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TOWARD A CRITICAL ASSESSMENT OF INDOOR-ENVIRONMENTAL QUALITY STANDARDS

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Abstract. Building design and operation requirements regarding indoor-environmental quality (IEQ) are of direct relevance to occupants' needs. In most buildings, occupant-related requirements pertain to the provision of conditions that support optimal task performance and are subjectively perceived as comfortable or pleasant. Standards and guidelines, which entail IEQ requirements specifications are commonly viewed as the main sources of reference for practitioners, who are expected to follow the provisions in these documents and provide corresponding proof of compliance. However, actual code compliance processes are not always accompanied by critical reflections regarding the evidentiary basis of the included mandates and recommendations. It is thus necessary to critically scrutinise standards in view of explicit or implicit references to the scientific basis of the entailed mandates. The present contribution explores and details a path toward such a critical assessment. To this end, we considered several frequently referenced standards pertaining to thermal, visual, and air quality aspects of indoor environments. The results of this illustrative assessment effort highlight the scope and limitations of the standards' default approaches to the definition of IEQ-relevant requirements. Moreover, they point to considerable gaps in the chain of evidence from standards' immediate content to the underlying factual sources.

Keywords: Indoor-environmental quality, standards, evidence.

1. Introductory remarks

For professionals and stakeholders involved in the building delivery process, codes, standards, and guidelines related to indoor-environmental quality (IEQ) represent a critical source of information and guidance. These resources typically define and specify the spectrum of quality requirements (including those directly relevant to the needs of occupants) to be addressed in the course of buildings' planning, erection, and operation. Specifically, IEQ-related requirements are directly relevant to occupants' needs. Broadly speaking, requirements pertaining to building occupants range from some rather basic principles (i.e., avoiding harm to human health, provision of the minimum thermal, visual, acoustic, and air quality conditions) to criteria that could be classified as less tangible (e.g., creating indoor environments that occupants perceive as being pleasing and pleasant). Risks in the former category should be obviously avoided. Those in the latter category could be presumably tolerated if the temporal extent of the exposure is limited. It is important to recognize that what constitutes a comfortable environment has a strong subjective background. But the same is not true of necessary conditions for occupants' health. Occupants do not always consciously perceive sources of adverse health effects. For instance, dangerous gases such as carbon monoxide and radon cannot be perceived by humans.

Standards represent a key source of information and support for professionals and stakeholders in the building delivery process. Building designs and the actual buildings' performance need to comply with the IEQ-related mandates in these standards [1]. The question is, however, if by the virtue of their entailment in the standards, mandates and requirements can be automatically assumed to be entirely objective and based on solid scientific evidence. This, we argue, cannot be assumed a priori, but must be rather examined carefully.

2. In search of evidence

One could assume that, in order to locate the scientific basis for standard-based IEQ mandates, one would need to look no further than the evidence provided by disciplines such as physiology, psychology, and ergonomics. However, neither standards themselves, nor the related compliance processes appear to explicitly address arguments for the applicability of standards in general and the uncertainty of their recommendations in particular. This circumstance may have negative implications. Professionals may concentrate solely on demonstrating compliance with minimum requirements instead of focusing on creating genuinely high-quality indoor environments. This underlines the importance of critical reflections regarding the availability and strength of sound scientific evidence behind the entailed prescriptions in the standards.

In this context, a key question is as follows: Do we

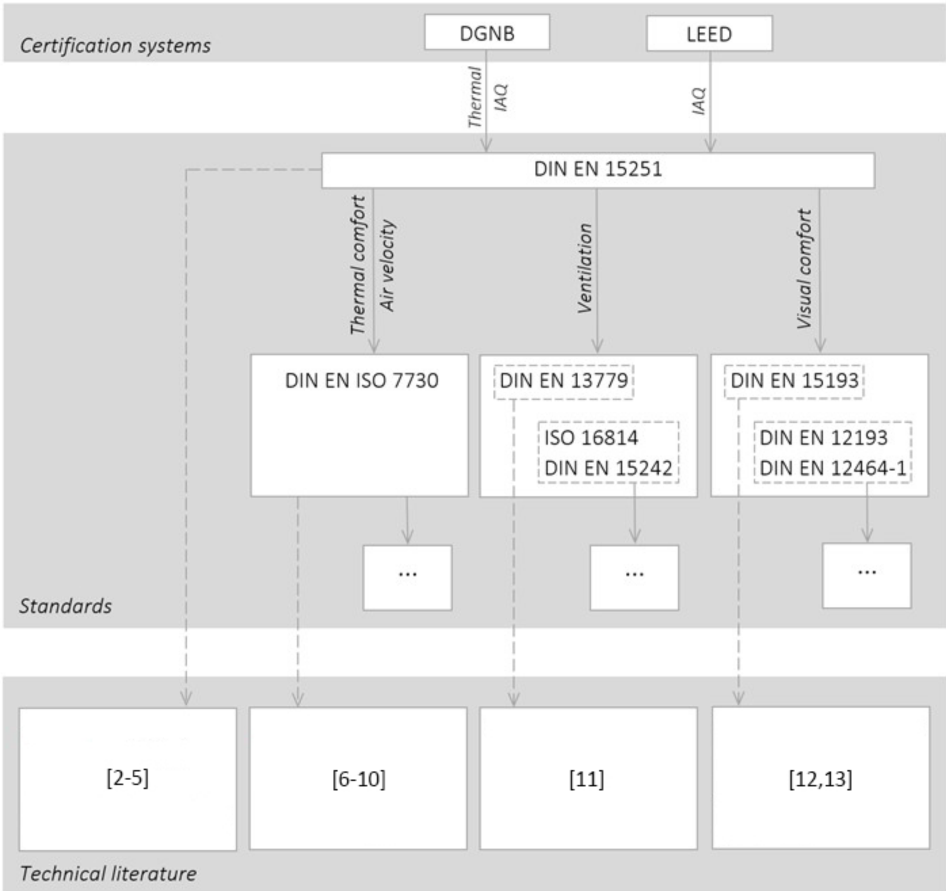

Figure 1. Illustrative exemplification of the chain of reference from certification systems, to different layers of standards, and technical literature. ([2–5], [6–10], [11], [12, 13]).

sufficiently understand the influence mechanisms of indoor-environmental factors on the health, comfort, productivity, and well-being of the building occupants? Despite the plethora of valuable research in the past, the identification and realization of occupants' health and comfort requirements remains a formidable challenge. Given the increasing popularity of various total building quality evaluation schemes and certificates, it would be useful, in principle, to examine not only commonly used IEQ-related codes, standards, and guidelines (and their recommendations), but also building evaluation and certification systems in view of any cited theoretical background and empirical evidence. However, as illustrated in Figure 1, common systems for building rating and certification (e.g., [14, 15]) appear not to entail explicit specifications of indoor-environmental requirements. Rather, they tend to refer to other thematically related national or international standards such as ISO, EN, DIN, or ANSI [1]. Some of these standards (e.g., DIN EN 15251) refer, in turn, to other standards. There are very few cases, where standards include direct evidence and justification for the specified requirements. They do, however, include at times either general literature or specific studies (see "technical literature" box in Figure 1). Nonetheless, it is not a straight-forward matter to isolate, in the referenced technical literature, the evidence underlying the standards' IEQ-related criteria and the mandated values of the relevant occupant-centric performance indicators.

3. About formats for the specification of requirements

For practitioners involved in the building delivery process, the primary utility of standards may be in the specification of IEQ-relevant performance indicators and their respective mandated values. These values can be specified in terms of various formats. For instance, maximum allowable values may be mandated for parameters such as pollutants' concentration, magnitude of glare, or sound level. Likewise, minimum values can be specified, for instance, for illuminance levels or ventilation rates. The specification of performance indicator values can help organize and streamline the procedures aiming at demonstration of compliance with standards and general quality assurance. Assuming that such values can be monitored after the commissioning phase, the examination of contractually specified performance can follow a rational path and liability issues can be resolved in an accountable man-

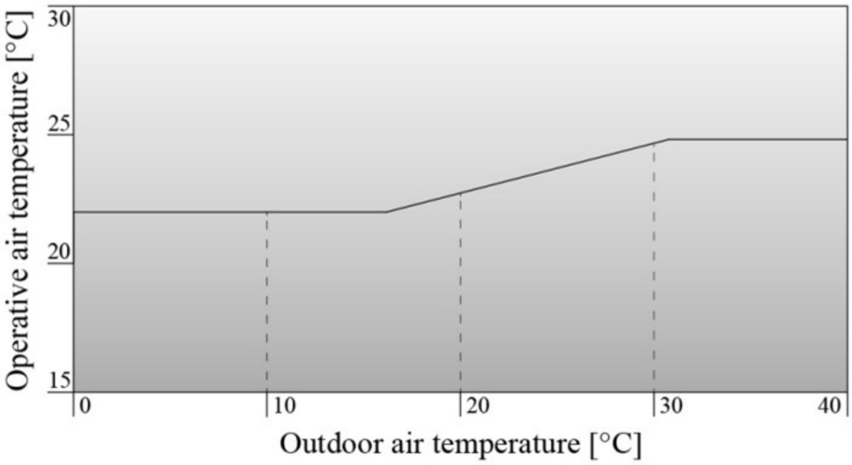

FIGURE 2. Example of a standard-based IEQ indicator (operative air temperature) and its value as a function of the outdoor air temperature (based on standards DIN EN 15251 and DIN EN ISO 7730).

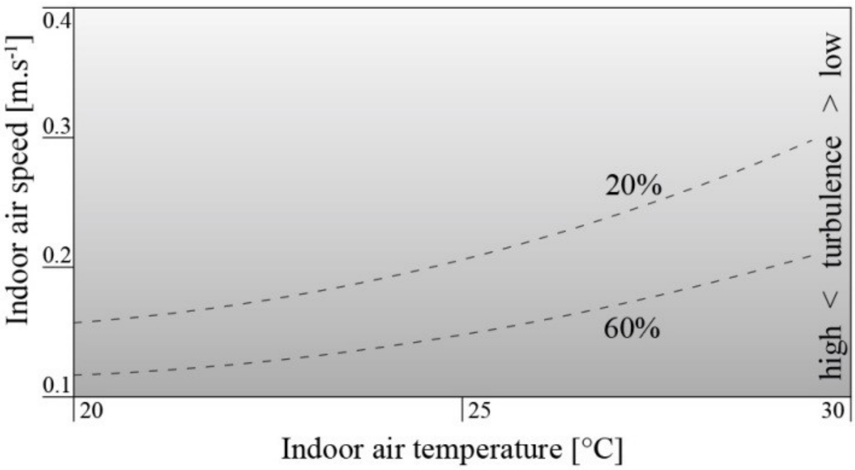

FIGURE 3. Illustrative exemplification of standard-based specification of an IEQ indicator (maximum permissible air flow speed) and its value as a function of indoor air temperature and turbulence intensity (based on standards DIN EN 15251 and DIN EN ISO 7730).

ner. Requirements can be also formulated in terms of "zones", involving the combined consideration of multiple variables and their values (e.g., thermal comfort zone that encompass air and radiant temperatures, air velocity, and humidity). To exemplify this, consider the following graphs (Figures 2 and 3), which are based on standards DIN EN 15251 and DIN EN ISO 7730. These graphs illustrate, in generic form, the dependency of the value of a performance indicator (i.e., recommended operative temperature, maximum allowable air flow speed) as a function of other variables (in this case, outdoor temperature, indoor air temperature, turbulence intensity).

The logic behind these kinds of requirements in the IEQ field has both similarities and dissimilarities with other code-based building regulations. Basic building codes prescribe, for instance, minimum dimensions of certain architectural elements in building design and construction domains (e.g., width of doors, stairs, corridors). Such requirements, for instance those pertaining to accessibility and universal design, are typically based on straightforward practical considerations such as human body and wheelchair dimension. They can be readily understood by designers and implemented in actuality. Hence the compliance can be fairly easily examined in the course of building commissioning. But the translation of this approach, namely inference from scientific facts to design requirements, is in case of IEQ-related requirements much more complex. It is thus important to explore if and to which extent IEQ-related standards bolster their credibility by provision of explicit references to scientifically established evidence.

4. Theory versus practice

A cursory inspection of IEQ-related standards leads to the conclusion that they entail much in terms of prescriptive requirements, but rather little in terms of explicit evidence behind those requirements. As mentioned before, rating systems typically refer to

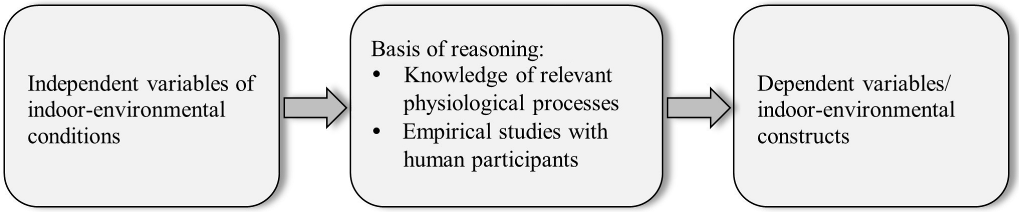

Figure 4. Illustrative schema of indoor-environmental comfort equation components.

	Thermal comfort	**Visual discomfort**
Presumed key indoor-environmental comfort parameters (independent parameters)	Ambient air temperature, radiant temperature, relative humidity, air velocity	Background luminance, glare source luminance
Indoor-environmental comfort constructs indicating building users' subjective evaluation (dependent parameters)	Predicted mean vote, Predicted percentage of dissatisfied	Unified glare rating (UGR), Visual comfort probability (VCP)

Table 1. Independent and dependent parameters with regard to thermal comfort and visual discomfort.

standards, which sometimes refer to other standards. Standards occasionally refer to technical papers and report, but a direct link from these resources to the stated requirements is rarely established. Hence, such references appear to have the function of a general topical bibliography, rather than repositories of directly relevant evidentiary material. Various reasons may be responsible for this circumstance. Firstly, standards could be argued to represent resources for practitioners, rather than repositories of scientific knowledge. Professionals involved in the building delivery process are more likely to consult standards in view of practical solutions and regulatory constraints, rather than contributors to their scientific understanding. Secondly, IEQ standards, in contrast to building construction and structure codes, cannot rely only on engineering sciences, but must also take into account findings from human and social sciences such as physiology, psychology, and sociology. This arguably adds an additional layer of complexity to the requirements specification process, given the significant role of subjective and qualitative parameters in the formation of occupants' perception and evaluation phenomena. Thirdly, the genesis of IEQ standards does not follow in all cases an entirely systematic process. Thereby, factors other than the occupants' health or comfort requirements may play a role. These other factors could include financial issues, policy considerations, or special interests. As with many other areas involving regulatory aspects, development of standards may require, from the involved stakeholders (e.g., government, industry, academia), various degrees of consent and the willingness to comprise. Consequently, not all aspect of the resulting standards could be expected to strictly adhere to scientific evidence.

The above reflections, however, should not be misunderstood. Many commonly applied IEQ standards do not explicitly elaborate on their underlying evidentiary basis. But they do provide implicit pointers to the kinds of principles and methods that inform them. In other words, standards frequently entail features that point a kind of implicit methodological and theoretical underpinnings. It may be thus interesting and useful, to engage in a kind of reverse engineering of standards and their syntax, terminology, and logic, so as to uncover their implicit theoretical foundations.

5. Sources of indoor-environmental comfort constructs

Conventionally, indoor-environmental comfort equations are used in standards focusing on thermal and visual comfort. Figure 4 schematically illustrates the elements of such indoor-environmental comfort equations. Thereby, a set of physical variables is intended to formulate dependent variables that capture building users' level of comfort [1]. Whereas physical variables can be typically derived by measurements, dependent variables result from subjective evaluations. Table 1 shows such constructs that are assumed to capture occupants' subjective evaluations concerning thermal and visual comfort/discomfort.

Thermal comfort standards typically refer to relevant (measureable) physical variables, such as air temperature, air speed, and water vapour concentration. Moreover, thermal comfort constructs capture subjective building users' evaluations by means of scales that are commonly used in studies in psychology. The underlying logic to map operations in the comfort equation often relies on two sources. On the one hand, the source is based on underlying physiological mechanisms. For instance, the humans' thermo-regulatory system to keep the human body's kernel temperature is of key significance when addressing thermal comfort [16]. On the other hand, occupants' evaluations of experiments with different indoor-environmental conditions provide another source of information.

In which way these two sources contribute in order to derive a comfort equation may be quite different. Concerning thermal comfort, the understanding of thermo-regulatory processes is crucial in order to formulate thermal comfort models. Moreover, studies involving subjective evaluations of participants provide relevant data of physiological-relevant variables. With regard to visual comfort, a physiological understanding of glare or light scattering is essential. Discomfortable visual indoor-environmental conditions are primarily evaluated by occupants' subjective evaluations.

6. Reflections on limitations

Codes, guidelines, and standards seldom bring to light the relevant and precise explanation for the particular requirements they demand, some of which provide exact limitations for or allowed ranges of different variables. Previously, we suggested some reasons for this situation. These include difficulties in accurately formulating occupant-oriented concepts for comfort, well-being, and health; recognising and estimating the proper IEQ proxies; the multi-domain character of indoor-environmental circumstances; the variance of occupants' requirements and the constantly changing nature of these requirements; the actual challenges of working procedures in standardization bodies.

It is important to emphasize that we did not embark on the present treatment with an unreasonably high expectation. Clearly, it is not likely that a single formula or scheme could provide definitive evidence for all certification systems and regulatory guidelines regarding indoor environment. However, this process revealed a repeated pattern, known from the fields of psychology, physiology, and medicine, which can be described in the following way. In standards, the values and ranges of the relevant variables meant to be representative of the indoor environment conditions are mapped onto the values of specific indicators of human comfort and health. This mapping process usually relies on the combination of two components, specifically

(1.) a psychologically or physiologically based theory, and

(2.) obtainable research data from experiments with human participants.

In cases where explicit comfort calculations are needed (e.g., visual discomfort or thermal comfort), the guidelines provide specific models defining occupant comfort and health (including their required values and ranges). Otherwise, these models may not be specifically provided. Rather, the assumption appears to be that when specific indoor-environmental variables (e.g., indoor air carbon dioxide concentration) are kept in mandated ranges, the requirements related to occupants' comfort and health are met.

We can summarize the foregoing discourse regarding the current and future state of guidelines, codes, standards as follows:

- To begin with, we need to acknowledge that it is at times difficult to follow the trace from guidelines back to their evidentiary basis. In practice, this may lead to a situation, where standards and their requirements do not serve as reliable sources of disciplinary guidance, but are reduced to opaque propositions that are thoughtlessly followed. It is not our intent to suggest that standards should reproduce the complete theoretical substructure and scientific evidence that they are built upon. Their focus needs to be on operational matters and specific directives, as they mainly serve as regulative tools. However, it would be justified to look for an explicit link between the standard-based requirements and their scientific basis. This link appears to be frequently untraceable.
- Secondly, we face numerous challenges, while trying to identify the theories and supporting data that would document the credibility of the requirements formulated the standards. Research in the fields of human health, well-being, and comfort continuously yields new and valuable results, but it also involves numerous challenges and uncertainties. While reputable scientists in the field commonly avoid expressing doctrinal standpoints and claiming the absolute truth, regulating authorities are obligated to derive from insufficiently uncertain knowledge mandatory rules and regulations. As such, it seems as if a certain level of uncertainty in the objectivity of mandated requirements is the price one is willing to pay in order to prevent chaos, confusion, and accountability issues in the building design and delivery process.
- Thirdly, the identified IEQ-relevant standardization challenges (especially, the scantiness of explicit arguments for the entailed requirements) may also point to gaps in our scientific understanding in the related domains. It is not always clear which physical characteristics of the indoor environment represent the "correct" variables to be considered when evaluating comfort and health. Further difficulties must be encountered when we try to define and validate the constructs for comfort and health that do not fully capture the relationship between psychological, physiological, and social aspects of occupants' perception and assessment of indoor environment. Moreover, the scope of available empirical data for the evaluation and validation of behavioural and perceptual theories is still rather limited. The indoor-environmental exposure circumstances are fundamentally multi-domain. Hence, isolated treatment of these separate IEQ domains is likely to fail in capturing their complexity. We have made some progress in our appreciation of occupants' diversity and the dynamic nature of their preferences.

However, probably the level of progress has not been high enough to warrant a translation of the respective findings in the appliable IEQ regulations.

The investigation of the formulation and implementation of IEQ-relevant standardization procedures structures points not only to their limitations, but also to certain shortcomings in our scientific understanding of occupants' preferences and necessities in indoor environments. There is a need for clearer, better structured and more objective procedure, when it comes to implementing our current scientific knowledge, with all its undeniable limitations, into IEQ standards, guidelines, and codes. At the same time, we urgently need to extend and refine the depth of our knowledge regarding the mechanisms by which indoor-environmental conditions influence human health, comfort, wellbeing, and productivity.

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