Critical reflections on indoor-environmental quality constructs

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ABSTRACT

The main focus of this paper can be summarized in terms of the following two presuppositions: *i)* The process through which we select and apply indoor-environmental quality (IEQ) constructs could be – perhaps should be – improved; *ii)* Such improvement would contribute to formulation of more robust IEQ standards and guidelines.

KEYWORDS

Indoor-environmental quality, measurement, constructs, proxies, scales

1 INTRODUCTION AND BACKGROUND

1.1 About IEQ constructs

A proper starting point in the indoor-environmental quality (IEQ) discourse is perhaps the generally recognized fact that a key objective of buildings is to provide comfortable conditions to the buildings' inhabitants. Indoor-environmental conditions are assumed to influence the health, comfort, wellbeing, and productivity of inhabitants. But judgements of what constitute comfortable indoor environments involve a strong subjective aspect. To make matters such as building users' comfort and satisfaction into operable criteria, that is to make them measurable, we must cast them in terms of well-defined constructs. A construct denotes here the shared understanding of how a specific aspect of IEQ is perceived and evaluated by inhabitants. In other words, a construct is a well-defined semantic place-holder for an specific aspect of IEQ. As such, for a given indoor-environmental setting, inhabitants can be asked to judge their perception of IEQ via assigning values or attributes to a suitably defined construct. For instance, perceived indoor air quality, or perceived thermal conditions can be assessed by asking inhabitants to rate the value of the corresponding constructs (e.g., thermal comfort, air freshness). Typically, various psycho-physical scales or semantic differentials are used in order to express the values of constructs in numeric terms.

1.2 About IEQ proxies and psycho-physical relationships

Professionals in the building design and operation fields cannot directly influence inhabitants' perceived IEQ and the values of the corresponding constructs. But they can influence the settings and conditions that are believed to contribute to the formation of inhabitants' perceptions and evaluations of IEQ. The operative rational in provision of adequate IEQ is based on the assumption that certain ranges of indoor-environmental parameters are more likely to increase the probability of positive evaluation of IEQ by inhabitants. Cast in terms of relationships or comfort equations, the rational can be formalized as follows. Salient physical features or parameters of the indoor environment act as the independent variables that can be mapped, via psycho-physical or comfort equations, onto dependent variables, i.e., inhabitants' perception as captured via constructs and their values. The physical parameters in these equations consist of measurable variables such as air temperature, air flow velocity, water vapor and other gas concentrations, illuminance and luminance levels, and sound pressure level.

Note that, some of the mentioned measurable indoor-environmental variables (e.g., task illuminance level, CO_2 concentration) are relevant to the quality of spaces in view of IEQ requirements (e.g., visual comfort, indoor air quality), but "they do not have direct phenomenal correlates: people do not 'see' illuminance; neither do they sense CO_2 concentration. But such performance indicators may be linked to others, which do have direct perceptual corollaries" (Mahdavi 2011). However, there are also variables that are "not only relevant to human occupancy, but also correlate directly with phenomenal experience. Examples of such indicators are luminance of light sources and room surfaces, indoor air temperature, sound pressure level, and reverberation time in a room. The evaluative utility of such variables is grounded in empirically documented correspondence between the variable values and people's report on their phenomenal experience (i.e., thermal, visual, and acoustical sensations)" (Mahdavi 2011). The mapping process of the physically measurable independent variables onto the values of the construct suggests that they are viewed as physical proxies (or predictor variables) of perceived IEQ (see Table 1).

Given this background, the default engineering process of handling IEQ in buildings may be formally summarized as follows:

- Inhabitants' perception and evaluation of indoor-environmental conditions can be captured via IEQ constructs (pertaining, for example, to comfort, satisfaction, annoyance);
- Construct values are assumed to be causally related to (or at least correlated with) specific ranges of independent variables that represent physical conditions in indoor environments;
- These causal relationships (or correlations), which are sometimes expressed as comfort equations, are frequently formulated based on the results of experimental studies (typically conducted under controlled settings);
- To provide adequate IEQ and to examine if it has been delivered, specific values of specific sets of indoor-environmental variables are mandated/maintained. As such, these variables are treated as physically measurable IEQ proxies, given their assumed correlation with construct values. These correlations are typically captured via the aforementioned psycho-physical equivalence relationships and comfort equations.

Conventional thermal comfort models provide a case in point for the above process (Fanger 1972). A common construct is in this case the "thermal sensation" of inhabitants in a specific environment, as obtained via a (typically 7-point) scale that ranges from very hot to very cold. The value of this construct is assumed to be predictable via an aggregated proxy (PMV), which is a function of air temperature, radiant temperature, water vapor concentration, and air flow velocity as well as personal factors, clothing and activity. Note that the point is not the validity of this specific construct and its calculation process. Rather, the example serves to illustrate a commonly used general formalism pertaining to psycho-physical equations.

Table 1: Illustrative instances of independent variables (candidate proxies of IEQ) and constructs (variables to capture subjective evaluations) in four key IEQ domains

	Thermal	**Visual**	**Auditory**	**Air Quality**
Independent variables	Air temperature, radiant temperature, water vapor content, air velocity	Illuminance, luminance, contrast, colour temperature	Sound pressure level, reverberation time, frequency (spectrum)	CO_2 and VOC concentration, Air change rate, Age of air
Constructs	Thermal sensation, thermal comfort	Visual comfort, glare rating	Loudness, annoyance	Air freshness

1.3 A note on the utility of IEQ constructs and proxies

The approach outlined in the previous sections above is operationally critical and is intended to provide accountability in designing and operating buildings with adequate IEQ. Related IEQ standards and guidelines typically entail requirements and mandates in one or both of two categories, namely prescriptive or performance-based. The former category specifies explicit mandates regarding the relevant attributes of building components and systems (e.g., the minimum window size in a room), assuming that compliance with such mandates would ensure that proxy variables of IEQ (e.g., daylight availability) can be kept in the proper ranges. The latter category spells out such ranges (e.g., the minimum illuminance level at a specific reference point in a room), leaving – to some degree – the technical details and choices to the discretion of the responsible professionals. In both cases, the assumption is that standards are firmly based on empirically established proxy-construct-correlations, and thus keeping the proxy values in the mandated ranges would ensure that a sufficiently large fraction of the population of building users would find the resultant IEQ acceptable and appropriate.

1.4 Paradigm and practice

The above remarks outline the state of the main theoretical paradigm as relevant to IEQ-related building design and operation and related standard-guided quality assurance and compliance verification procedures. However, as in many other similar areas, the state of theory and the state of actual practice are, to put it mildly, not completely aligned. This implies the need for critical reflections on the genesis and application of common IEQ constructs and the implications for IEQ standards and guidelines development processes. The next section of the paper offers a number of such reflections, addressing foundational questions regarding measurement challenges of subjective qualities, challenges in definition and operationalization of constructs, and approaches toward more transparent and evidence-based IEQ standards.

2 COMMON CHALLENGES IN IEQ DEFINITION AND ASSESSMENT

2.1 About standards

As alluded to before, the default approach toward provision of adequate IEQ in buildings involves the specification of required value ranges for selected proxy variables that are thought to be relevant to inhabitants' perception and evaluation processes. Note that a central argument in favour of this approach is the accountability exigency in the building delivery process: The stakeholders (building owners, operators, occupants) need a transparent and binding process to decide if a building's design and performance meet relevant legal and contractual obligations. Standards and guidelines are not only a primary source of related information and guidance to the practitioners, but also act as the reference documents in quality arbitration procedures. More generally, standards are often portrayed as representing the state of knowledge in the field to which they apply. In the building domain, standards may be dealing with purely technical considerations (e.g., structural resilience, construction integrity). However, IEQ-related standards go beyond purely technological issues and must consider physiological and psychological processes and phenomena involved in inhabitants' perception and evaluation of indoor environments. However, recent reviews of standards and guidelines in the IEQ domain reveal certain gaps between the explicitly stated requirements and mandates in the standards on the one side and their evidentiary basis in the scientific literature (Berger et al. 2022, 2023). These reviews suggest that standards do not routinely refer to the studies that are supposed substantiate their content, nor do they routinely disclose the procedures through which occupant-centric constructs are selected or validated. The point of this assertion is of course not to suggest that standards should be designed in the manner of scientific dissertations or papers. But transparency regarding the lineage of the included performance indicators in general and constructs in particular would have been conducive to improving standards' credibility and their impulses toward identification of research needs.

2.2 The measurement problem

In physical sciences, the act of measurements appears to comprise a straightforward mapping of physical entities to numbers. It has been thus suggested to think of measuring length, weight, or speed of objects as representing these attributes via numbers. Hence, the relationships between physical attributes of objects can be expressed in terms of the mathematical relationships between the numbers representing those attributes. For instance, the relationship between the weights of two objects can simply be expressed by the relationship (e.g., the ratio) of the two numbers that express, in proper units, their respective weights. However, matters are arguably much more complicated when we consider concepts and entities in social sciences or psychology. A measure in economics such as GDP (Gross Domestic Product) does not represent an already existing entity in the real world, but in a sense, it constructs the very entity that it is intended to measure. This circumstance could apply, at least to some degree, to IEQ-related constructs that are meant to measure occupants' wellbeing or satisfaction. Selecting the appropriate constructs for measuring such states involves pragmatic considerations and choices, a fact, which is also reflected in the methods that are used to obtain meaningful values for the respective constructs. This is not meant to suggest that measuring IEQ-related subjective phenomena would be infeasible. Researchers in fields such as psychology have indeed developed ingenious methods to define and validate constructs pertaining to subjective feelings and sensations. However, as previously implied, the use of such methods in IEQ-related research is not always consistent and systematic. Respective studies in this field do not routinely document the provenance of the applied constructs or the reasoning for the selected methodological tools (e.g., specific scales or differentials) to obtain their values. Hence, even if different studies use the same label for the constructs they use, it is not clear if they agree on the nature of what is being measured. This can negatively impact the reliability and usability of research results. Specifically, it can impede the possibility to conduct meta-studies that would coalesce the results of multiple research efforts toward formulation of generally valid conclusions.

2.3 Construct and scales inconsistencies

As mentioned before, constructs may be interpreted as formalized containers of semantic information extracted from the results of empirical IEQ-related research involving human participants. This suggests that the practical value and usefulness of research pertaining to people's health and comfort in indoor environments depend on how rigorously constructs are defined and deployed. Specifically, obtaining and understanding occupants' evaluation of IEQ via interviews, questionnaires, and surveys needs to rely on the fidelity of constructs and the scales used to obtain them. In this context, previous findings indicate that both single-domain and multi-domain studies regarding occupants' IEQ evaluations involve a number of limitations and inconsistencies in the use of common numeric (e.g., 3-point, 5-point, and 7-point) scales to obtain the response of both participants in lab studies and occupants of actual buildings. An extensive review of multi-domain studies arrived at the conclusion that existing multi-domain studies focused mainly "on the investigation of subjective perceptual responses, most commonly through numeric scales (including 3-point, 5-point, and 7-point scales) to capture test participants' responses regarding perception, comfort, satisfaction, and preference. At

times, a different number of points and different labels were used, even though the same assessment category was involved. This, as well as the inconsistent use of dimensions in analogue scales, disables the comparison of results from different studies and poses a problem for conducting large-scale meta-analyses" (Chinazzo et al. 2022).
This suggests that, even if we assume that such scales can properly reflect occupants' perception, comfort, satisfaction, and preferences, frequent inconsistencies (e.g., scale steps, labels, dimensions) can be observed in their application in related research. However, as another recent topically similar contribution suggested, "the problem goes further, particularly if we consider the complexity of transferring research results to real-life applications: The practical fitness and interpretative potential of commonly deployed formats for eliciting and representing people's response remains a formidable challenge. We simply miss a conclusive treatment (e.g., a rigorous meta-study) of the expressive power and consistency of typical scales and formats used in IEQ research even in single-domain studies, let alone in the more challenging field of multi-domain investigations. In a nutshell, occupant-centric IEQ constructs need to be of a kind that can be obtained with low level of semantic distortion and can be applied with high level of practical usability" (Mahdavi and Berger 2023).
These reflections underline a key challenge in current studies of IEQ and its effects on building users. To achieve accumulation of knowledge in the field, it would be desirable to maintain continuity in the use of constructs, but insufficient rigor in past research's validation of constructs lessens both their reliability and the value of the findings. This problem is aggravated by the circumstance that the rigorous validation of constructs is a rather laborious endeavour.

3 SCOPE OF SOLUTIONS

3.1 General research direction and quality issues

There is perhaps no one single solution to the challenges expounded on in the previous section. However, the effectiveness of constructs is a necessary condition for the viability of research on IEQ factors and their implications for inhabitants. We discussed, in a previous paper (Mahdavi and Berger 2023), a number of measures and strategies toward enhancing IEQ-related research efforts. It would be useful to briefly revisit those as follows:

- Studies regarding the variables relevant to IEQ typically involve short-term controlled experiments. These can be very useful when queries are highly focused and narrowly defined, but their results are not directly transportable to real-life (long-term and in part chaotic) occupancy situations in buildings. To address this limitation, multiple options could be taken into consideration. One could try to render the experimental settings more realistic and the population of the test participants more representative. One could also try to conduct the experiments over longer periods of time, and under different external boundary conditions. Moreover, it would be helpful if the scope of investigation approaches is widened so as to include long-term field studies and large-scale surveys. A further option lies in the so-called living lab scenarios (Cureau et al. 2022), which can provide the opportunity to monitor inhabitants in real working environments and thus more reliably capture their views on (and intervention tendencies with regard to) indoor-environmental conditions.
- Specialized researchers in fields such as neuroscience and experimental psychology investigate response patterns of test participants to all kinds of sensory stimuli. As it has been suggested previously (Mahdavi and Berger 2023), the respective studies "are typically conducted by highly experienced researchers, who are not necessarily interested in or familiar with practical IEQ issues and associated research needs. On the other hand, experimental studies by professionals closer to building design and

operation fields display at times certain shortcomings in view of the research designs' rigor and research results' interpretation, documentation, and communication (Chinazzo et al. 2022). This implies the potential for improved research quality via collaborative efforts involving both highly qualified specialized scientists and professionals familiar with specific need and challenges in the IEQ domain."

- A further point regarding the improvement potential of IEQ-related research concerns its relevance to the practice. Viewed as a form of applied research, IEQ-related investigation should ideally focus on the kinds of constructs whose values can guide decision-making processes in building design and operation. This requirement implies "the need for the reassessment of the way constructs are defined in research designs and quantified based on research results. Ideally, the obtained values of constructs should provide useful information about how inhabitants perceive, evaluate, and react to multi-domain exposure in indoor environments and how the related processes influence their health and comfort" (Mahdavi and Berger 2023).
- A final reflection on general IEQ research quality issues pertains to the presence of underlying theoretical foundations. It is of course possible to view the relationship between the values of the indoor-environmentally relevant independent variables and the values of the constructs as mere correlational patterns and arrive at respective statistically-based comfort equations. However, grounding such regularities on explicit (e.g., causal) theories can arguably offer a deeper understanding of the underlying physiological and psychological processes. Professionals in the building design and operation domain could benefit from such deeper insights that can be obtained based on explanatory white-box models describing how indoor-environmental conditions influence inhabitants' state of mind vis-à-vis comfort and wellbeing.

3.2 Thoughts on validation of constructs

Building research in the past entails instances of explicit construct validation related to human perception. However, these efforts have not routinely followed standardized processes as recommended in psychological research. Rather, as the following two instances exemplify - they appear to have been devised in a specific – and not necessarily scalable – experimental situation:

- A study of the subjective evaluation of architectural lighting via computationally rendered images (Mahdavi and Eissa 2002) involved the use of semantic differential rating scales. The idea was to compare the test participants' subjective assessments of real spaces with those of computationally generated renderings. To this end, bi-polar pairs of terms were collected via a survey and compared with semantic differential scales developed by Flynn et al. (1973). This resulted in a set of 28 pairs of terms. In the absence of a global validation result for these bipolar scales, it was decided to test the collected set locally "using a small group of test participants who evaluated the lighting quality of a number of office spaces as projected in slides. The final metric was derived based on a statistical analysis of the results of this test. Principal component analysis (PCA) was used as a data reduction method to eliminate the redundancy among the selected scales. The resulting scales are 10 pairs of terms under seven categories", which were subsequently used to conduct the actual study (Mahdavi and Eissa 2002).
- Another study involved a construct for the judgement of the compactness of architectural objects. The traditional indicator of compactness as used in building physics is the so-called characteristic length (Mahdavi et al. 1996), which denotes the ratio of the volume of an object to its total surface area. Mahdavi and Gurtekin (2001,

2002, 2004) proposed a different indicator, namely the "Relative Compactness" (RC), which is suggested to more closely correlate with people's visual judgement of shapes' compactness. RC is derived by comparing the volume to surface area of a shape (V/A) to the volume to surface area of the most compact shape (i.e., sphere) of the same volume ($RC = 4.84 \times V^{2/3} \times A^{-1}$). Given the novelty of the RC concept and hence lack of prior validation, it was necessary to empirically explore the degree to which RC captures the subjective assessment of the compactness of building shapes. To this end, a sample of 14 representative residential building shapes were subjectively assessed by 40 participants in view of their compactness. The statistical analysis of this empirical study confirmed the viability of the proposed relative compactness construct and its perceptually relevant advantage over characteristic length indicator (Mahdavi and Gurtekin 2004).

Many such locally limited validation efforts can be cited in IEQ-related test designs, and one can understand their frequently ad hoc tendency, given the fact that external validation of constructs requires considerable time, effort, resources, and expertise. But if the state of knowledge in the IEQ field and the respective reliability of respective guidelines and standards are to be substantially improved, the underlying research efforts need to elevate the quality of research designs in general and the quality of constructs in particular. To this end, both specific – rigorously designed – case studies in experimental psychology and instructive literature on methodology (e.g., Cronbach 1990, Fowler 1993, Peterson 1999, Patten 2000, Fischer and Hüttermann 2020) can provide guidance.

4 CONCLUDING REMARK

Recent reviews of both IEQ-related standards and scientific studies regarding the effect of indoor-environmental conditions on people's health, comfort, and wellbeing point to a number of persistent limitations. The critical reflections presented in this paper point to a paucity of explicit evidence underlying the standard-based IEQ mandates, and deficiencies in the technical literature, which is expected to provide that evidence. The latter deficiencies pertain to the underlying research designs in general and the precise definition and careful validation of the deployed constructs in particular. These limitations must be addressed and mitigated if one expects major qualitative leaps in the quality of IEQ research and derivative standards. Whereas we outlined some of the necessary steps for this purpose, we have no illusions regarding the formidable nature of the task and the considerable level of required efforts. Shortcuts, piecemeal steps, and ad hoc fixes may appear as progress, but do not represent true alternatives to rigorous systematic research practices. To echo what Euclid reputedly said of geometry, there is also no via regia to construct validation. It requires solid knowledge of statistics, considerable experience with experimental design, as well as deep knowledge of the relevant domain (in the present context, IEQ) and its underlying theoretical foundations.

5 ACKNOWLEDGEMENTS

Ardeshir Mahdavi is supported by the FWF (Austrian Science Fund: "Der Wissenschaftsfonds") Project MuDoCo (Project I 5993). In developing the ideas underlying the present paper, the authors benefited from discussions in the framework of IEA EBC Annex 79 – Occupant-Centric Building Design and Operation.

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