Approaches toward multi-aspect indoor-environmental performance indicators

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Abstract

This paper explores the prospects for defining multi-aspect indoor-environmental performance indicators. Specifically, it discusses potential approaches to aggregating the values of performance indicators from different domains into the value of unified construct intended to capture the overall quality of indoor environments as relevant to occupants' comfort requirements. To this end, the potential of numeric weighting strategies and controlled experimental studies are discussed. The key objective is to provide a structured conceptual framework and a preliminary feasibility assessment with regard to the formulation and operationalization of multi-aspect indoor-environmental performance indicators.

Key innovations

- Structured analysis of the problem of multi-domain indoor-environmental performance
- Classification of methods for the derivation of aggregate performance indicators

Practical implications

Critical presentation of the possibilities for and limitations of expressing the multi-fold results of building performance simulation runs in terms of aggregated building performance indicators.

Introduction and background

The results of building simulation studies are typically expressed in terms of the values of building performance indicators (Han et al., 2021). In earlier contributions (Mahdavi, 2004; 2011), a conceptual classification of performance indicators was suggested as follows.

Some performance indicators, such as buildings’ heating and cooling loads, are not directly relevant to buildings’ indoor-environmental performance. Knowledge of a building’s energy performance does not necessarily say anything about its indoor-environmental performance. A second class of indicators, such as task illuminance levels or CO₂ concentrations in the indoor air are relevant to buildings’ indoor-environmental performance (e.g., visual comfort, indoor air quality). Yet they do not have direct phenomenal correlates: People do not see illuminance or sense CO₂ concentration. However, these performance indicators may be linked to a third class of indicators that are not only relevant to occupants' health and comfort requirements, but also directly relevant to phenomenal experience. Examples of such indicators are luminance of light sources (relevant to brightness perception), indoor air temperature (relevant to thermal sensation), and sound pressure level (relevant to auditory experience).

The focus of the present contribution is on certain characteristics of these last two categories of performance indicators. Specifically, we address the circumstance that, whether relevant phenomenally or not, the indicators in these two categories are frequently obtained for isolated aspects or domains of indoor environment (Schweiker et al., 2020). In other words, the indicators are associated with differentiated dimensions of environmental exposure situations. These dimensions are typically referred to under labels “thermal”, “visual”, “auditory”, and “olfactory”. These terms can be indeed suggested to express the underlying link to respective human sensory channels responsible for perception of heat, light, sound, and odours.

Buildings' indoor-environmental performance is typically measured, simulated, and mandated in terms of these separate dimensions or domains. Likewise, building codes and standards typically specify the quality requirements in terms of the ranges of the values of these distinct performance indicators. However, this practice, particularly as applied to perceptually relevant performance indicators, may not be ideal. Occupants' evaluation of indoor-environmental conditions arguably emerges from a unified field of perception (Searle, 2015). Hence, comfort constructs as defined for separate dimensions of the exposure situation may not simply capture the aggregate impact of a complex indoor-environmental exposure situation on buildings’ occupants. As such, the aggregation of the values obtained for such isolated indicators into the value of a unified indoor-environmental quality indicator remains a non-trivial challenge.

Given the complexity of this challenge, the present contribution does not intend to provide a worked-out solution. Rather, the objective is to provide a structured conceptual framework and a preliminary feasibility assessment concerning the formulation and operationalization of multi-aspect indoor-environmental performance indicators. The contribution is thus expected to provide a systematic map of necessary short-term, midterm, and long-term efforts toward establishing computable cross-domain performance indicators for the evaluation of indoor-environmental conditions.
A tale of three paths

Consider the problem of constructing aggregate indoor-environmental performance indicators that would capture comfort evaluations across multiple domains. To tackle this problem in a structured manner, we start with the working assumption that the navigation of the solution space for this problem can unfold along three distinct paths, which are labelled, in the following discussion, as "expert views", "occupants' evaluations", and "empirical investigations".

Expert views

The first path involves the formalization of the problem in terms of a multi-variable function. The aggregate performance indicator, which is meant to capture a unified evaluation of indoor-environmental conditions constitutes the independent variable in this function. Let us call this variable PIx. Dependent variables are assumed to represent salient measures (quantitative, numerically harmonized proxies) of domain-specific performance aspects related to thermal, visual, auditory, or olfactory dimensions of indoor environments. Let us call those PIy, PIz, Pla, Plb. The general form of the multi-variable function would be thus:

$$PI_x = f(PI_y, PI_z, PI_a, PI_b)$$

(1)

The exact mathematical formalism for the expression of this function is not of concern here. Consider thus a simple (linear) instantiation of this expression (Eq. 2) involving domain-specific coefficients w_t, w_v, w_a, and w_o (Eq. 2 and 3).

$$PI_x = w_t PI_y + w_v PI_z + w_a PI_a + w_o PI_b$$

(2)

$$w_t + w_v + w_a + w_o = 1$$

(3)

This formulation leads to the familiar numeric weighting-based formalization and involves the likewise familiar weighting problem. In other words, it requires the knowledge of the values of the weighting coefficients. In the absence of codified knowledge, one might take a form of heuristic approach, referring to, for instance, on views and judgments of the expert in the relevant domains. In such a scenario, the relative weight of single-domain performance indicators toward the derivation of a unified indoor-environmental performance indicator is pursued following a Bayesian strategy. Thereby, judgements are solicited and iteratively refined from expert panels.

The emerging matrix of coefficient weights could then be structured, among other things, in relation to a variety of building types and contexts. Table 1 shows a conceptual instance of such a matrix, with weighting coefficients for the two dimensions of sensory domains (t, v, a, o) and building types, namely residential (R), commercial (C), educational (E), and healthcare (H) buildings. Theoretically, the two-dimensional matrix of Table 1 could be extended to include other potentially relevant dimensions, such as the pertinent climatic region.

### Table 1: A conceptual matrix of weighting coefficients in multi-domain functions for different building types.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Building type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
</tr>
<tr>
<td>t</td>
<td>Wt</td>
</tr>
<tr>
<td>v</td>
<td>Wv</td>
</tr>
<tr>
<td>a</td>
<td>Wa</td>
</tr>
<tr>
<td>o</td>
<td>Wo</td>
</tr>
</tbody>
</table>

Occupants’ evaluations

The second path involves initially a similar strategy to the first path. In this case too, a multi-variable equation is established including multiple domain-specific independent variables (quality proxies for individual domains) and corresponding weighting coefficients (see Eq. 1 to 3). However, we consider a different approach toward the derivation of the values of the weighting coefficients. To this end, we envision the utilization of large-scale occupant surveys and interview campaigns in different buildings and different locations. Such surveys and interviews would have to be carefully planned. Specifically, robust constructs must be formulated that not only elicit indoor-environmental quality aspects and comfort implications in individual domains, but also include an effective total quality evaluation scale. The resulting accumulated information facilitates the mathematical mapping of subjective single-domain evaluations of single aspects of sample environments onto the values of the aggregate construct, resulting in the calibrated values of the coefficients in the multi-variable function. As such, existing databases of past comfort-related surveys could potentially entail useful material for this approach. However, their usability is hampered by limitations in the definition of domain-related constructs and their relation to an aggregate construct, which is often not conclusively defined or not included at all. On the other hand, efforts involving carefully crafted constructs have not yielded conclusive results to the small size of conducted surveys (Mahdavi et al., 2019; Mahdavi et al., 2020a).

Before embarking on the third and last path, some critical reflections on the last two are in order. Even if operationalized – and it has been operationalized in certain applications – the weighting-based derivation of aggregate evaluations has some inherent limitations. To elaborate on this point, consider a recently completed review of common building rating schemes (DGNB, 2020; LEED, 2020; Mahdavi et al., 2020b; WELL, 2020). These schemes aim definition and assessment of buildings’ total quality across multiple fields, including criteria related to, for instance, energy use, environmental impact, and indoor-environmental quality. To achieve total quality ranking, the schemes often adopt the weighting approach we discussed before.

Even though these schemes recognize the multi-domain nature of occupants’ exposure to buildings’ indoor environments, but they do not implement them in a consistent way. For instance, the manner in which proxies
and indicators are selected and treated in each domain is diverse, inconsistent, and arguably incomplete. For instance, they ignore the available degree of personal control (perceived control) and its important role in evaluation processes of indoor environments (Paciuk, 1990). More important, for the present discussion, is a further challenge common ranking schemes face, namely the aggregation of evaluation results from individual domains into unified ratings. As such, the adopted procedures for score aggregation into whole-building quality ranking is largely opaque and in part arbitrary. In the absence of a deeper understanding of cross-domain processes of perception and evaluation, building quality ranking schemes lack evidence-based methods for the distribution of quality scores and corresponding weights to different criteria.

Note that even mandated requirements (e.g., recommended value ranges of indoor-environmental performance indicators) in single-domain standards are not always fully evidence-based (Mahdavi et al., 2020b). Nonetheless, it is often possible to trace such mandates back to some material from empirically-based studies. This is true, for instance, of the definition of maximum exposure times and levels to noise, maximum tolerable glare intensity, desirable ambient temperature ranges, or maximum concentration of air pollutants. However, a comparable level of empirical grounding cannot be detected in building quality assessment schemes that aim at aggregating multiple domains and associated respective performance indicators (ASHRAE, 2016; Mahdavi, 2020; Mahdavi et al., 2020b). There is thus a need for further in-depth study of the combined effects of multiple influence factors from multiple indoor-environmental quality domains.

**Experimental investigations**

The previous discussion naturally brings us to the third path, which is at once the most rigorous and the most demanding. As such, it requires an experimentally grounded understanding of the emergence of the unified field of perception and associated aggregate quality evaluation of indoor environments. To this end, presumably a wide spectrum of empirical methods can be applied, including methods from disciplines of physiology, neuroscience, and cognitive psychology. A common approach in indoor environment quality research involves experimental studies with human participants conducted under controlled conditions. Such controlled studies facilitate, in principle, the systematic modulation of suspected independent variables pertaining to different dimensions of the exposure situation and documentation of the resulting feedback from participants. The objective is to explore possible cross-modal and combined effects of multiple indoor-environmental factors on building users’ perception and behaviour tendencies.

To assess the state of art in this area, we recently reviewed a relatively extensive set of previous studies of multi-domain exposure situations (Mahdavi et al., 2020c). The majority of these studies explored the consequences of multi-domain exposure. Thereby, they considered different combinations of environmental variables. Notwithstanding their valuable contributions, the review concluded that the findings of these studies remain limited and inconclusive. As such, specific, consistent, and significant instances of perceptually relevant cross-model interdependencies have not been unequivocally established. A number of issues may be responsible for the inconclusiveness of these studies. They are typically short-term, they are hampered by challenges such as ethical issues, privacy constraints, limited, artificial, and unrealistic settings, limited sample size, diversity, and representativeness, the Hawthorne effect (Diaper, 1990), and required technical and monetary resources. The review revealed also the lack of a real carryover effect of past research. Frequently, research efforts start from scratch, and there is a paucity of standardized research designs. Consequently, the majority of past efforts in this area do not lend themselves to comprehensive meta-analyses. Moreover, the critical importance of collaboration between professionals from both engineering disciplines and human sciences has not been truly recognized. Finally, the reviewed research efforts have been mostly conducted without reference to foundational theories of human perception and behaviour. This points to yet another challenge, in this area, namely the arguably sparsely filled theories of human perception and behaviour that would offer the right level of resolution and specificity for multi-domain experimental studies of complex indoor-environmental exposure situations (Mahdavi, 2020).

A more specific illustration of these challenges can be provided via reference to a recently conducted original case study (Berger and Mahdavi, 2021). Whereas this study could not remedy the entire list of previously mentioned shortcomings in multi-domain experiments, certain aspects of the research design were intended to increase the possibility of detection of cross-domain influences in participants’ perception and evaluation processes. These aspects relate to a tight research design (with clearly specified dependent and independent variables, formal hypotheses, and systematic descriptive and inferential statistical analysis). Moreover, the study could also rely on feedback from close to 300 participants, which is an atypically large number for controlled laboratory studies.

Nevertheless, a clear signal of cross-domain influence of visual and/or auditory conditions on participants’ thermal sensation and thermal comfort vote could not be detected. To exemplify the results, consider the distributions of participants’ reported thermal sensation votes under the same thermal conditions but different visual and auditory conditions (see Figure 1). Thereby, V1 and V2 denote visual conditions without and with traffic noise exposure. As Figure 1 shows, no discernible shift in participants’ thermal sensation votes could be observed as a consequence of fairly significant changes in visual or auditory conditions.
Conclusion

Let us take stock of the preceding discussion. Application of computational building performance assessment tools can generate a host of data in a variety of domains. This data is often processed and compiled over time (from sub-hourly intervals to multi-year periods) and space (from individual details and zone to entire urban districts) and expressed in terms of the values of respective performance indicators. As with other domains, common building quality evaluation procedures involve the comparison of the obtained values of performance indicators with benchmarks in codes, standards, and guidelines. Frequently, performance indicator values are obtained for alternative options of new building designs or retrofit solutions and compared to establish rankings and priorities. This last use case (i.e., comparison of options, ranking of solutions) has particularly motivated attempts to derive more general (e.g., whole building) performance indicators from values of performance indicators in multiple domains. The aforementioned building quality certification and rating schemes regularly use weighting methods (DGNB, 2020; LEED, 2020; Mahdavi et al., 2020b; WELL, 2020).

In this context, the outcome of our inquiry can be summarized as follows.

- Simulation results (computed values of performance indicators) from highly diverse individual domains can be numerically aggregated via weighting procedures. However, the related procedures are inherently susceptible to subjective considerations and could be biased or even arbitrary. Hence, caution and appropriate provisions are in order when using weighting methods. At a minimum, the deployed weighting schemes and their numeric features must be communicated in a transparent and reproducible fashion.

- There may be rational, objective, and evidence-based methods for aggregation of performance indicators related to effects and impacts within a specific category. For instance, within the life-cycle analysis category (e.g., "global warming"), magnitudes of different contributors (e.g., greenhouse gas emissions) can be aggregated, via normalization, into the equivalent value of a designated substance (e.g., CO₂-equivalent emissions).

- It may be possible also in the indoor-environmental quality assessment area to aggregate indicators of occupants' comfort in different domains (thermal, visual, auditory, olfactory) into the value of a single construct, representing the overall level of occupants' satisfaction or comfort given a multi-domain exposure situation. However, to do this objectively, one would have to provide empirical evidence for the applicability and suitability of the aggregation strategies. Such evidence is currently not available.

These insights can be further summarized as follows. In many instances of simulation-based building performance assessment, parallel presentation of results from separate domains may be unavoidable. Proper documentation and visualization techniques (e.g., differential graphs and polar diagrams with multiple axis for separate performance categories) can support the interpretation process. But this would not replace the need for expert human judgment toward making overall quality inferences and option ranking. Numeric weighting processes can support the compactification of multiple strands of performance indicator values, but is frequently based on rather opaque premises. Here, the minimum requirement would be the transparent communication of the reasoning behind the applied weighting approach.

An evidence-based method for the aggregation of single-domain indicators of buildings' indoor-environmental quality indicators is still out of reach, but it would be possible at least in principle. It would need, however, further in-depth advances in terms of possible avenues of exploration. To this end, substantial progress would be required in acquisition of substantiated expert input, large-scale field studies of occupants' building quality evaluations, controlled studies of occupants' perception of multi-domain exposure situations, and fundamental – neuro-physiologically oriented – research into the nature of multi-sensory perceptual phenomena.

Figure 1: Distributions of participants thermal sensation votes under the same thermal conditions with and without presence of glare and noise (Berger and Mahdavi, 2021).
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References


