Research, standards, practice: Necessary conditions for occupant-centric indoor environments

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Abstract. The precise definition of appropriate indoor-environmental conditions for human occupancy is not trivial. Practitioners in the building delivery process frequently rely on applicable standards and guidelines to identify the relevant performance variables and their required values. In this context, recent inquiries have pointed out a number of gaps in our knowledge. Certain aspects of these gaps can be explored in terms of the following three basic questions: *i)* Are current codes/standards compliance processes limited to meeting formal criteria and minimum requirements, thereby losing sight of the essential task of producing high-quality indoor environments? *ii)* Do currently deployed standards entail a clear, transparent, and evidence-based logic underneath their recommended or mandated quality requirements? In other words, have the results of scientific research on indoor environment been adequately translated into the language of codes and standards? *iii)* What is the degree of precision and validity of the indoor-environmental research results? In other words, are we asking the right questions and using the right methods to answer them? To address these questions, the present contribution considers a number of common indoor-environmental quality standards pertaining to thermal and visual comfort, as well as indoor air quality. The outcome of this preliminary appraisal point to gaps in the chain of evidence from research to standards. The results also point to a number of areas in which the scientific research on indoor-environmental quality could benefit from a strategic rethinking of a number of its underlying methodological premises.

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1. Introduction

Indoor-environmental quality (IEQ) standards and guidelines represent important sources of reference for those involved in the building delivery process. They are expected to represent the state of knowledge regarding building performance requirements, including those related to occupant needs. Performance criteria cover, at a basic level, elementary mandates relevant to occupants' health and comfort. Specifically, they define acceptability criteria for thermal, visual, acoustic, and air quality conditions in indoor environments. Note that the evaluation of what is assumed to be a healthy or comfortable environment is not a trivial matter. Particularly the perception of the comfort level of an environment involves a considerable number of subjective factors.

Aside their function as a source of knowledge and guidance for professionals, standards are also relevant with regard to accountability and compliance (quality assurance, liability) issues in the building delivery process [1]. But this does not mean that all content entailed in standards and guidelines must be assumed to be completely objective and entirely evidence-based. Rather, in the IEQ domain too, the scientific basis and technical validity of standard-based requirements must be regularly scrutinised, amended, and updated.

2. Requirements and rationale

The inquiry after the evidentiary basis of IEQ standards and guidelines is at times met with the following objection. Standards, we are told, are comparable with legal documents. As such, they do not need to provide a justification for the requirements entailed. Their justification is argued to be based on the circumstance that they have been developed and issued by a body of entrusted experts. We consider this claim an obvious instance of *argumentum ab auctoritate* and hence clearly fallacious.

It can be of course argued that standards and guidelines are primarily meant to guide professional in the relevant domain and as such must not explicitly include their evidentiary basis in the respective contents. But it seems reasonable to expect that there would be a traceable and unbroken chain of reference from the standards' content to underlying supportive documents (e.g., technical publications, research reports).

In the specific case of standard-based IEQ mandates, a reasonable assumption would be that their scientific basis could be traced back to the findings of studies in fields such as biology, physiology, psychology, neuroscience, and ergonomics. However, a cursory look at most IEQ standards does not confirm this expectation. Rather, neither the standards nor the modes of their application appear to the evidence for or the uncertainty of entailed performance requirements. The downside of this circumstance lies in the risk of limiting the deployment of standards to compliance and liability issues only. This would be a missed opportunity, in the sense of focusing on minimum requirements instead of reaching for truly high-quality indoor environments.

An important issue in this discussion is the state of knowledge regarding the mechanisms by which indoor environment conditions influence occupants' health, comfort, well-being, and productivity. Thereby, the causal factors in such mechanisms are not only postulated in "classical" IEQ codes and standards, but also in an increasing number of building quality evaluation and certification schemes and systems. Yet searching for explicit theoretical basis and empirical evidence in these schemes and systems is no more fruitful than looking in the standards. This point can be exemplified based on the case of two common building rating/certification systems, namely LEED [2] and DGNB [3].

As illustrated in Figure 1, these systems frequently do not explicitly include IEQ requirements, but refer to various other national or international standards [1]. Occasionally, the referenced standards themselves refer to further standards for specific requirements and perhaps provide a list of technical literature, without making the mandates-to-references clear and transparent. There are rather few instances, where IEQ standards and codes entail direct and explicit evidence to justify the requirements regarding preferable or necessary indoor-environmental conditions. However, even in these instances, it is not a simple matter to locate, in the referenced scientific publications, the explanatory reasoning behind the standard-based IEQ mandates.

3. Approaches to specification of IEQ requirements

Arguably, the main utility of IEQ standards for building professionals and other relevant stakeholders lies in establishing the definitions and values of suitable performance indicators. In case of certain IEQ-related variables (e.g., concentration of pollutants in indoor air, presence of glare in working spaces, background noise levels in offices) it would be meaningful to establish maximum permissible values. In case of some other variables (e.g., task illuminance levels, air change rates) minimum necessary values could be specified.

Prescription of specific maximum and/or minimum values for performance indicators is especially helpful to the practitioners in connection with quality assurance questions and compliance checking procedures. Ideally, the expected values of relevant performance variables could be part of contractual framework. As such, the actual values of these performance variables could be objectively measured in the course of the commissioning process. This would provide, at least in theory, a rational approach to accountably address and resolve potential liability issues.

A further modus of IEQ-related performance specification involves the definition of multi-variable "zones". For instance, indoor air temperature, mean radiant temperature, air flow velocity, and indoor air humidity are considered concurrently to define a recommended thermal comfort zone. Generally speaking, recommended or mandated values of performance indicators are typically specified as a function of other, mostly indoor-environmental, variables. Illustrations of this approach are provided in Figures 2 and 3, which generically depict the dependency of desired operative temperature or maximum acceptable air flow speed on outdoor temperature, indoor air temperature, and turbulence intensity.

This approach is in principle not much different from the one adopted in basic building-related codes, when variables such as minimum dimensions of doors, stairways, or corridors are specified. The difference is that, in the latter cases, the reasoning behind the requirements may be explained in a more straight-forward manner (e.g., reference to dimensions of the human body or wheelchairs). In contrast, the reasoning behind most IEQ-related mandates is more complex. The complexity, however, does not absolve us from looking for the scientific evidence underlying the performance mandates in IEQ standards.

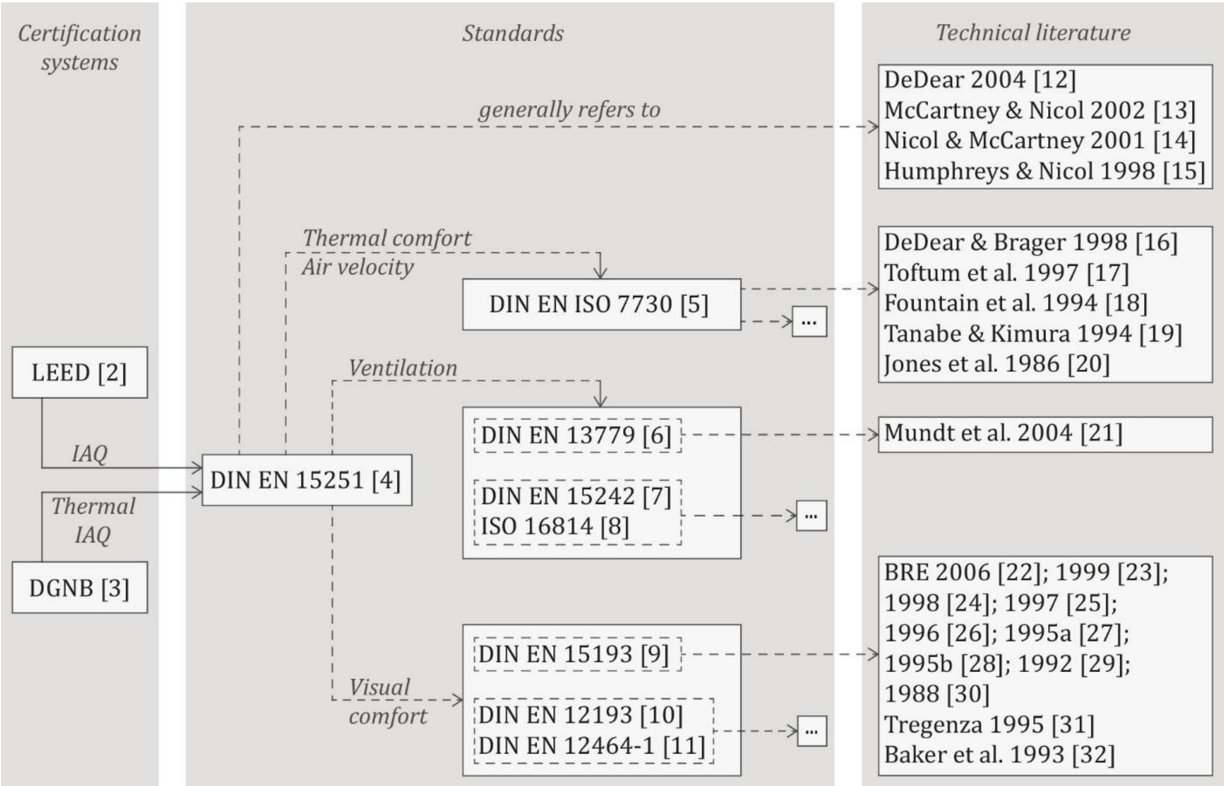

Fig. 1 – Exemplary illustration of chain of references from certification systems to standards and technical literature.

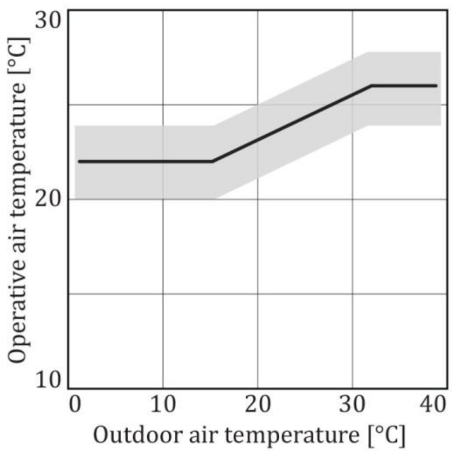

Fig. 2 – Standard-based declaration of the dependency of the recommended values of operative air temperature on the outdoor air temperature (DIN EN 15251 [4], DIN EN ISO 7730 [5]).

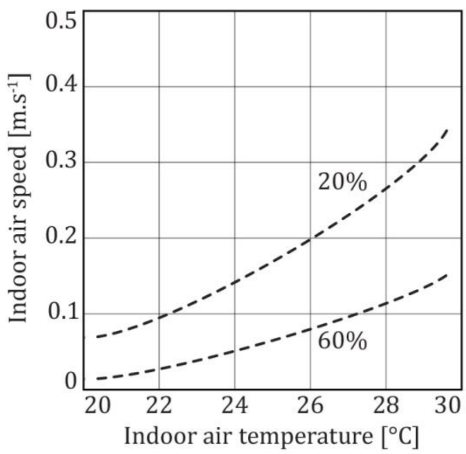

Fig. 3 - Standard-based specification of the dependency of the maximum permissible values of indoor air speed on the indoor air temperature depicted for two turbulence intensity levels (20% and 60%) (DIN EN 15251 [4], DIN EN ISO 7730 [5]).

4. From expectation to reality

It was already indicated that various prescriptive mandates are included in typical IEQ standards, for which rather little supporting evidence is explicitly provided. It was also noted before that, when dealing with specific performance requirements, building certification and rating systems typically refer to standards. The referenced standards may in turn refer to further standards. In some instances, standards do refer to scientific publications and technical reports. But it is often quite difficult to establish a direct and explicit link from such resources back to the requirements entailed in the standards. The provided technical literature appears frequently to act as a rather general bibliography. But the search therein for evidentiary basis of standard-based mandates is rather arduous and frequently inconclusive. Let us consider some of the factors that could have contributed to this situation:

- As mentioned earlier, for many practitioners, standards are not sources of scientific information or educational material, but rather sources of practical guidance and regulative norms.

- There is arguably a key difference between standards in core areas of building construction and building structures on the one side and IEQ standards on the other sides. Whereas standards in the former category need to rely mainly on engineering sciences, those in the latter category need to address information and insights from human and social sciences (i.e., biology, physiology, ergonomics, psychology, and sociology). The path from material science and statics to building structure codes is presumably much more straight-forward than the process by which the results from health and comfort sciences are to be translated into IEQ standards' content. The complexity of the latter translation lies to a large part in the inherently qualitative and subjective factors involved in how people perceive, evaluate, and react to conditions in indoor environments.
- General statements about codes and standards relevant to the building design, construction, and operation processes should be made with care, given their broad spectrum and diversity. Nonetheless, it should be noted that, similar to standards in other areas, IEQ standards do not necessarily come about in the course of an entirely systematic and meticulously structured process. For better or worse, the standardization process does not only address occupants' health and comfort requirements, but is also influenced by factors such as financial considerations, policy constraints, and special interests. Hence, the process requires that the stakeholders involved, be those from governmental bodies, industry representatives, or academic experts, are open to consent and compromise. The point is that objective scientific evidence is not the only aspect driving the final formulation of standard-based IEQ performance mandates.

These points are of course not meant to suggest that IEQ standards and their recommendations are not scientifically based. Rather, the point is that whatever their underlying evidentiary basis is, it is rarely included as an explicit component of the standards. As alluded to before, this may or may not be considered appropriate. But be that as it may, it is important to note that IEQ standards do entail implicit clues with regard to the principles they follow and the approaches they adopt. This suggests that one could, through a kind of reverse engineering of IEQ standards' terminology and composition, arrive at the underlying theoretical reasoning of their requirements.

5. Derivation of IEQ standards' comfort constructs

The underlying logic of the various comfort constructs in IEQ standards cannot be covered here. However, we can exemplify one common approach adopted by such standards, using the case of indoor-environmentally relevant comfort equations in thermal and visual comfort standards. The ingredients of such comfort equations are schematically illustrated in Figure 4. The approach involves the identification of a set of physical parameters that act as the independent variables in the comfort equations. Using information obtained from empirical psycho-physical studies involving human participants, these independent variables are mapped onto dependent variables (constructs) that are meant to capture occupants' level of comfort [33]. The values of the independent (physical) variables typically result from measurements. Values of dependent variables, on the other hand, are determined based on people's subjective statements. Examples for the constructs emerging from this process are provided in Table 1. They are suggested to reflect subjective evaluations pertaining to thermal and visual comfort (or discomfort) obtained from human participants.

In thermal comfort standards, various measurable (physical) variables are identified as relevant independent variables (e.g., ambient air temperature, air velocity, water vapour concentration). On the other hand, the values of constructed thermal comfort indicators are determined via participants' subjective evaluations. To this end, typical physiological scales (e.g., thermal sensation scale) are deployed. The mapping logic from independent variables to comfort constructs is primarily accomplished based on two sources. One source stems from descriptions of physiological processes. For instance, the function of the thermo-regulatory system of human's body toward maintaining a stable body core temperature plays a central role in understanding the processes related to people's evaluation of thermal comfort [34]. The operationalization of this theoretically relevant source requires a second, empirical source. Specifically, participants' thermal comfort responses in the course of controlled experimental studies (conducted under varying indoor-environmental conditions) provide the information necessary to test and calibrate the physiologically-based theoretical model.

To reiterate, in care of thermal comfort equations, the physiological knowledge of the thermo-regulatory processes in the human body represents the key aspect. Experimental studies with human participants capture subjective evaluations of the prevailing conditions and thus facilitate the operationalization of the physiological process model. Likewise, in the visual domain, the physiological understanding of glare-inducing processes (such as light scattering) is an important component of the theoretical comfort (or discomfort) model. Non-comfortable visual circumstances are evaluated via participants' subjective judgements.

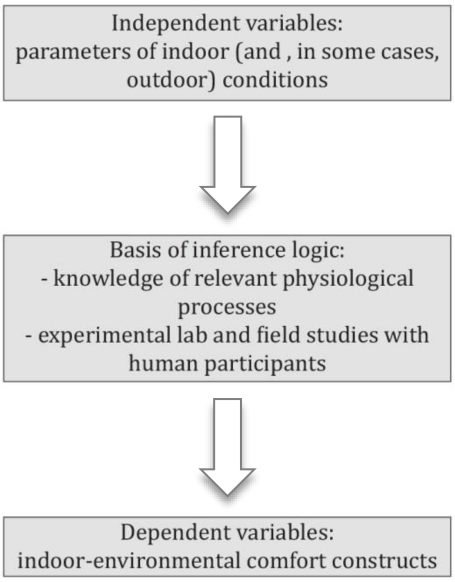

Fig. 4 – Schematic depiction of the derivation process of indoor-environmental comfort equations.

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

	Key indoor-environmental comfort parameters (independent parameters)	Indoor-environmental comfort constructs related to users' subjective evaluation (dependent parameters)
Thermal comfort	Air temperature, water vapour concentration, air velocity, MRT	Predicted mean vote, Predicted percentage of dissatisfied
Visual comfort	Background luminance, luminance of the glare source	UGR (unified glare rating), VCP (visual comfort probability)

6. Conclusions and discussion

Our investigation so far suggests that IEQ codes and standards rarely state, in explicit terms, the reasoning for the performance mandates they entail. Some of the reasons for this circumstance were alluded to before. It is difficult to precisely define – and subsequently arrive at constructs and proxies for – notions such as health, comfort, and well-being. Whereas the basic tendency of common IEQ standards is to address performance mandates in isolated domains (e.g., thermal, visual, auditory), exposure situation in actual indoor environments is always multi-domain. Building occupants are diverse in terms of their capabilities and requirements, and the nature of these requirements is not static, but changes continuously. The working processes in standardization bodies are complex and are not guided solely by purely scientific considerations.

Nonetheless, our observations so far do reveal recurrent logical patterns common in fields involving medicine, physiology, and psychology. IEQ standards frequently identify a number of indoor-environmental variables as relevant to occupants' health and comfort. The relationship between indoor-environmental states on the one side and occupants' comfort on the other side is established via *i)* psychologically or physiologically based theories, and *ii)* results of experimental studies involving human participants. In some cases (thermal, visual) comfort equations are established explicitly in order to compute the necessary combination of the value ranges of pertinent indoor-environmental variables. In other cases, explicit comfort models are not provided. Rather, it is suggested that compliance to applicable standards is demonstrated as long as the values of certain indoor-environmental parameters (such as carbon dioxide concentration) are kept in mandated ranges.

Given the preceding discussion, a number of observations concerning the current and future IEQ-related codes and standards can be formulated as follows:

- Our review of IEQ standards thus far suggest that it is frequently difficult – or even infeasible – to track back from standards to the specific body of evidence that would explain the formulation of entailed performance mandates. A potentially negative corollary of this circumstance would be to look at standards not as primary sources of technical guidance, but as mere regulatory constraints that must be addressed to avoid contractual or legal issues. It is important to understand what is not suggested here. It is certainly not suggested here that standards must routinely include in detail all theoretical and evidentiary details relevant to their requirements and recommendations. In fact, it is fairly obvious that codes and standards need to be specific and focused on operational and regulative fronts. Nonetheless, the link – or the chain of references – between formulated mandates and scientifically-based arguments for their validity is important and should be, in principle, traceable.
- The paucity of explicit references to theories and data that would unambiguously substantiate the standard-based performance requirements is perhaps not entirely a matter of documentation. Doing science in the domain of human health, comfort, and well-being has its own challenges. Research in this area has generated much in terms of valuable results, but it has to deal with serious sources of uncertainty. Having these uncertainties in mind, serious scientists working in this domain typically abstain from doctrinal claims. But regulative bodies and standardization organizations are expected to deliver, despite insufficiently certain knowledge,

clear and specific rules and mandates. Hence, it appears that living with certain levels of inconclusiveness in the results of scientific studies is perceived as a price to be paid, if codes and standards are to reliably address the accountability and liability matters in the building delivery process.

- There are indeed considerable gaps in the scientific areas expected to support the formulation of IEQ-related performance requirements. It is not always fully clear what features of indoor-environmental conditions are the right variables affecting occupants' comfort and health. The definition and verification of comfort and health constructs can rarely cover all psychological, physiological, and social aspects of exposure situations. Progress in this area is also hampered by the difficulty to obtain sufficient (detailed and long-term) observational data toward validation of theories of human perception and behaviour. Further challenges pertain to the aforementioned multi-domain nature of indoor-environmental exposure situations and the inadequacy of treating these situations in terms of isolated IEQ domains. Likewise, the increasing appreciation of the diversity of the occupants and the highly dynamic of their perceptual processes has not sufficiently reflected the scope and attitude of current IEQ standards.

The contribution could only accommodate a relatively brief and high-level treatment of IEQ-related standards and guidelines. Nonetheless, the discussion of these resources highlights not only a number of their inherent – and in part understandable – limitations, but points also to existing gaps in our scientific understanding of people's health and comfort requirements regarding indoor-environmental conditions. What is needed is an improved and more readily trackable procedure for the translation of the available knowledge in this area (with all its limitations and uncertainties) into IEQ standards and guidelines. Furthermore, our understanding of how occupants perceive and evaluate indoor-environmental conditions and how these conditions influence their health, comfort, and well-being, needs to be both expanded and enhanced.

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Data Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.