the air, nitrogen (~78%), but to its other constituents, which are relevant to health, well-being, behavior, and productivity. These components, which constitute less than 1% of the breathed air, include, among others, CO_2,

VOCs, and particles. Moreover, anthropogenic processes such as agriculture and industrial development not only influence the composition of the air and the relative concentration levels of CO_2 and O_2, but also contribute to the emission of other potentially harmful substances [1,2]. As humans can spend a large majority of their life indoors, it is important to consider the air quality conditions in these indoor environments—mostly called indoor air quality (IAQ). There are numerous studies showing the relationships between one or more components of IAQ and the aforementioned human-related variables. For example, in a review from 2016 on the effect of IAQ on humans, Tham [3] pointed out that the main points of concern are indoor chemistry, airborne infection, and the impact on performance. Others have shown the effects of IAQ on health-related aspects [4], well-being [5], human satisfaction [6], and behavior [7].

1.2. General Reflections on the Role of Standards in Building Design and Operation

Given the importance of good IAQ in improving occupants' health, well-being, behavior, and productivity, the design and operation of buildings should include considerations about indoor air. To increase the number of buildings meeting minimum requirements, IAQ standards have been stipulated by many organizations worldwide, such as the International Organization for Standardization (ISO), European Committee for Standardization (CEN), and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The most common standards that set criteria for IAQ are ISO 17772-1 [8], EN 16798-1 [9] (successor of EN 15251 [10]), and ASHRAE 62.1 [11]. However, many other IAQ standards are used at a national or regional level—a list and comprehensive review of them may be seen in [12].

The main objective of IAQ standards is to prescribe design criteria for healthy and satisfactory indoor spaces to provide acceptable IAQ conditions for building occupants or to reduce the risk of harmful conditions. The standards can be applied for both existing and new buildings, while requirements for new buildings frequently go beyond those that have been applied to existing buildings. To reach these conditions, designers should comply with a set of requirements (e.g., minimum/maximum values, specific indicators of IAQ, such as minimum ventilation rates or maximum concentration levels of various pollutants) that are context-dependent, i.e., may change according to the building type (e.g., residential, or non-residential buildings) and ventilation type (natural, mechanical, or hybrid) [13].

The standards are commonly based on some scientific evidence and/or practical experience [12]. IAQ standards are frequently based on the results of experimental studies whereby people were asked to express the perceived air quality regarding exposure conditions (i.e., satisfaction levels). However, potential health effects are also taken into consideration [14]. Thereby, related studies written in English predominantly stem from North America and Scandinavia [15].

Recently, due to COVID-19 pandemic and the acknowledgment that the main mechanisms for the transmission of SARS-CoV-2 is via airborne particles and droplets, there have been increasing research efforts to combat the spread of indoor respiratory infections [16–21]. This led to ventilation and other recommendations for the operation of indoor spaces, which could influence future revisions of current IAQ standards.

1.3. The Need for the Provision of Evidence in Indoor Air Quality Standards

Given the prevalence of standards and their importance for building design, construction, and operation, as well as the humans residing in buildings, it would be arguably helpful if standards were formulated in a transparent and reproducible manner in terms of their underlying reasoning and evidence [22,23]. Therefore, a key question is the evidence that these standards provide to justify such recommendations or requirements. This key question contains several aspects on three levels. On a very high-transparency level, whether experts or laypeople are directly guided to the underlying evidence from the standards or whether this path is untraceable is a matter of interest. High transparency might be characterized by the direct provision of evidence (i.e., in the standard content); a

mid-way would be general references at the end of a standardization document, and low transparency might be characterized by a lack of evidentiary references. The characteristics of reproducibility of a standard have two sub-levels. First, content-wise reproducibility is related to the extent to which the referred references actually contain the evidence for the regulations and recommendations set in the corresponding standard document. Second, reproducibility can be defined in an operational matter with respect to the extent to which the standards disclose any information about the process through which the requirements were arrived at (e.g., discussions and conclusions of expert groups).

In this work, we investigate to what extent (a) direct or indirect evidence (references to technical literature) is provided in selected air quality standards (transparency), (b) the provided references contain the evidence underlying the standard (content-wise reproducibility), and (c) the standard reveals the process of its development (procedural transparency).

It should be noted that several past studies have reviewed IAQ standards in view of their coverage and consistency [14], development history [24,25], and specific ventilation requirements [26,27]. Nonetheless, a general reflective consideration of IAQ standards of the kind intended in this contribution has not previously been undertaken. Given the essential importance of IAQ standards (see Sections 1.1–1.3), such a critical reflection effort is arguably of outmost importance both for practitioners and researchers. As such, the present contribution intends to fill a perceived gap in the IAQ standards discourse domain.

2. Approach

2.1. Selection of Standards

As alluded to above, the main objective of this effort is to assess and reflect on the extent of evidentiary material provided in common IAQ standards. The intention of the papers' approach is not to conduct an exhaustive review of all indoor air quality standards internationally available. Rather, the idea is to identify a sample of typical and widely used representative standards. To this end, we provisionally selected, in a first step, several IAQ standards that appeared to be relevant to the intended assessment. Thereby, well-known international standards, as well as national standards, were considered. In a second step, the authors assessed the arguments for and against including the suggested standard within the framework of an open forum discussion.

Key arguments in favor of the inclusion of candidate IAQ standards are as follows:

- The standard provides information on: (i) known health effects of indoor air contaminants; (ii) indoor sources of air contaminants; and (iii) recommended exposure limits.
- The national standard provides prescriptive information on building design requirements including those that affect IAQ conditions.
- The standard includes thresholds and limits for pollutants, calculation of concentrations, pollutant sources, and assumptions for emissions.
- The standard offers IAQ-related definitions, ventilation rate and air distribution requirements.
- The standard includes related technical reports and/or references to research papers.

Candidate IAQ standards were not considered for further assessment if they did not include any references at all to other related standards or to relevant scientific literature.

Section 2.2, below, describes the review process of the selected IAQ standards in detail.

2.2. Standard Assessment Matrix

To systematically analyze the selected IAQ standards, an assessment matrix including five main categories was developed by means of expert discussions among the authors (see Table 1). Thereby, the following five main categories were considered:

(i) General (bibliographic) information
(ii) Basic parameters
(iii) Target design and performance variables
(iv) Evidence

(v) Usability

Table 1. Overview of the standard assessment matrix schema.

General (Bibliographic) Information	(a) Full title; (b) abbreviation; (c) publication year
Basic Parameters	(a) Geographic coverage; (b) target IEQ domain(s); (c) combined effect of multiple domains; (d) user controls addressed; (e) relevant building type(s); (f) scope (e.g., subject, purpose of the standard)
Target Design and Performance Variables	(a) Design variables; (b) design variable values; (c) design classes/categories; (d) performance variables; (e) performance variable values/ranges/functions; (f) performance classes/categories
Evidence	(a) Direct evidence for the requirements; (b) general reference to other standards; (c) specific reference to other standards; (d) general reference to technical literature; (e) specific reference to technical literature; (f) other potential evidence
Usability	(a) Effectiveness; (b) efficiency; (c) satisfaction

Within the usability category, the criteria related to effectiveness, efficiency, and satisfaction were qualitatively assessed by the authors using a four-point evaluation scale (fully agree–somewhat agree–somewhat disagree–strongly disagree). Please note that neither the previously addressed selection process of the standards nor the rather qualitative setup of the questions regarding the standards' usability was meant to represent an exhaustive endeavor. However, the collective of the co-authors involved in the assessment can in fact be argued to possess the expertise-related credentials to provide a preliminary qualitative assessment of the selected standards. This process admittedly entails a subjective component. Nonetheless, an effort was made to increase the consistency of the assessment by structured consideration of several salient aspects as applicable to each of the usability criteria. These aspects can be briefly summarized as follows:

Effectiveness:

- General effectiveness: "This standard is generally highly effective".
- Clarity of stated criteria: "This standard states the design/performance criteria in a clear and unambiguous manner".
- Flexibility: "This standard encourages the flexibility toward identifying creative and effective solutions through its entailed requirements".
- Up-to-dateness: "This standard reflects the latest state of the domain knowledge and technology".

Efficiency:

- Ease of navigation: "The relevant information is easily found in this standard".
- Accessibility of the language/material: "The language/material of this standard is easily accessible".
- Ease of compliance control: "The requirements of this standard can be readily addressed in specific projects".

Satisfaction:

- Motivation and inspiration: "This standard is highly motivational and inspires the development of good solutions".
- Non-objective, non-transparent agenda: "Agenda, other than the objective criteria, is pursued in this standard".
- Experience in the application of standard: "Studying, using and working with this standard is a positive experience."

2.3. Selection of Technical Literature

In the course of the review of the selected standards, we identified the recommended design and performance variables specified therein. For each of these recommendations,

we explored the evidentiary basis. Some standards included justifications for their recommendations. In some cases, standards referred to other standards. Regarding design or performance variables, if the standard referred to another standard or justified the recommended values based on other standards, then these latter standards were also included in the assessment matrix. Please note that, in the context of the present contribution, design variables are understood in terms of prescribed values related to building components and systems (e.g., prescribed minimum ventilation rates to be provided by the ventilation system). Performance variables, on the other hand, pertain to required conditions to be maintained in indoor environments. These are typically expressed in terms of specific thresholds (e.g., maximum concentration levels of specific pollutants).

At times, the scientific literature that was supposed to support a standard's mandate was referred to in the included general bibliography. As such, this bibliography was meant to include the entire literature relevant to the standard's content. However, specific one-to-one relations between the standard's recommendations and the purported evidence in the cited literature were not necessarily established.

If the standard referred to specific technical or scientific literature, then, subsequent to a verification step, the respective papers were included in the matrix that served the assessment process pertaining to the strength of the provided evidence. A detailed description of this assessment process is provided in Section 2.4. Please note that in certain instances, the authors were aware of literature relevant to the evidentiary basis of a standard, even though the standard did not mention the said literature. In such cases, the respective literature was also included in the evidence assessment matrix.

2.4. Evaluation of the Strength of the Provided Evidentiary Material

The evaluation of the strength of evidence was carried out in four stages by means of a dedicated matrix. An overview of the evidence assessment matrix schema is provided in Table 2. The first part of the matrix entails information about the experts who identified and evaluated the selected studies as well as bibliographic data pertaining to the studies. The second part is information on why the source was included in the matrix: which standard it refers to, in what context, and how the source was referred to. The third and fourth parts of the matrix are a description of the evidence the source describes: the method of the study, whether it was a laboratory or in situ study, the climate context, the duration of the study, the number and demographics of the participants. The fifth part of the matrix describes the data that the study collected. Half of the columns are descriptive: IEQ data, occupant-related data, and outdoor condition data, whereas the other half consists of expert ratings of the quality and resolution of these data via a qualitative scale (very high, rather high, rather low, very low). The sixth part entails a description of the data processing method as well as the treatment of the results and their interpretation using the same qualitative scale as in part five (from very high to very low).

The seventh part is a response to the question of whether the results presented had been validated using data from another, similar study. Furthermore, a two-part expert assessment of the strength of the evidence presented was included in the matrix. Based on the information gathered, the expert assessed whether the results described were consistent with the guidelines of the standard that referred to the source. This included a summary judgement in terms of a qualitative scale (strongly agree, agree, disagree, strongly disagree). This summary evaluation was supplemented in a separate column with descriptive justification. In the last column of the assessment matrix, experts could also add general comments regarding the investigated source.

Table 2. Evidence assessment matrix schema.

General Information	(a) Information on the selecting and reviewing experts; (b) information on the selected study (authors; full title; keywords; publication year)
Arguments for Selection	(a) Standard(s) which reference(s) this paper; (b) type of reference (reference included in bibliography or given as direct evidence for a requirement); (c) design variables for which the reference is relevant; (d) performance variables for which the reference is relevant
Basic Information about the Study's Design	(a) Method of the study; (b) physical context (e.g., lab, living-lab, field study); (c) climatic context; (d) date/duration of the study
Participant Information	(a) Number and gender of participants; (b) age of participants; (c) cultural/ethnic background
Collected Data Information	(a) IEQ data; (b) quality/resolution of IEQ data; (c) occupant-related data; (d) quality/resolution of occupant-related data; (e) outdoor conditions data; (f) quality/resolution of outdoor conditions data
Data Analysis Method	(a) Data processing method (e.g., statistical method, regression analysis); (b) clarity of the results and interpretation
Data Validation	Were the results validated with reference to other or similar studies in the relevant domain?
Evaluation of the Evidence	(a) Are the results consistent with the related requirements in the standard? (b) Argument(s) or reasoning for the judgement stated in the previous column

3. Findings

3.1. Overview of the Analyzed Standards and Technical Literature

This section reports on the findings of the analysis of direct and indirect evidence provided in the selected IAQ standards for the validity of their recommendations and mandates.

Overall, 13 standards were analyzed, as shown in Table 3. Whereas the selected international and European standards cover both residential and non-residential applications [8,9,11,28,29], national standards are more targeted to specific spaces such as residences [30] or workplaces [31]. The international and European standards' scope comprises building and system design, energy calculations, and partial exposure. On a national level, the focus is more specifically on system design [30] and diverse exposure limits [32].

The most important design variable in almost all standards and guidelines is the ventilation rate; international standards target ventilation flow rate per person and ventilation flow rate per floor area (to account for emissions from buildings). Residential design ventilation flow rates are given for specific room types (e.g., bedroom, bathroom, or kitchen), while the Canadian standard NR24-28/2015E [33] requires a certain outdoor air flow rate, implying that recirculation of air for heating or cooling reasons is part of the design considerations, which is not the case in all countries.

The main performance variable is the level of carbon dioxide concentration in indoor spaces. Some standards include classes depending on expectation levels [8,9,28,29]. The Canadian Residential Indoor Air Quality Guideline [32] names maximum pollutants levels (e.g., several volatile organic compounds), which can be measured during the operation phase to evaluate the indoor air quality performance of the space.

Evidentiary basis, meaning references to technical or research publications, were given in six of the overall 13 documents. Three documents only provided references to other standards or guidelines. ASHRAE guideline 10 contains a very high number of direct references to technical research publications. However, it is a guideline without direct legal relevance to design variables and performance evaluation.

ISO/TR 17772-2 [28] and CEN/TR 16798-2 [29] are the technical reports for ISO 17772-1 [8] and EN 16798-1 [9]. A technical report (TR) "gives information on the technical content of standardization work" [34]. Both TRs contain seven [28] and 35 [29] references to other standards, and two [28] and three [29] references to technical reports, but both have 23 references to research publications. The research publications of both documents are identical. Nineteen of those are related to indoor air quality based on their title. In ISO/TR 17772-2 [28], two of those IAQ-related publications are cited for matters related to the thermal environment (here: activity level and body heat loss). These are also referenced directly in the text in CEN/TR 16798-2 [29]. However, in CEN/TR 16798-2 [29], no IAQ-related references are included directly in the text. Furthermore, in ISO/TR 17772-2 [28], four references are included directly in the text serving as evidentiary basis for the person-related ventilation airflow. Two more references serve to underpin evidence for the existence of adaptation to bio effluents. Nine references appear only in the bibliography. ASHRAE Standard 62.1 [11] refers to 60 research publications, albeit only in the bibliography. Normative references are listed separately. Interestingly, even though ISO, EN and ASHRAE target IAQ for residential and non-residential buildings, they rely on different research publications. As such, no publication is referenced in both ISO/EN and ASHRAE standards. ASHRAE's bibliography reaches from 1992 to 2017, with a median publication date of 2009. EN/ISO's research references reach from 1982 to 2008, with a median publication year of 1994 [35,36].

CIBSE Guide A [37] has a long reference list, and they are referenced directly, although it was not possible to check this for all references due to their large number.

In the case of the German Rule of Workplace Ventilation [31], the rule refers only to five occupational safety and health (OSH) guidelines of the OSH insurance organizations and not to any research publications (see comments in Section 3.3).

Table 3. Analysis of selected standards (note that ST refers to standard; TR to technical reports, and RP to research publication).

Standard	Year	Geographic Coverage	Scope					Targeted Variables		References ST/TR/RP
			Residential	Non-Residential	Building/System Design	Energy Performance Calculations	Exposure Limits	Design	Performance	
ISO 17772-1 [8]	2017	International	x	x	x [3]	x [13]	x [9]	Ventilation rate per person, ventilation rate per floor area	Carbon dioxide levels (several classes)	37/7/0 [14]
EN 16798-1 [9]	2019	Europe	x	x	x [3]	x [13]	x [9]	Ventilation rate per person, ventilation rate per floor area	Carbon dioxide levels (several classes)	38/6/0 [14]
ISO 17772-2 [28]	2018	International	x	x	x [4]	x [4]	x [9]	Ventilation rate per person, ventilation rate per floor area	Carbon dioxide levels (several classes)	7/2/23 [14]
CEN/TR 16798-2 [29]	2019	Europe	x	x	x [8]	x [8]	x [9]	Ventilation rate per person, ventilation rate per floor area	Carbon dioxide levels (several classes)	35/3/23 [14]
EN 15665 [38]	2009	Europe	x	-	x	-	x	Ventilation rate, pollutant emissions	Pollutant concentration	2/0/0
ANSI/ASHRAE Standard 62.1 [11]	2019	US/international	x	x	x	-	-	Ventilation rate	Minimum ventilation rate	24/0/60
ANSI/ASHRAE Standard 62.2 [39]	2019	US/international	x	-	x [5]	-	-	Ventilation rate (bedroom, kitchen, bathrooms)	Ventilation rate	23/0/0
ANSI/ASHRAE/USGBC/IES Standard 189.1 [40]	2009	US/international	x [1]	x	x	x	-	Ventilation rate, prescriptive: materials (emissions from materials)	Sum of volatile organic compounds	131/0/0
ASHRAE Guideline 10 [41]	2016	US/international	all indoor spaces	all indoor spaces	n/a	n/a	n/a	n/a	n/a	13/0/58 [14]
CIBSE Guide A [37]	2015	UK	x	x	x	-	-	Ventilation rates [12]	Carbon dioxide levels (several classes)	101/3/114 [14]

Table 3. *Cont.*

Standard	Year	Geographic Coverage	Scope					Targeted Variables		References ST/TR/RP
			Residential	Non-Residential	Building/ System Design	Energy Performance Calculations	Exposure Limits	Design	Performance	
Residential Indoor Air Quality Guidelines [32]	2021	Canada	x	-	-	-	x [6]	n/a	Maximum pollutants' concentrations [10]	3/10/142
NR24-28/2015E [33]	2015	Canada	x	x	x [3]	-	-	Ventilation rate, maximum outdoor air flow [11]	n/a	6/2/0 [15]
ASR A3.6 [31]	2012	Germany	-	x [2]	x [7]	-	x [9]	Minimum opening area and maximum room depth, adjustability to weather conditions	Carbon dioxide levels	0/5/0

[1] Above 3 stories [2] Workplaces and related places [3] Thermal environment, indoor air quality, lighting, and acoustics [4] Technical report on how to use ISO 17772-1 [5] Mechanical and natural ventilation systems and the building envelope [6] Including (i) known health effects of indoor air contaminants; (ii) indoor sources of air contaminants; (iii) recommendations to reduce exposure to pollutants [7] Minimum requirements for the commissioning and operation of workplaces, natural ventilation design [8] Technical report to EN 16798-1 [9] Carbon dioxide levels [10] Carbon dioxide, acetaldehyde, acrolein, benzene, carbon monoxide, formaldehyde, fine particulate matter (PM2.5), mold, naphthalene, nitrogen dioxide, ozone, radon, toluene, and 25 different volatile organic compounds (VOCs) [11] Complete building code, contains all kind of areas in building design, among others other domain design variables [12] Thermal properties, moisture transfer, adaptive comfort [13] Indoor air quality boundary conditions for energy calculations to provide comparable indoor environmental conditions [14] Contains references regarding all four domains: thermal environment, indoor air quality, lighting, and acoustics [15] Numbers refer to part division B, Part 6.3 on ventilation systems, section refers in part generally to ASHRAE, SMCNA and HRAI standard/manuals.

3.2. Content-Wise Reproducibility

In this section, we report on the provided references, which contain the evidence underlying the standard. In this context, we analyzed technical references in order to find an evidentiary basis for the ventilation rate: specifically, the level of carbon dioxide concentration as performance variable, as mentioned in ISO 17772-1 [8], EN 16798-1 [9], addendum draft to ASHRAE Standard 62.1 [11], ASR A3.6 [31], and Residential Indoor Air Quality Guidelines [32].

The ventilation airflow rate per person and the ventilation airflow rate per floor area (to account for emissions from building materials) are mentioned in ISO 17772-1 [8] and EN 16798-1 [9], as well as ASHRAE Standard 62.1 [11].

Carbon dioxide concentration has been used since Pettenkofer's [42] pioneering work as an indicator for indoor air quality when human bio effluents were the major source of emissions or odor in indoor spaces. Pettenkofer also introduced a carbon dioxide concentration of 1000 ppm (absolute) as the value marking the upper end of good indoor air quality.

ISO 17772-1 [8] and EN 16798-1 [9] contain a method for determining the person-related airflow based on perceived air quality (Section 6.3.2 and Annex I of the standards). Thereby, the ventilation airflow is determined based on categories I to IV, which are related to an expected number of dissatisfied persons and the respective airflow for non-adapted persons. ISO/TR 17772-2 [28] mentions four references [43–46], in which, following the formula for the calculation of the airflow, it states: "As we add the odors from people, we also have to add the odor from other sources. The knowledge about the people component is relatively well-established".

The experimental study of Berg-Munch and Fanger [43] concluded that temperature has a minor influence on the perception of body odor. Given its approach, this research cannot serve to provide evidence for specific airflows. However, it does imply that temperature is not a key variable for the specification of required airflow rates.

Fanger and Berg-Munch [45] describe 95 experiments at moderate air temperatures (17–22 °C) as the basis for establishing a relation between the carbon dioxide concentration or airflow per person inside auditoria with students (assumed body hygiene of 0.7 baths per day) and the percentage of dissatisfied visitors evaluating the IAQ. As such, they concluded that carbon dioxide is a reasonable index of body odor emitted. The paper states further: "The present results show [...] that 20% dissatisfied correspond to a CO_2 concentration of 0.10% (1000 ppm) and a required steady-state ventilation rate of 7 l/s.person". The experiments were carried out at an outdoor CO_2 concentration of 0.035% (350 ppm). Therefore, 1000 ppm corresponds to a CO_2 level of 650 ppm above the outdoor concentration. Consulting Table C1 in ISO/TR 17772-2 [28], it is stated that there are still 20% dissatisfied persons, corresponding to 7 l/s.person (category II). However, consulting Table C8, category II gives a CO_2 level above the outdoor concentration of 800 ppm. Category I gives 550 ppm above the outdoor concentration. This may be due to the circumstance whereby Table C8 gives a range for outdoor CO_2 concentration (350 to 500 ppm).

Fanger [46] introduced the units olf and decipol based on experiments published in Fanger and Berg-Munch [45] and Berg-Munch, Clausen, and Fanger [47]. Therein, a figure summarizing the results gives the impression that 20% dissatisfied still corresponds to 7 l/s.person (original unit here: 7l/s.olf based on above mentioned standard person). Directly accessible evidence for any of the values given in ISO 17772-1 [8] could not be located. Consulting the work by Berg-Munch, Clausen, and Fanger [47] gives an airflow of 8 l/s.person at 20% dissatisfied, whereby hygiene standard differs slightly from Fanger and Berg-Munch [45].

Bluyssen et al. [44] reported on an IAQ audit in 56 European office buildings, aimed at developing assessment (audit) procedures and guidance on ventilation and source control. The research underlines the importance of including the building and furniture as major pollution sources and the importance of source control, hence considering both sources of

emissions (at the time, smoking was not yet completely banned from office buildings). It further confirmed that, in the field, the IAQ perception of non-adapted visitors differs from adapted occupants. However, given its approach, this research cannot serve to provide evidence for specific airflow rates.

Direct references to technical literature are included in ISO/TR 17772-2 [28]: "In ISO 17772-1 [8] the perceived air quality levels are set for non-adapted persons". This statement has its evidentiary basis already in Berg-Munch and Fanger [43]. Another statement in ISO/TR 17772-2 [28] that refers to Gunnarsen and Fanger [48] and Gunnarsen [49] reads as follows: "Studies [. . .] have shown that people adapt to the odor from bio effluents, but very little to the emission from building materials and furnishing [. . .]" (ISO/TR 17772-2 [28], Section 6.3.2.2).

Gunnarsen and Fanger [48] conclude that "perception of bio effluents reached a low level independent of concentration after a few minutes [. . .] adaptation to tobacco smoke caused acceptability to increase but votes still depended on concentration". With regard to the investigated effect of building materials, the material polluted the incoming air only slightly and therefore the interpretation of the results was difficult in this study. Therefore, this study cannot be seen as the evidentiary basis for the referring text from ISO/TR 17772-2 [28]. However, the study does compare the quantified relationship between the percentage of dissatisfied and the ventilation rate (10% dissatisfied at 7 l/s.person) with the results from Fanger and Berg-Munch (20% dissatisfied at 7 l/s.person) [45].

Gunnarsen [49] reported on the dependence of the emission from construction products on the area-specific ventilation rates. The publication did not investigate the effect of (non-)adaptation to the emission from building materials and furnishing.

Furthermore, ASHRAE Standard 62.1 [11] removed, in its 2018 revision process, the informative Appendix D "Rationale for Minimum Physiological Requirements for Respiration Air Based on CO_2 Concentration", with the explanation that the content was outdated. The subsequent 2019 version did not contain anything about carbon dioxide concentration. However, a newly proposed addendum, which is currently under review, contains calculation procedures for carbon dioxide emissions from people and for carbon dioxide concentration in rooms [50]. The addendum refers to a study by Persily and Longe [51] proposing a new approach to estimating CO_2 generation rates based on concepts from the fields of human metabolism and exercise physiology. In the mentioned study, the authors derive equations to calculate the rate of CO_2 generation as a function of the basal metabolic rate (BMR), physical activity level, air temperature, and pressure. Using data on body mass and physical activity, the authors then estimate the variability in CO_2 generation rates from building occupants.

Often, those involved in the development of standards, and guidelines have insider knowledge of why and how certain phrasings, requirements, or specific design and performance variables were included. For instance, it has been suggested that the German "Rule of Workplace ventilation" ASR A3.6 [31] is based on a scheme originally developed by the German Federal Environment Agency for schools [52]. This assessment scheme is the result of a scientific literature analysis involving 36 research papers and 21 international and national rules and guidelines on indoor air quality and carbon dioxide as an indicator by the members of the Indoor Air Hygiene Commission (IRK) of the Federal Environment Agency (UBA). The IRK provides professional counsel to the UBA on all matters of indoor air hygiene. The paper describes in Section 6.2 the developed scheme (stepwise scheme based on carbon dioxide concentration along with concrete behavior recommendations), which was based on international and national scientific literature. The scheme was taken over by the Rule of Workplace Ventilation [31]. However, this is not mentioned in this Rule.

The Canadian Residential Indoor Air Quality Guidelines [32] consist of several parts, each addressing one indoor air quality indicator or pollutant. The part on carbon dioxide contains extensive technical evidentiary basis and justification for the formulation of the recommended 24 h exposure limit of 1000 ppm. There is even a chapter included on uncertainties and future research needs.

They approach the topic from a health perspective and perceived air quality perspective and benchmark it against other countries' regulations. Interestingly, Pettenkofer [42] argued with (subjective) perceived air quality when entering a room and comparative studies on sickness for 1000 ppm. When reading this 164-year-old publication, two things need to be considered: (a) outdoor carbon dioxide level increased from approximately 285 ppm (delta 715) in 1858 when Pettenkofer did his studies, 355 ppm (delta 645) in 1990, to 417 ppm (delta 5983) in 2021 all data from [53–55] and (b) the body hygiene standards of that time and the likely connected expectations towards IAQ. Body hygiene standards also certainly differed from Fanger's 0.7 baths per day, which again may differ from today's body hygiene habits in highly industrialized and urbanized societies [46].

3.3. Procedural Transparency

In this section, we address issues pertaining to the standards' reporting on their development process. One criterium to keep track of documents is a version follow-up with revision and errata documentation (e.g., NR24-28-1 [33], ASHRAE 62.1 [11] and following) or mentioning when the basic version was published and the last changes implemented (ASR A3.6 [31] with last changes in 2018). At times, the number of standards changes, as in the case of EN 16798-1 [9], which supersedes EN 15251 [10]. The introduction mentions in a few sentences the major changes introduced with this new standard; further detail is not given in this document. The ASHRAE Standard 62.1 [11] reports on the history of the standards and lists the areas with major changes. Furthermore, it provides a detailed Appendix O, which documents all addenda and their approval, the reasoning the addenda are not always provided.

The EN standard states the number of the Technical Committee who drafted the standards and the CEN member states. Whereas ISO and EN do not list the members of the standardization committee in the respective documents, ASHRAE does so. CIBSE Guide A [37] and NR24-28-1 [33] list as well all members contributing to the development of the guidelines and their roles.

In the case of the German Rule of Workplace Ventilation, which defines mandatory minimum requirements on ventilation [31], it should be mentioned that, in general, the Rules for Workplaces contain no references to other standards. This is because standards such as ISO, EN or the German national standards (DIN) are only available commercially. As such, the German Institute of Occupational Medicine and Hygiene argues that small and medium-sized enterprises should not be requested to buy those standards in order to be able to evaluate whether a building or room is suitable to be used as a workplace. Therefore, those rules refer to guidelines of OSH insurance organizations, which are freely available. Recently, this practice changed, and standards can now be referenced. However, technical literature, e.g., research publications, are still not referred to. Nonetheless, the absence of such referencing does not imply that no evidentiary basis exists. For the process of developing rules for workplaces, the German Committee for Workplaces itself has set rules [56]. A workgroup, established through the initiative of the committee, drafts a new or revised version of a rule. The draft is subsequently sent to the Committee of Workplaces for comment [57]. The committee consists of three appointed voting and three appointed member representatives from the stakeholders, including OSH insurance organizations, employers, unions, federal states, and science/practice. They are asked to comment themselves and to collect feedback from their network within a defined period of 6 weeks. All comments are collected, and provided to and answered by the workgroup, before being given back to the Committee for approval. The process is documented and stored with the Federal Institute for occupational Safety and Hygiene [57].

ASHRAE establishes a project committee to draft or revise standards, guidelines, or addenda to standards. It has established a public review process, which was set up to allow commenting on proposed or revised standards, guidelines, or addenda to a standard. The project committee will respond to each comment unless it decides to submit a revised

draft for another full public review. Available public review drafts are listed in the online comment database [58].

3.4. Usability

This section includes a discussion of the authors' perceived usability of standards. The usability-related questions covered three main areas: effectiveness, efficiency, and satisfaction. The results are shown in Figure 1 (in terms of the frequency of subjective scale rankings) and discussed in the following.

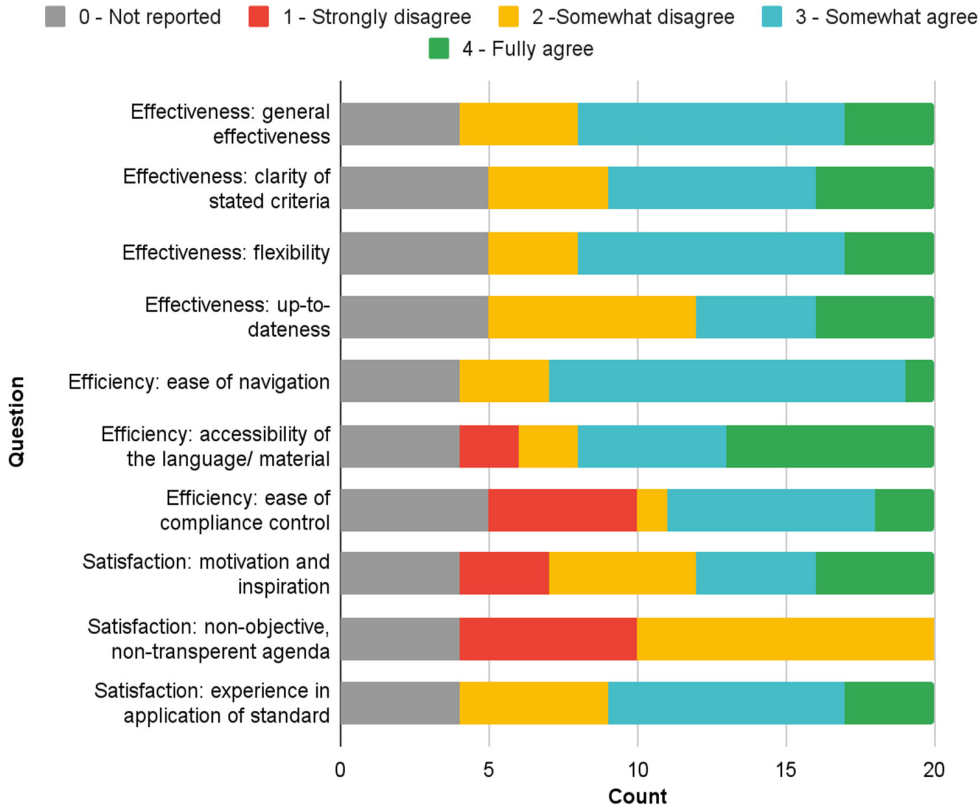


Figure 1. Responses to questions on the usability of the reviewed standards.

Starting with the perceived effectiveness of the standards' content, it appears that standards state the pertinent design and performance criteria in a clear and unambiguous manner. Moreover, the standards can be suggested to encourage flexibility toward identifying creative and effective solutions through their entailed requirements. On the other hand, the qualitative assessment of the standards' up-to-dateness was not conclusive, as almost half of the views on the subject disagreed with the suggestion that the reviewed standards reflect the latest state of domain knowledge and technology. This finding is not surprising, as the mean publication date of the supporting literature cited in the codes is the year 2001.

Moving on to the perceived efficiency of standards, there is general agreement that the relevant information is intelligible and easy to access. In terms of ease of compliance control, the majority view was that the requirements entailed in the reviewed standards can be conveniently addressed in specific projects, some views expressed strong disagreement. This result could be partially attributed to the diverse nature of the reviewed standards. For instance, the Canadian Residential Indoor Air Quality Guidelines define acceptable IAQ conditions without prescribing pathways (e.g., design or operation guidelines) to achieve those conditions.

The opinions were also divided with respect to the satisfaction levels with standards, specifically when asking if standards are highly motivational and inspire the development of good solutions. However, everyone agreed that standards do not pursue non-transparent

or non-objective agendas. These findings hint that any lack of evidence reported earlier is unintentional and not by design. Finally, using or working with the reviewed standards was perceived by most reviewers as a positive experience.

4. Conclusions and Future Recommendations

Earlier sections summarized the evaluation of IAQ standards' transparency, content-wise reproducibility, operational reproducibility, and usability. It must be noted that, to varying degrees, one or more of these four criteria is insufficiently addressed in the 13 analyzed standards. Hence, this section aims to answer the question as to how future standardization efforts could be improved, assuming there is a need for such improvements.

Before providing recommendations for future standards, a key question needs to be addressed: What is the purpose of the standard and who are the addressees? ISO writes about standards "Think of them as a formula that describes the best way of doing something. [. . .] Standards are the distilled wisdom of people with expertise in their subject matter and who know the needs of the organizations they represent—people such as manufacturers, sellers, buyers, customers, trade associations, users, or regulators" [35]. As such, the scientists are not included in the list of main target groups. Still, scientists are also among those using standardized products and procedures for their research. Therefore, how can a standard fulfill all stakeholders' needs despite the likely variations in their approaches?

First and foremost, a standard should provide high usability (an effective, efficient, and satisfactory way to design/assess IAQ) for its users. Considering the two main user groups, practitioners are mainly concerned with complying with IAQ requirements of the standards, while researchers use the standards to adopt a specific measurement method or to compare the requirements with their study's results, which may influence potentially necessary updates of the standards' requirements given new evidence. Understandably, standards generally have a more direct writing style, targeting practitioners. Nonetheless, it would be beneficial if they were also to contain links to the evidentiary sources. This could be accomplished, for instance, in terms of informative appendices that are not necessarily meant to be targeted toward practitioners who primarily use standards for design guidance or compliance checking.

Providing evidence for the requirements is extremely important, especially for international standards such as ISO and ASHRAE that usually serve as references to inform local/regional standards and guidelines. For instance, if required minimum ventilation rates are geared toward the dispersion/dilution of the main pollutants (e.g., from people and building components emissions) in the context of Scandinavian and North American study samples with relatively low air exchange rates, they may not be adequate for locations with different contextual characteristics. Hence, transparency can be argued to be one of the key quality features of standards. Moreover, transparency and usability cannot be considered independently, as, at least for the user group of scientists, it is decisively important to gauge the standards' evidentiary basis. At the same time, one may argue that a standard is not a scientific document, and is meant to serve a different purpose. Hence, it might be meaningful for each recurrent standard revision to reassess the scientific basis in terms of a separately published systematic review paper alongside the standard itself.

Such steps might also improve reproducibility. Reproducibility is important for the decision regarding which requirements make sense for the specific context, and which ones need to be changed or disregarded. At the same time, reproducibility goes beyond transparency. As standards are based on a negotiation between different stakeholders and balancing different needs (e.g., human health, economics, ecological or social sustainability), knowing the scientific evidence alone, might not be sufficient to reproduce all aspects of the standards' contents. Hence, reproducibility requires information on the process and discussions that lead to the relevant features of the standards. Consider, as a conceptually interesting instance, the case of the German medical guidelines ("Leitlinien"), such as the one related to the usage of heart rate variability [59]. This guideline not only clarifies the

procedure of collecting and extracting evidence from the scientific literature, it also clarifies who was involved in the guideline's genesis, which potential conflicts of interest existed, and to what extent the persons involved agreed with statements made in the guideline, i.e., what percentage of experts agreed with each specific statement or mandate. Concerning reproducibility, such steps would also facilitate tracking changes throughout time, so that the users of the standards are enabled to understand why certain points have been changed from one version to another. Please note that, in the authors' experience, even members of standardization committees do not necessarily recall in each instance why and when a specific point was added or modified.

Major parameters used in standards, such as ventilation rates, CO_2 concentration levels, pollutants, etc., should be evaluated under the collaboration of multiple professionals from different disciplines. Moreover, based on the beneficiaries, different experts from practice and science should be involved in the development. For this purpose, the collaboration of committed experts from different fields is essential. In most cases, indoor air quality is strongly related to outdoor air quality [60] and air quality of course influences human health [61]. Recognition of existing and future outdoor air condition/quality/pollution is important for development of sound guidelines in view of more usable metrics and pertinent thresholds. Regional standards are frequently based on international ones, and are supported by research in developed countries [14]. Inclusion of an increased number of participants from different areas around the world may help standards to be more relevant, more inclusive, and more readily applicable.

IAQ is directly related to social health protocols and policies [62]. In the near future, based on the devastating effects of the COVID-19 pandemic, more attention is expected to be paid to airborne transmission of respiratory viruses. Hence, updates and developments in current standards might be expected. Moreover, indoor airborne microplastics, which have not been thoroughly researched [63,64], might also be expected to be one of the important topics in future. Therefore, further research efforts toward developing and defining limitations in the IAQ standards would be essential. It is also important to more clearly specify the focus of standards. As such, the focus may be requirements pertaining to human metabolism (O_2 concentration), perceived air quality (odors), or protection from outdoor/indoor contaminants and pathogenic microorganisms (e.g., radon, SARS-CoV-2, PM2.5, microplastics). The focus may also be related to building construction integrity (e.g., moisture impact) or other technological issues [30].

Consequently, more collaboration of practitioners and scientists, integrity of different fields of science, and definitions of new metrics and limitations might be listed as expected future efforts related to IAQ standards.

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