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TOWARDS PREDICTING THE SATISFACTION WITH INDOOR ENVIRONMENTAL QUALITY IN BUILDING PERFORMANCE SIMULATION

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SUMMARY

Can computer simulations be used to predict occupant satisfaction and stimulate the design of energy-efficient, healthy buildings? This is the central question of this paper. In everyday practice, simulations are mostly used for building energy analysis and for limiting the occurrence of discomfort. There are, however, also opportunities for a more holistic prediction of indoor environmental quality (IEQ) with a focus on creating a positive experience for occupants. The aim of this position paper is to connect the field of building performance simulation (BPS) with IEQ research, by discussing the needs, recent advances and remaining challenges for prediction of overall occupant satisfaction. First, we highlight the importance of taking into account multiple performance criteria and physical domains. Based on a review of software tools, we then present a classification of their capabilities to simultaneously assess the various physical interactions. In the discussion that follows, we evaluate the merits and drawbacks of combined IEQ indices, and show how simulations can be used for predicting them. The paper concludes with an overview of research needs and possible directions for further development based on recent advances in the building performance simulation field.

INTRODUCTION

Designing buildings with indoor climates that are optimized for occupants' comfort and productivity, yet allow for energy-efficient and cost-effective operation, requires careful reconciliation of many different performance aspects. During the design phase, simulation tools can be of great assistance to support well-informed decision-making (Hensen & Lamberts, 2011). These predictions allow for analysis of multiple building and systems design options and they enable virtual performance testing under various usage scenarios.
The common use of simulation support for building design has almost exclusively focused on HVAC system sizing and performance prediction of energy conservation measures. Because of this focus, this design activity is often referred to as building energy modelling. In such studies, aspects of indoor environmental quality (IEQ) tend to play an inferior role; typically in the form of imposed temperature set points and

ventilation rates, or a permitted number of exceedance hours to guarantee an acceptable level of performance or compliance with building codes.

As we will show in this paper, many simulation programs offer underappreciated possibilities for bringing performance prediction of IEQ more to the forefront. In addition, and in contrast with the focus on limiting discomfort, opportunities for increased emphasis on healthy building design and the positive aspects of IEQ are arising. Nevertheless, there exists still a discrepancy between the industry-standard type of simulation projects, and the need to predict more holistic concepts such as occupant satisfaction, productivity and well-being.

This position paper was developed in two stages. First, we envisioned what the prediction of occupant satisfaction with BPS tools could look like, and then we reasoned backward to identify what is needed to get there. Based on literature and software reviews, this paper describes the analysis of different steps to predict occupant satisfaction, and concludes with an overview of research needs and possible directions for future development based on recent advances in the BPS field. Figure 1 provides a graphical outline of the concepts that we discuss.

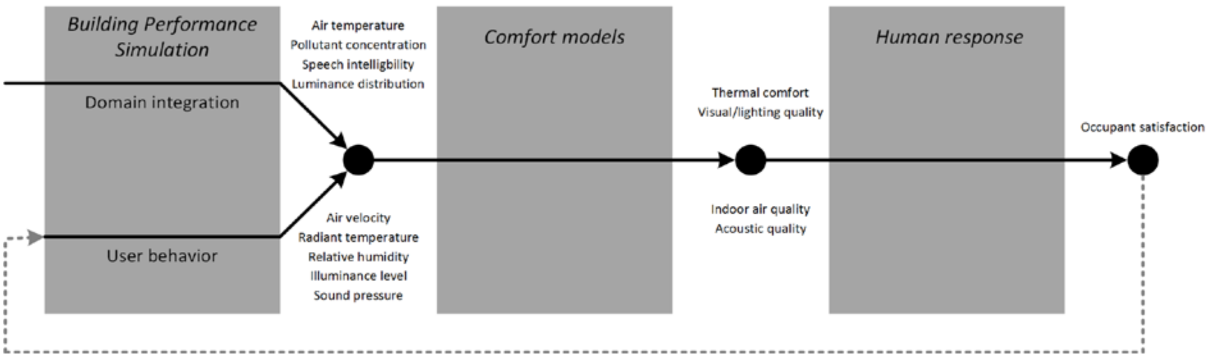


Figure 1. Relationships between the concepts and models discussed in this paper.

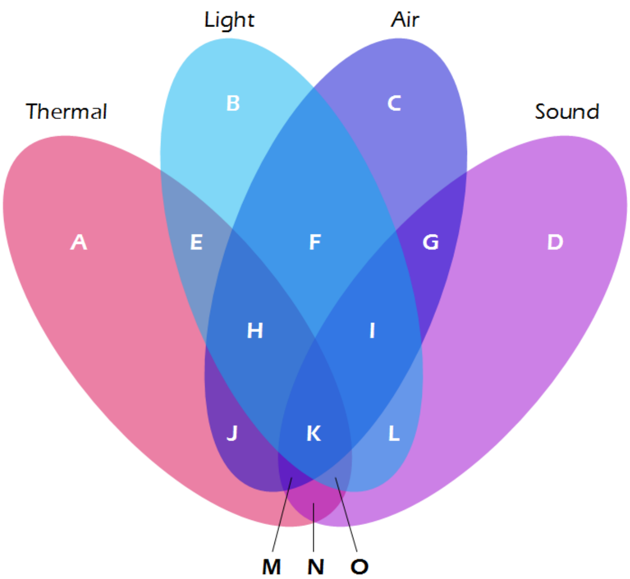
SIMULATION-BASED IEQ ASSSESSMENT

Indoor environmental quality is a multi-dimensional construct that consists of many different aspects. Four categories are typically distinguished: thermal comfort, visual/lighting quality, indoor air quality (IAQ) and acoustical quality (Bluyssen, 2010). For each of these sub-fields, computational models have been developed to predict the performance of proposed building designs (Chen, 2009; Hensen & Lamberts, 2011; Reinhart & Wienold, 2011; Vorländer, 2013). Tools are available at different spatial resolutions; ranging from component-level simulations to the whole-building and urban microclimate scale (Crawley et al., 2008). As a result, they also predict performance indicators at different levels-of-detail.

The calculations and algorithms for each of these computational models have initially been implemented in standalone software tools. The tools were developed by rather disconnected research communities, and are used by practitioners of different engineering disciplines (Kusuda, 1999). The drawback of such domain-specific models is that they cannot account for the interactions and combined effects with other (IEQ) performance aspects (Citherlet et al., 2001). This creates some shortcomings, given the increasing demand for higher performance of buildings, and the trend towards integrated, innovative design solutions. In such design processes, there is a need for more advanced decision-support, but domain-specific calculation methods tools often fail to deliver information at the intended level (Mahdavi, 2011). Two examples are given to illustrate the importance of this domain integration:

- Thermal mass plays an effective role in reducing overheating risks because it can attenuate diurnal variations in indoor temperature. However, exposed materials with high thermal storage capacity (e.g. concrete) often perform poor in terms of sound absorption (Lehmann et al., 2007). To find a good trade-off between room acoustics, thermal comfort and system efficiency, it is important that their mutual impacts are considered in an integrated way (Citherlet & MacDonald, 2003).
- If a design team wants to get a balanced view of the impact of a double skin façade with integrated solar shading or other types of climate adaptive building shells (Loonen et al., 2013), it is needed to assess performance in multiple dimensions. Dynamic interactions between the four physical domains that constitute IEQ are directly influencing each other, and a simulation model should simultaneously consider all these effects to allow for well-informed decisions.

SIMULATION STRATEGIES



A	ApacheSim, eQUEST, TRACE, VABI Elements
B	Daysim, DeLight, Dialux, Radiance, SPOT
C	Airpak, COMIS, CONTAM, Fluent
D	CATT Acoustic, ODEON, Sabin
E	MIT Design Advisor, Sefaira
F	
G	
H	EnergyPlus, IDA ICE, IES-ve
I	
J	TRNSYS
K	Ecotect, ESP-r
L	
M	COMSOL
N	
O	

Figure 2. Coupling between physical domains in several state-of-the-art building performance simulation tools (non-exhaustive list).

Figure 2 gives an overview of different BPS programs and their ability to predict the various aspects of IEQ. The fields A, B, C and D represent the four separate domains, whereas all other fields indicate one of the many possible combinations/overlaps. The majority of current software tools originated as single-domain tools, and still focus on one aspect, which implies that multiple analyses in different software tools are needed to assess the implications of a design option on more than one IEQ aspect. Some programs share their building data model with other tools, for example in the form of Revit or SketchUp plugins. This avoids redundancy, and eases the simulation process, but does not overcome the inability to solve coupled physical interactions.
The aim of an "integrated simulation approach" is to preserve the integrity of the entire building system by simultaneously processing all energy transport paths and physical interactions (Clarke, 2001). The thermal domain is the one with most connections to other physical aspects, especially with coupled airflow predictions or

daylight models. Models for room acoustics are mostly disconnected. Only two of the 417 programs in the Building Energy Software Tools Directory, maintained by the U.S. Department of Energy are capable of performance simulation in all four physical domains (US DOE, 2015). It should be noted that the occurrence of published projects with integrated simulation studies involving all four aspects is very rare.

COMFORT MODELS

The previous section on simulation strategies dealt with the prediction of physical conditions in indoor spaces (refer to Figure 1 for some examples). In terms of comfort prediction, this output of BPS models can be seen as observable states, physical descriptors (Bluyssen, 2010), exposure types (Tuomainen et al., 2002) or environmental stressors (Sensharma et al., 1998). Instead of analysing all the factors separately, it is usually convenient to aggregate them into compound IEQ indicators (e.g. thermal comfort, visual/lighting quality, IAQ, acoustical quality) with the use of appropriate comfort models. Simulation results act as input for such models. Various comfort models are available for different applications (Loomans et al., 2011), and it is beyond the scope of this paper to describe them at length. Knowledge in this field is continuously progressing, for example with recently reported research on the impact of view to outside (Hellinga & Hordijk, 2014), glare perception (Sarey Khanie et al., 2013) and satisfaction with automated dynamic facades (Bakker et al., 2014). Provided that all relevant physical aspects and their interactions are modelled at an appropriate level of detail, we suffice to say that this step can be completed by converting raw simulation output in the post-processing phase.
The use of comfort models leads to one indicator for each IEQ aspect. To be able to evaluate and rank the performance of different designs on a comparable scale, and to relate the different IEQ scores to one another, it is a common strategy to express the results in comfort classes or categories (e.g. A, B, C or i, ii, iii, iv) (EN15251, 2007). Doing this is not without controversy (Heinzerling et al., 2013), as the classification limits vary widely between studies and between physical domains. Another approach proposed by e.g. Nagano & Horikoshi (2005) and Huang et al. (2012), devised classification charts with multi-criteria satisfaction zones as a visual way of comparing the performance of different indoor climates.

OCCUPANT SATISFACTION

Going one step further than a side-by-side comparison of different comfort aspects is the articulation of IEQ into a single overall measure of how well a space is performing (Humphreys, 2005; Rohles et al., 1989). The main motivation for predicting overall occupant satisfaction as a composite acceptability rating is that it can explicitly include the *importance* of different IEQ aspects in the assessment. Numerical ratings that are able to express the quality of an indoor environment in one single number are often referred to as IEQ indices. They can be obtained via IEQ models. Such IEQ models employ data-driven correlations (e.g. weighting factors) that link objective measurements of indoor conditions to perceived overall IEQ satisfaction from post-occupancy field surveys or databases. It involves a weighted subjective averaging process that accounts for the combinatorial effects of all IEQ aspects, and how this is perceived by building occupants (human response) (Frontczak & Wargocki, 2011; Wong et al., 2008). The scores or ratings can directly be used for ranking and comparing the multi-criteria performance of different existing buildings. Occasionally,

such models have also been used for bottom-up occupant satisfaction prediction to support design decision-making in simulation-based studies (Catalina & Iordache, 2012; Jin et al., 2012). In such studies, the IEQ models act as dose-response model (Bluyssen, 2010), linking observable environmental states to human responses.
Currently available IEQ models are not perfect and probably they will never be. Many physical, physiological, and psychological factors complicate the development of comprehensive IEQ models, and as Heinzerling et al. (2013) puts it: "devising a universal weighting scheme that applies to all buildings at all times is unlikely".
In 2005, Humphreys raised some questions regarding the usefulness of combined indices for the indoor environment. Since then, much research has been done, but most of the questions are still only partially addressed (Bluyssen, 2010; Humphreys, 2005; Kim & de Dear, 2012; Levin & Emmerich, 2013):

- Does dissatisfaction with one aspect imply that the environment is rated poorly overall? How to avoid this type of "revenge variables" (Leaman & Bordass, 1999)?
- Does the positive evaluation of one aspect of the environment mean that the whole environment is favourably rated? This would indicate the existence of so-called "forgiveness factors" (Deuble & de Dear, 2012).
- Does the overall perceived comfort correlate with the average level of satisfaction with the several aspects?

IEQ models and combined indices for satisfaction with the indoor environment are not a silver bullet solution for design of energy-efficient, cost-effective, healthy and productive buildings. However, despite the limitations, we argue that there is certainly an important role for IEQ prediction in performance-based building design. The main advantage lies in having an *objective* basis for comparisons. From a simulation point-of-view, a major challenge comes from making the connection between the sensory basis for environmental factors (physical models) and the resulting evaluative judgment or human response (Levin, 1996; Mahdavi, 2011). As our understanding of these complex issues grows, and more information comes available, it should be integrated in the interfaces and input-output structures of BPS software.

USER BEHAVIOR

Assumptions about occupant behaviour play an important role in the evaluation of building performance (Hoes et al., 2009). Attempts to model occupant satisfaction should therefore include appropriate sub-models for taking this human influence into account. In the first place, such models need to account for occupants' presence and activities. This information acts as boundary conditions to the simulation models (e.g. internal heat gains, pollutant sources, etc.). In the second place, they need to consider actions and reactions, such as light usage, shading control, window opening, and personal control over HVAC systems (Boerstra et al. 2013; Haldi & Robinson, 2010). To model this correctly, a feedback mechanism between occupant satisfaction and model inputs needs to be implemented (Figure 1).
The modelling approaches and occupancy scenarios that are available in traditional simulation programs (e.g. pre-defined schedules) are a simplified representation of reality; perhaps too simple for accurate IEQ models. Many ongoing research activities aim to make the simulation models for occupant influence more powerful. The recently started IEA ECB Annex 66 project has as goal to harmonize these concurrent developments, and establish best-practice guidelines.

CONCLUSIONS AND FUTURE PERSPECTIVES

The contribution of this paper is positioned at the interface between building performance simulation research and the multi-disciplinary field of indoor environmental science. In the ideal scenario, building design decisions should be made with full cognizance of the interdependent, dynamic relationships between indoor environmental variables, and how they would be perceived by occupants. The central question that we addressed in this paper was: Can computer simulations be used to predict occupant satisfaction and stimulate the design of energy-efficient, healthy buildings? One may disqualify this question as not yet relevant because of the many knowledge gaps and inherent psycho-social difficulties in translating measured/predicted environmental variables into IEQ indices. We acknowledge the incompleteness of existing IEQ models, and stress that the prediction of occupant satisfaction in buildings is a challenging task with many multi-scale, multi-physics features. Nevertheless, we also argue that there is a role for simulations to advance these developments in research settings and engineering practices. We conclude the paper by showing a number of trends in BPS research that may ease this process.

- Even though IEQ models are not yet mature, many things can be learned with the use of simulations. By taking advantage of uncertainty analysis techniques, different scenarios (IEQ models and parameters) can be tested to identify the dominant principles in a systematic way. In addition, structured design space explorations can be performed to increase our understanding of the governing relationships between building design variables and their IEQ implications.
- Enhanced domain integration in simulation tools remains an important point of attention. Due to interface limitations and other constraints in legacy software programs, it is not always feasible to embed all relevant physical interactions in one simulation environment. A promising alternative is the use of co-simulation, where multiple physical domains are handled by independent solvers, but share information through run-time communication (Trcka, Hensen, & Wetter, 2009). The recent advances in terms of standardization of protocols for data-exchange (i.e. Functional Mock-up Interface (FMI)) hold the promise of significantly increased scalability of co-simulation solutions.
- A practical obstacle for multi-domain building performance assessment in practice is the lack of interoperability and incongruence of data/input requirements for the various types of models. The diffusion of building information modelling (BIM)-based software in practice is a hopeful sign that these issues will be relieved in the near future.
- A new development in building simulation is the introduction of thermo-physiological models for a more holistic prediction of thermal sensation (Schellen et al., 2013). Such models also account for local effects and can be used to analyse the performance of innovative room conditioning concepts. Moreover, they predict individualized IEQ experience instead of the “average” person, and are therefore an interesting direction for further research in this area.
- Productivity is often regarded as the economic expression of human performance. Building performance simulation output can be coupled to economic models that compute the financial effects of productivity, concentration, creativity, sick leave, etc. (Jin et al., 2012; Kershaw & Lash, 2013; Tuomainen et al., 2002). Predicted overall occupant satisfaction can be an intermediate step in this process, and enable economic assessment of design decisions over the whole building lifecycle.

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