THE HUMAN DIMENSION OF BUILDING PERFORMANCE SIMULATION

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ABSTRACT

The human dimension of building performance simulation can be approached from different vantage points. This contribution addresses the following three. First, building simulation tools and environments need to exhibit a high degree of usability. They are expected to provide effective support for generating building models and processing simulation results. Second, the representation of people's presence and actions in building simulation models requires a sound empirical basis. It must be properly gauged toward applicable objectives of the modeling activity. Third, the human dimension is central to a large and important class of building performance indicators. These indicators are expected to properly capture the indoor environmental quality of built spaces in view of their suitability for human users.

INTRODUCTION

The human dimension of building performance simulation has not been thoroughly addressed in the past. A deeper understanding of this dimension may divulge promising opportunities for progress in the building performance simulation domain. The subject matter of the human dimension of building performance simulation can be approached from different vantage points. The present contribution circles around the following three:

i) Performance simulation applications are developed and applied by people. Professionals (architects, engineers, researchers, educators) are expected to use performance simulation tools to understand, analyze, and predict the behavior of buildings. For such tools to be effective, it is necessary but not sufficient that the embedded algorithms be reliable. Simulation environments must also exhibit a high degree of usability in order to effectively facilitate generating building models and processing simulation results toward decision support throughout the building delivery process.

ii) Buildings are used and inhabited by people. People's presence, activities, and actions affect the performance of buildings in view of energy use, indoor environment, etc. Building performance simulation applications typically include some representation of people's presence and activities in buildings. However, the representations' underlying knowledge bases and the applied modeling approaches can vary considerably. A proper representational approach regarding the people component of building simulation models requires a sound empirical basis. It must also consider the intended utility or purpose of the modeling activity: Are simulations conducted to benchmark a specific design solution against applicable standards? Are they meant to compare the performance of alternative design solutions? Or do they mean to reveal the uncertainty implications of people's control actions for the values of building performance indicators?

iii) Performance simulation runs primarily generate numeric results pertaining to the physical behavior of buildings. These results provide the quantitative basis of performance indicators such as estimated heating and cooling demands of buildings. However, a large class of building performance indicators pertains to the indoor environmental (e.g. thermal, visual, acoustical) quality of built spaces in view of their suitability for human occupancy ("habitability"). For such indicators, simulations of buildings' physical behavior need to be supplied with knowledge and models pertaining to human physiology (consider, for example, the thermal comfort case). To further enhance their evaluative utility and expressiveness, occupancy-relevant building performance indicators would benefit from assimilation of insights from human ecology and psychology.

These issues are multi-faceted and complex. They cannot be treated here in a comprehensive (let alone exhaustive) fashion. Rather, a limited number of pertinent viewpoints are considered that may be amenable for evaluation on rational and empirical grounds. Thereby, the intention is to not only approach a deeper understanding and appreciation of the human dimension of building performance simulation, but also to encourage further creative developments in building performance simulation tools and practices that are sensitive and responsive to (both tool and building) users' characteristics, needs, and requirements.

TOOLS AND THEIR USERS

Discussions on the usability of building performance simulation applications typically involve a host of explicit or implicit presuppositions, i.e., statements of alleged facts or opinions. Some of these may appear self-evident. Some are controversial, and some can be shown to be inconsistent if not downright false. The following discussion includes – in no stringent order – examples of such presuppositions, together with some comments on their standing and implications.

a) *Application of performance simulation tools in the design process can improve the design quality and hence the future performance of buildings.*

As such, this postulate could be viewed as *conditio sine qua non* for any meaningful discussion in the building performance simulation domain. Confirmatory references could include the introductory section of most papers and books on the subject. Interestingly enough, there is paucity of hard proof for it (e.g., systematic long-term performance comparisons of buildings with and without a simulation-assisted component in their design history). In this author's experience – especially in case of simulation-supported decision making in building retrofit projects – the balance of evidence points to the validity of the above conjecture. We can report on multiple cases, where simulation-based design interventions prevented implementing design measures that would have invariably lead to failures. However, documented instances of failure prevention via performance simulation pertain mainly to well-defined and specific queries such as assessment of surface condensation risk on building elements (e.g., thermal bridges) given known boundary conditions, or illuminance level distribution in rooms due to electrical lighting configuration, or shortening of reverberation time due to the introduction of additional sound absorption material in a room. These instances seem to be less prone to uncertainty implications of time-dependent (dynamically changing) model input assumptions such as occupancy behavior and weather fluctuations. But the same inference may not be applicable if we consider performance indicators such as predicted annual energy use of a building. In this case, there is arguably less solid evidence for the claim that performance simulation studies are more likely to improve the future performance of a building than, let us say, conforming to prescriptive-type code requirements or conducting simplified calculations.

b) *Provision of simulation-based feedback is particularly important in the early design stages: design modifications are, in these stages, high-impact yet low-cost.*

This postulate underlines many efforts to implement simulation tool usage for early design support in architectural practice (see, for example, Morbitzer et al. 2001). Given its evident plausibility, the question of empirical evidence is perhaps less critical for the present discussion. Consider, for example, the case of buildings' heating and cooling energy demand prediction: Few would argue against the assertion that performance implications of design modifications (e.g., iterations in building's massing and orientation) could be systematically inquired in the early stages of design using parametric performance simulation. In such cases, normative rules or simplified calculations would be less effective than early design simulation support. It is true that, provided careful normalization of boundary conditions, a statistically significant correlation between the results of thermal simulations and simplified calculations can be established (Pessenlehner and Mahdavi 2003, Pont et al. 2010). But the same studies also reveal the considerable fluctuations in simulation results as a result of certain idiosyncratic design features. Most such idiosyncratic features of design are conceived in the early design stages. Exactly those experimental features (e.g., unusual and complex geometries) cannot be adequately treated via rules and simplified methods, thus providing arguments for the critical necessity of early design performance simulation application.

c) *Currently, building performance simulation tools are applied in the building delivery process neither regularly nor consistently. Building performance simulation is rarely applied by primary building designers toward optimization of early designs. Rather, simulation is typically conducted late in the process by specialists for design verification and system configuration.*

This frequently stated assertion (see, for example, Hensen and Lamberts 2011) could be criticized as being too sweeping, given the diversity of both the building delivery process across regional (national) backdrops and the attributes of building projects (size, building type, budget, etc.). It is nonetheless consistent with the outcome of a number of international studies (Lam et al. 1999, Mahdavi et al. 2003). However, consensus on the statement's validity does not mean that there is agreement as to the causal factors and promising remedies for it, as illustrated by the following two contrasting conjectures:

d) *The paucity of simulation tools usage in the building sector is largely tool-driven: contributing factors include expensive and high-maintenance applications, poor and difficult-to-use interfaces, lack of interoperability, missing features, deficient documentation and support, etc.*

e) *The paucity of simulation tools usage in the building sector is largely process-driven: under-endowed resource allocation to design analysis, ill-structured building delivery process, deficient clarification of points and modes of information*

> *exchange amongst professionals involved, missing protocols for documentation of performance-related triggers of design decisions in a collaborative design context, etc. (see Augenbroe 2003 for a thematically related discussion).*

Both of these statements contain valid points. Tools and processes have a complex relationship. Ideally, coordinated advances would be required in both areas. The author has addressed elsewhere such requirements in extenso (see, for example, Mahdavi 1998a, 1998b, 1999, 2004a, 2004b). Hence, only three particularly relevant issues are summarily discussed below, namely tool usability, interoperability (or integration), and cost.

i. About usability – Concerning building performance simulation tools, usability features in general and user interfaces in particular lag behind computational tools in other – commercially more viable – areas (operating systems, popular applications, games, etc.). Early simulation tool developers were mostly engineers and physicists, not experts in HCI (Human Computer Interaction). Especially if conceived as research tools, simulation applications were not meant for broad usage. Even though usability features of building performance simulation tools have noticeably improved in the last decades, there is still significant potential for enhancement. Advanced visualization, for example, is becoming – thanks to incorporation of data visualization routines – an integral part of performance simulation applications. There is a further need for tools and routines for effective data compression and aggregation: increasingly powerful numeric simulation applications can generate massive amounts of data. CFD applications, for example, can generate excessive data sets that, in the absence of proper data processing support, could overwhelm, rather than inform. Effective decision making requires distillation and streamlining of information (in the sense of "exformation" as per Norretranders 1999). Toward this end, performance-based reasoning methods, e.g., evaluation of alternative designs based on comparison of performance indicator values, require appropriate and effectively supported methods for information visualization and data aggregation in spatial and temporal domains. An important step in this direction would be the development of well-structured and generally applicable data taxonomies and schemes for building performance indicators. Surprisingly, few efforts in this direction have been undertaken. A related initial concept was introduced in Mahdavi et al. 2005a. The starting point was the recognition that the multitude of currently available performance simulation tools provides a broad range of simulation results. Moreover, these results are computed, formatted, and presented in very different ways. We hypothesized that the multiplicity of output specification could be organized into a unified information matrix with a few, distinct dimensions (see Table 1).

Table 1
Dimensions of a generic schema for the unified representation of performance simulation results

		Illustrative indicators	
Performance output dimension		Heating load	Illuminance
Magnitude	Scalar component	45.5	450
	Vector component	-	-
	Unit	kWh.m^{-2}	lx
Spatial	Point	-	Task
	Plane	-	-
	Bounded volume	All rooms	-
	Resolution (grid)	-	-
	Aggregation mode	-	-
Temporal	Duration	Annual	10:30, March 3rd
	Resolution	1 hour	1 minute
	Aggregation mode	Arithmetic summation	-

This matrix involves three main dimensions, i.e. magnitude, spatial extension, and temporal extension. The "magnitude" is expressed in terms of a scalar and – if applicable – a vector component and is specified via a proper unit. The "spatial extension" may be expressed, for example, in terms of a point, a plane, or a bounded volume (e.g. one or more or all spaces) in a building. Moreover, the spatial resolution of the output information may be specified in terms of a grid. The mode of summation (or averaging) of the indicator's magnitude over space rounds up the specification of the spatial extension of performance simulation output information. As to the "temporal extension" of the indicator attributes, the duration and the resolution (i.e. interval sizes) of the simulation period must be specified, along with the mode of temporal aggregation (summation, averaging, etc.) of a performance indicator's values over a series of time steps.

We tested this scheme against the output generated by a sample of eight typical performance simulation applications. The scheme could be shown to effectively accommodate all but one category of simulation results, namely the "analogue" kind. The two main instances of such "analogous" representations include "pictorial" outputs (such as computer-generated renderings of architectural scenes) and "symbolic" or graphic outputs (e.g., depictions of light and sound propagation and reflection patterns as well as air flow patterns in spaces via arrows).

The potential of such a well-structured and unified building performance output space could be significant. First, a uniform performance output space would simplify the categorization and comparison of tools and the declaration of their capabilities and coverage. Second, given a harmonized output specification framework, it would be possible to more efficiently re-apply the experience made by one tool in learning and using other tools. Third, the explicit specification of the dimensions of the performance output space could facilitate the development of more flexible user interfaces for formulating a variety of performance queries based on organized multiple simulation runs. Fourth, such a uniform framework would allow for the effective adaptation of generic information visualization applications in performance simulation tools, thus providing more scalable interfaces for navigation of the simulation results space (Mahdavi et al. 2005a).

Regrettably, these potential benefits of a general systematic simulation output schema remain unexploited.

ii. About integratio n – The interoperability between simulation applications and other digital tools and environments used in the building delivery process promises more efficient patterns of tools deployment. An integrated building model would mean a unified, structured, multi-resolutional, and multi-disciplinary building information repository. If realized, such an integrated model could alleviate the problems associated with the diversity of views and levels of abstraction in building information (communication overhead, redundancies, errors, and inefficiencies). In fact, preparation of a building model for performance simulation purposes out of the conventional building information media is a time-intensive and error-prone process and has been thought to be one of the hindrances against a more pervasive use of building performance simulation tools in the building design process.

Some progress has been made in the last decades to address the problem of integration, even if efforts to establish comprehensive building information models (BIMs) and common representational standards (IFC 2011) have not yielded the initially implied grand solutions. The top-down program of creating a universally agreed-upon description of building information has faced both conceptual and practical impediments (debatability of a "true" representational scheme for building products, the vast overhead of a "design by committee" approach to standard building product descriptions, etc.). Likewise, the successes of a "bottom-up" approach to creating links between specific building information systems and performance simulation applications have been limited. Difficulties and expenditures associated with generating, maintaining, and updating a large number of mapping routines between diverse applications may have been responsible for the rather slow and inconsistent pace of progress in this area.

In our experience, the research and development in this area has been hampered by a lack of both:

i) a clear vision of what is possible, and *ii)* a consistent pursut of what is possible.

As we could demonstrate in the course of a relevant research and implementation effort (Mahdavi 1999, Mahdavi et al. 1999), it is possible, in principle, to seamlessly obtain design information from a properly structured shared building model and map it into the domain models of a number of technical building analysis applications for energy simulation, thermal comfort prediction, building HVAC (heating, ventilating, and air-conditioning), air-flow, lighting model, room acoustics model, and life-cycle assessment. While domain representations in our integrated performance analysis support environment used different internal spatial representations for their computations (e.g., a thermal zone, an airflow control volume, or an acoustical space), they were nonetheless homologous (configurationally isomorphic) to pertinent entities in the shared building model. This homology was exploited to a certain extent for mapping operations from the shared building model to the domain models of the applications incorporated in the environment (Mahdavi and Mathew 1995, Mahdavi et al. 1997, Mahdavi and Wong 1998, Mahdavi et al. 2001).

But none of these processes and functionalities were claimed to be universal, i.e., catering for all kinds of simulation queries and througout the entire design process (Mahdavi 2004b). The main reason for this limitation lies in the complex discontinuities both in the temporal evolution of design information in the course of a building delivery process and the kinds and resolution of performance queries. For a certain set of applications, a certain set of queries, and a certain level of building information resolution, a well-balanced representational labor division between a reasonably detailed shared building model and a number of behavioral domain models (for building performance simulation) is possible, and that the latter can seemlessly infer their informational requirements from the former via mapping operations. It remains an open question, if and to which extent this integrative framework could have been expanded to accommodate other applications and other levels of building information resolution.

iii. About effort – Required time, effort, and cost to master and apply building performance simulation applications has been frequently alluded to as one of the main impediments to their wide-spread use in the praxis. This contention, self-evident as it may seem, has not been necessarily documented in stringent empirical sense. The extent and structure of time investment requirements for building performance simulation has been addressed before (see, for example, Madjidi and Bauer 1995, Bazjanac 2001, Mahdavi et al. 2003, De Wilde 2004, Hensen and Lamberts 2011). But little factual and systematic information is available as to the time requirements of design activity in general and simulation-assisted explorations in particular.

In a past research effort (Mahdavi and El-Bellahy 2005), an attempt was made to estimate the time and effort needed by novice designers to computationally evaluate the performance of building designs. A group of senior architecture students participated in the study, learning and using a software application to assess the energy performance of six designs for a school building design competition. The outcome of this study (time investment ranges for various components of the modeling activity) was evaluated and further extrapolated to estimate the effort needed for a more comprehensive computational assessment of the environmental performance of these designs. The study resulted also in a simple tool, which could be used to roughly estimate the time needed to conduct simulations as a function of the project size, number of (geometric or semantic) design iterations, the number of performance indicators, whose values were to be calculated, and the expertise level of the simulation tool user.

The results of the study led to the conclusion that, given the overall time budget for the design of a building, the time expenditure requirement alone does not explain the paucity of energy simulation tool usage, at least not for limited preliminary investigations in the early stages of design (to obtain, for example, the heating and cooling load implications of alternative choices of massing and materials). However, the time expenditure requirements for simulation-based performance analysis can of course quickly go beyond simple design exploration scenarios. It might be the case that more design iteration would be desirable (building morphology iterations are particularly time consuming). Likewise, further performance indicators (e.g. those addressing thermal comfort issues in the summer period, daylight availability, system design, acoustics, and life-cycle considerations) may have to be considered. Considering such multi-criteria simulation and evaluation scenarios (of the kind suggested, for example, in Augenbroe 2011), one can appreciate how readily time and effort implications of comprehensive performance-based design guidance can go beyond typically deployable resources in the design process. This suggests that, while the paucity of tool usage to derive the preliminary indicators of building performance (such as energy indices) cannot be explained solely based on the required effort, regular and comprehensive computational assessment of detailed building designs does necessitate a radical change in the magnitude and allocation of the resources allocated to the design process.

A final point in the present discussion of performance simulation user groups concerns a recurrent debate, as to the proper agent for conducting simulation studies. As such, a case could be made for the position that primary building designers (typically architects) would be the logical candidates: Being responsible for the performance of the buildings they design, one would presume that primary building designers would be responsible for (and should be interested in) predicting and evaluating their performance via – amongst other means – simulation. Buildings are of course highly complex artifacts with multi-faceted properties and performance requirements, requiring the collaboration of multiple agents in the building delivery process. Nonetheless, this does not appear to contradict the postulate of an active – perhaps even leading – role for the primary building designers in conducting simulation studies at least in the early design stage.

There are two typical responses to the circumstance that building performance simulation is conducted in the practice, if at all, by specialists and not by primary building designers. Despite their contrasting arguments, these responses share a common starting point, which is a view of architects as lacking sufficient requisite technical knowledge (especially building physics) to correctly construct performance simulation models, properly execute simulation runs, and systematically process and interpret simulation results:

f) The knowledge base of buildings' primary designers must be improved. Efforts are needed to popularize simulation tool usage in architectural practice (Morbitzer et al. 2001, Hobbs et al. 2003). Moreover, the architectural education systems needs to be reformed, so as to equip future architects with requisite technical knowledge and skills for building performance application in the design process. Such education must be made available also to professionally active primary building designers – for example through continued education and training services.

g) Given the immutable ineptness of primary building designers (typically architects) concerning proper application of performance simulation, simulation specialists (typically engineering consultants) must be involved – preferably as part of a "design team" – already in the early stages of the building design process.

Once again, cases can be made for both positions: First of all, why should one argue against either more knowledgeable primary designers or expert input in early design stages? There is no logical reason, while understanding of building performance and a basic level of dexterity in using elemental simulation tools should be beyond the reach of properly educated primary designers of buildings. In fact, in the course of the previously mentioned study of required effort for performance simulation (Mahdavi and El-Bellahy 2005), senior architecture students, who had previously attended a course on the fundamentals of thermal performance of buildings (involving a time investment of approximately 60 hours) learned – within a semester-long graduate class – to properly apply a thermal performance simulation application toward assessing and improving the energy performance of building designs. The circumstance that such rather basic faculties are apparently beyond the prevailing professional standards must be attributed, at least in part, to a troubling inertia in the architectural education and profession. Arguably, this same inertia has been also at least partially responsible for the steady loss of technical competence to other disciplinary experts in the building engineering domain. A considerable fraction of architects do not seem to consider performance assessment as integral to their professional role. As with the structural analysis, they seem to believe that such tasks should be "out-sourced" (i.e., performed by building physics "experts"), even though the majority of the architects do believe they should know more about building performance and its evaluation methods (Mahdavi et al. 2003).

On the other hand, the arguments in favor of team decision making as well as recommendations to involve disciplinary experts early in the design process are entirely coherent. But they often ignore – or at least underestimate – a likewise prevailing inertia in the structure of the building delivery process (Mahdavi 1998b). A process that, independent of its numerous manifestations (a function of construction culture and financial constraints), is geared toward design cost reduction, exacerbates collaborative design and engineering due to legally binding disciplinary boundaries and responsibilities (not to mention liability), and fosters a kind schism between the worlds of primary design and performance assessment.

The previous discussion provides an impression of the complexity involved in the view of people as tool users. There are a variety of views on who, when, and why should be making use of building performance simulation tools. Likewise, contrasting views persist concerning the desirable direction of the development of future simulation environments. The attempt to arrive at ultimate answers and solutions would probably remain futile. It may be thus more useful to opt for a more practical stance: Perhaps one should not dogmatically strive for a unique panacea, but rather pursue multiple measures and strategies, that are likely to contribute – albeit in different degrees – to both wide-spread and competent use of performance simulation in the building delivery process. Such measures include, for instance, improving the fidelity, usability, and interoperability of building performance simulation applications, improving the knowledge base of primary building designers in view of building physics and performance modeling techniques, and incentives in advancing and rationalizing practices in the building delivery process in terms of collaboration and accountability.

MODELS OF PEOPLE

The reliability of results obtained from building performance simulation applications depends not only on the validity of computational algorithms, but also on the soundness of input assumptions. While there has been significant progress concerning methods and practices for specification of building geometry, material properties, and external (weather) conditions, the resolution of input information regarding people's presence and behavior in buildings is still rather low.

The importance of the "people factor" in building performance simulation seems evident. For example, buildings' thermal performance of buildings is not only affected by the people's presence as a source of (sensible and latent) heat, but also due to their actions, including use of water, operation of appliances, and manipulation of building control devices for heating, cooling, ventilation, and lighting. User-based operation of luminaires and shading devices in a room affect the resultant light levels and visual comfort conditions. Presence of people in a room and the associated sound absorption influences the sound field and thus the acoustical performance of the room. Safety performance of a building cannot be evaluated without considering the behavior of people under emergency (Mahdavi 2011).

Nonetheless, until recently, detailed consideration of the effects of people's presence and their actions on buildings' performance was not a priority in simulation research and application. In fact, practically applied models of people presence and actions in building performance simulation studies are still rather simplistic. Moreover, there is a lack of well-established and widely shared methods and standards for representing people in the building simulation practice. Likewise, the ongoing research efforts to develop occupancy presence and (control) action models suffer in part from both conceptual and methodical shortcomings.

In this context, the present discussion mainly provides a conceptual framework to systematically situate people (users and occupants) in the context of building performance simulation. It addresses some of the mechanisms and corresponding models of how people's presence and interactions with buildings' environmental systems influence the outcome of performance simulations in terms of the values of relevant performance indicators. Specifically, possible approaches to the representation of occupants' presence and actions in terms of input information to simulation applications are discussed.

Passive and active effects

Discussions about occupancy models in building performance simulation can benefit from a distinction between "passive" and "active" effects of people on buildings' performance:

- Passive effects of people on the hygro-thermal conditions in buildings denote those effects caused by the "mere" presence of people in the building. Depending on their activity, people release not only various quantities of sensible and latent heat, but also water vapor, carbon dioxide, and other execrations and odorous substances. Likewise, in the building and room acoustics domain, presence of people in a space has an effect on the sound field via introduction of additional sound absorption. To model the passive effects of people's presence in buildings, simulation specialists typically rely on external sources of information such as occupancy load schedules derived from measurement results of people's metabolic rates. Provided such external information is available, the modeling process is as such straight-forward, barring two possible complexities. Firstly, different levels of resolution are conceivable regarding temporal and spatial distribution of the passive effect in the model. For example, occupancy-based internal loads may be modeled for a global occupancy schedule or, alternatively, in terms of autonomous agents representing individual occupants with distinct individual occupancy patterns. Secondly, the passive people effects such as heat emission may depend on the context (e.g., thermal conditions in occupants' rooms). This interdependence would require – at least in case of highly detailed numeric simulation models – a dynamic coupling between the agent and its immediate environment.
- In most buildings, occupants operate control devices such as windows, shades, luminaires, radiators, and fans to bring about desirable indoor environmental conditions. These control actions are here referred to as people's active effects, and have obviously a significant impact on buildings' performance. Realistic simulation-based building performance predictions necessitate reliable models of such control-oriented user behavior and their incorporation in performance simulation applications. General information about building type (residential, commercial) and environmental systems (free-running, air-conditioned) as well as organizational and administrative information (e.g., working hours) can only provide rough directions regarding such active effects. More representative people presence and action models require, however, extensive observational data based on empirical studies of occupancy and control-oriented user behavior (as related to buildings' environmental systems) in a large number of buildings. Thereby, possible relationships between control actions and environmental conditions inside and outside buildings could provide the underlying basis for derivation of user behavior models to be incorporated in building simulation applications.

Empirical observations and predictive models

There is a substantial and growing body of observational studies to capture the patterns of occupants' presence in buildings their interactions with buildings' environmental control systems such as windows, blinds, and luminaires. Frequently, such studies attempt to establish a link between user control actions (or the state of user-controlled devices) and measurable indoor or outdoor environmental parameter (see, for example, Hunt 1979, Love, 1998, Reinhart 2001, 2004, Boyce 1980, Lindelöf and Morel 2006, Rea 1984, Inoue et al. 1988, Herkel et al. 2005, Nicol 2001, Mahdavi 2011). Observational data, processed through derivative descriptive or stochastic methods, can lead to predictive occupancy and activity models that may be integrated in building performance simulation applications (Fritsch et al. 1990, Bourgeois 2005, Nicol 2001, Rijal et al. 2007, Wang et al. 2011).

While highly useful, these studies often are variously limited, due – amongst other things – to the small number of buildings and rooms involved, the duration and consistency of data collection, the accuracy of the measurements, the robustness of the analyses, and the clarity of the documentations. The author and his team tried to address some of these limitations and their implications in the course of recent case study, involving a number of office buildings in Austria. Thereby, an attempt was made to systematically collect an extensive and consistent set of observational data regarding building occupants' presence and control action patterns pertaining to lighting and shading systems while considering the indoor and outdoor environmental conditions under which those actions occurred (Mahdavi et al. 2008a, 2008b, Mahdavi and Pröglhöf 2008, Mahdavi 2011).

This research effort – given its relatively large-scale, long-term, and high-resolution nature – represents an appropriate case in point to demonstrate the potential, complexities, and challenges associated with the derivation of empirically grounded user presence and behavior models in buildings. In fact, one of the initial objectives was to conceive the research in terms of a model case, proposing and testing a general process for designing and conducting user behavior observations in buildings.

In the following, a few related observations are presented, addressing mainly the issues of data collection and model development.

Data collection issues

To properly structure and subsequently query the monitored data, a schema compromising of events (E) and states (S) was found useful (see Table 2). In this taxonomy, events are either system-related (E_s) or occupancy-related (E_o). States can refer to systems (S_s), indoor environment (S_i), outdoor environment (S_e), and occupancy (S_o).

Table 2
Proposed for the structure of observational data regarding occupancy presence and actions in buildings (Mahdavi 2011)

Data	Type	Illustrative instances
Events (E)	System-related (E_s)	Switching lights on/off
	Occupancy-related (E_o)	Occupant entering into (or leaving) an office
States (S)	System-related (S_s)	Position of shades/windows
	Indoor environ. (S_i)	Illuminance level
	Outdoor environ. (S_e)	Outdoor temperature
	Occupancy-related (S_o)	Room occupied/vacant

An important consideration in observational studies involving people is the so-called Hawthorne effect. The idea is that subjects may modify their behavior (for example, operation of thermostats, luminaires, blinds, windows) once they know they are being observed (Diaper 1990). Ideally, subject should not know they are being observed. There are, however, limits of both organizational, legal, practical, and ethical to the extent this can be achieved in actual studies. In our case study, presence of sensors and loggers in workstations was broadly explained as part of general building management services. In future, the growing feasibility of pervasive monitoring infrastructures and building automation systems in buildings may not only provide a solution for the collection of comprehensive and reliable observational data regarding user presence and actions in buildings, but also effectively address the Hawthorne effect.

Model development issues

Occupancy pattern is typically the starting point for modeling development. It is important to understand that it cannot be simply inferred from building type and function (e.g. residential versus commercial). Nor can it be based solely upon organizational information from building and facility managers. In our study of five office buildings in Austria, the mean occupancy patterns (see Figure 1) was unlike either common assumptions in pertinent building performance simulation practices or presumptions of the organizations involved. Moreover, the five buildings we studied displayed very different occupancy patterns (see Figure 2).

A further potential challenge for occupancy prediction would arise, if a building houses multiple functions with potentially very different occupancy patterns (mixed use). But even if all offices belong to the same organization and housed in the same building – as it was the case in our case study – there could be drastic differences between their occupancy patterns. To illustrate this point, Figure 3 shows monitored occupancy patterns in seven offices in one of our case study buildings. The considerable statistical variance of occupants' presence in their offices is further exemplified in Figure 4, which shows mean presence level and respective standard deviations.

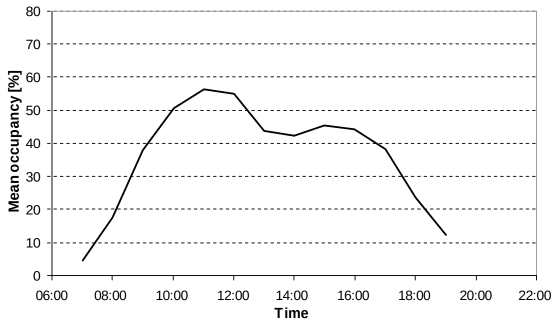

Figure 1 Mean reference work day occupancy based on data from five office buildings in Austria

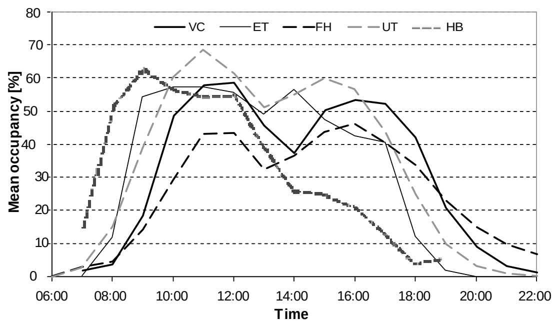

Figure 2 Mean reference work day occupancy patterns for five office buildings in Austria

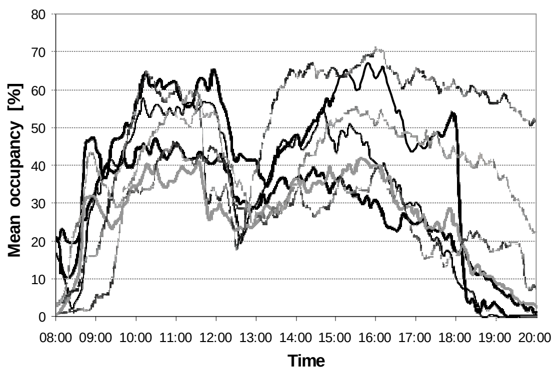

Figure 3 Observed reference working day occupancy levels in seven offices in an office building (FH)

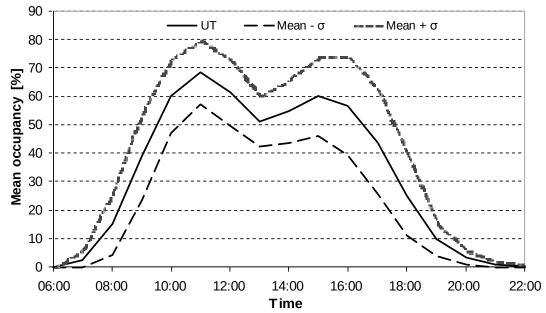

Figure 4 Mean and standard deviation of occupancy for a reference work day in an office building (UT)

But that is not all. A building's usage (the functions it supports) can repeatedly and considerably change over time, yet again implying variable and hardly predictable occupancy patterns. Moreover, offices can be, in the course of time, assigned to different individuals (or user groups) with inherently different occupancy tendencies. Ultimately, the same individual occupant might, over time, display varying patterns of presence, given professional or personal circumstances. Such factors lead to the considerable uncertainty in the predicted degree of occupancy in any specific office space or building.

To highlight the relevance of these observations in the context of building performance simulation, let us consider tool applications in scenarios involving both building design and building operation:

- To conduct performance simulations toward design decision support, occupancy input assumptions could use one or a combination of: *i)* standardized (typically aggregate) functions; *ii)* assumptions provided by the client (pertinent building owner or organization entity); *iii)* available empirical (observational) data pertinent to the relevant building type and function. All these resources involve uncertainties both considerable and indelible.
- Occupancy information intended as input for simulation models used in a specific existing building (e.g. for applications in facility management or building automation) can acquire higher predictive potency if based on systemic monitored data in that building. However, a considerable residual uncertainty might be unavoidable even in this scenario.

Independent of their predictive utility, occupancy models of course "only" address the passive effects of people's effects on buildings' performance. Predictive models of people's active control-oriented interventions in buildings come with their own challenges. Our specific case study did result in a number of empirically-based statistically significant relationships between the frequency or probability of user control actions (e.g. lights and blinds operations) or state models of user operated devices and some independent variables pertaining to occupancy, indoor environment, or outdoor conditions. Figures 5 to 7 exemplify (for office buildings, work days, Austria) instances of these kinds of relationships, namely the light switch on probability as a function of task illuminance level immediately prior to the onset of occupancy (Figure 5), light switch off probability as a function of the duration of absence from the workstation (Figure 6), and shades deployment level as a function of façade orientation and the incident global (vertical) irradiance on the façade (Figure 7).

Such empirically-based models are sometimes referred to, erroneously, as deterministic. In fact, they are simply observation-based statistically aggregated relationships. They might provide clues and indications concerning the environmental triggers of behavioral tendencies. But they certainly do not represent causal models of human control actions in buildings. Moreover, as with all statistically derived relationships, these kinds of models are limited in at least two regards:

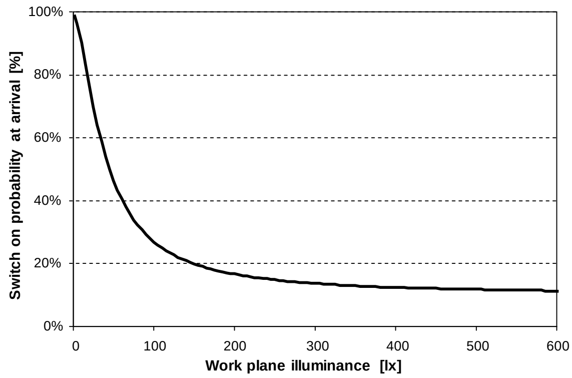

Figure 5 Manual light switch on probability as a function of task illuminance level immediately prior to the onset of occupancy

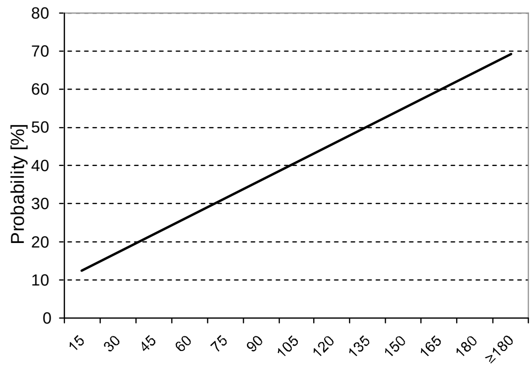

Figure 6 Manual light switch off probability as a function of the duration of absence from the workstation

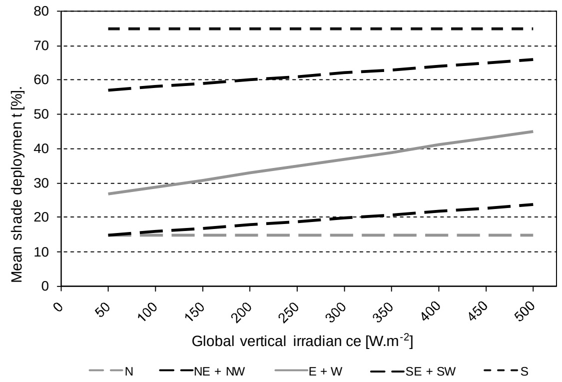

Figure 7 Shades deployment level (in %) as a function of façade orientation (S: South, NE: North-East, NW: North-West, E: East, W: West, SE: South-East, SW: South-West, S: South) and global (vertical) irradiance on the façade

First, they cannot be divorced from the population from which they are derived and simply applied to other contexts (at least not without losing much of their statistical credence): A large number of diverse factors, such as the climate, cultural issues, building type and functions, organizational specifics, building systems peculiarities, space orientation, and interior design features influence behavioral tendencies and their dependencies on hypothesized independent variables. Second, aggregate models do not explicitly reflect the inherently probabilistic nature of most control-oriented control actions. Nor do they capture the dynamism of actual processes and events in buildings, as stochastic models can – at least in principle (Fritsch et al. 1990, Nicol 2001, Macdonald and Strachan 2001).

The latter models have been used to generate time series of both occupancy intervals and user control actions that "look" similar to actual (real) processes and event sequences. Thus, if grounded in quantitatively sufficient and qualitatively adequate empirical data, stochastic occupancy and control action models, while realistic in their random fluctuations, could represent, in toto, the general occupancy-triggered processes in a building. Such models can be implemented in simulation applications in terms of autonomous agents with built-in methods (Bourgeois 2005, Chang and Mahdavi 2002, Liao et al. 2011) to generate behavioral patterns that appear realistic. However, the promise of stochastic occupancy needs to be qualified against both reliability and applicability concerns.

Considerations of model reliability

The capacity of stochastic models to generate realistic occupancy and control action patterns does not necessary translate into predictive potency. This point deserves emphasis, given the persistence of some misunderstandings in related discussions. If properly calibrated based on observational data from a building, stochastic methods may realistically emulate the patterns of occupancy-related processes and events in that building (assuming the building usage remains generally unchanged). But this does not necessarily establish their scalability toward anticipation of future processes (predictive potency) or toward transportability to other buildings.

Judging based on the recent frequency of subpar paper submissions on stochastic models of people's occupancy and actions in buildings, it appears that this area of inquiry might be going through the "inflated expectations peak" phase of the so-called "hype cycle" (Fenn and Raskino 2008). Implied contentions concerning the stochastic model's predictive potency are premature: Emulation of realistically looking patterns or efforts to obtain probabilistic estimated of future event frequencies are sometime mistaken with actually predicting future events in specific spaces of specific buildings. Such misconceptions can be partly encountered via general reflections on the complexity of human behavior, especially in a socially relevant context (see, for example, Watts 2011). More specifically, researchers working in this field need to assiduously upheld the proper scientific criteria for model validation, such as: careful collection and preparation of sufficient and representative observational data, clean separation of underlying data sets for *a)* model generation and *b)* model validation, and candid explication of the limitations in model application scope.

Ultimately, double-blind studies (where the empirical data collection, the model development, and the comparison of measurements and predictions are done by separate groups) or round-robin tests would be most convincing in examining and documenting models' true predictive performance. Few such rigorous studies have been conducted with regard to stochastic models of occupancy and user control actions. A related recent attempt, in which the data collection and model development tasks were conducted by different research groups (Haldi et al. 2010), did not provide a convincing display of predictive performance on the side of the stochastic model. Until proper scientific criteria are explicitly and consistently met in stochastic model validation studies, claims pertaining to models' performance cannot be trusted.

Considerations of model applicability

Aside from validity concerns, with which all kinds of occupancy presence and control actions models must grapple, we must also address model applicability issues and scenarios.

An argument can be made for the utility of simple (code-base or descriptive) occupancy-related simulation input assumptions in the design development phase, where simulation can be used to obtain numeric values for a number of aggregate performance indicators such as buildings' annual heating and cooling loads. Such aggregate indicators allow to *i)* benchmark a specific building design proposal against applicable codes, standards, and guidelines, or *ii)* comparatively assess the likely performance of multiple design alternatives. Thereby, concise statements are expected concerning the quality of the proposed building "hardware" vis-à-vis design variables pertaining to the building's envelope, massing, orientation, shape, construction, etc. Naturally, this is done under "standardized" conditions pertaining to external climate (typically represented in terms of a standard weather file) and internal occupancy-related processes (typically represented in terms of fixed, more or less detailed assumptions regarding internal gains, ventilation rates, etc.). Theoretically speaking, the use of a probabilistic presence and user action models would generate, per definition, more or less different occupancy-related input data for each simulation run, resulting in correspondingly different simulation results. This could represent a problem not only for code-based compliance checking, but also for the performance analyses of design alternatives, when the aim is to compare multiple (alternative) designs irrespective of variance in contextual boundary conditions (weather) and occupancy. Even so, presumably one can argue that the repeated simulation runs with a properly calibrated probabilistic occupancy model can also converge to stable values for aggregate performance indicators. But in this case the implied level of required means in terms of time and effort does not appear to justify the end.

A different circumstance arises, however, if we consider those – perhaps more involved – simulation use scenarios, which require us to consider the implications of uncertainties associated with occupancy processes in buildings. Let us consider a concrete example: As it was alluded to before, differences in occupancy patterns over time and location can be quite significant. Such differences can be important especially while trying to gauge the variance of thermal loads or conditions in various zones of a building. Information regarding temporal and zonal load variations is critically important, for example when essential data for design and sizing of indoor climate control systems is to result from simulation studies. Thus, rigid models of user presence and behavior that ignore associated stochastic fluctuations (and the resulting uncertainties) would be rather problematic, if the detailed configuration of a building's mechanical equipment is the main concern: While dealing with the requirement of providing sufficient heating and cooling capacity to different zones of a building, the variability of required thermal loads must be systematically explored. This cannot be based on spatially and temporally averaged occupancy assumptions. In such instances, application of properly calibrated models with probabilistic features may be critical.

It seems as though different approaches to representation of occupancy-related processes in building performance simulation may be appropriate given different scenarios. If consideration of the implications of variance in input assumptions is evidently critical to a specific performance inquiry, then probabilistic models of occupancy presence and control actions would be appropriate. On the other hand, when the objective of a simulation-based inquiry is to benchmark design proposals against applicable codes and standards or to parametrically compare design alternatives, inclusion of random variations of boundary conditions and internal processes in simulation runs may be counter-productive. Thus, to select the right kind of occupancy presence and control actions model for a specific line of performance inquiry may be argued to be a critical sign of competence in the "art" of building performance simulation.

Future directions

High-resolution and dynamic simulation of environmental processes in buildings would have to include, ultimately, comprehensive and well-integrated representations. To illustrate this vision, Figure 8 provides a highly schematic depiction of such a multi-faceted representation, including occupancy, building, and context models.

In this scheme, the occupancy model, which can be implemented computationally in terms of a society of autonomous agents, is based on an underlying presence sub-model. Given information on agents' presence in building, passive effects and control actions are derived. While passive effects may be computed based on physiological models of human body and metabolism, action probabilities would be generated based on both physiologically and psychologically based models (e.g., thermal comfort and thermal pleasantness models).

Computed passive effects (e.g., sensible and latent heat generation) and predicted control action probabilities (e.g., operation of windows, luminaires, blinds) are provided to the room and system components of a coupled building model, which, in turn, provides boundary information (e.g., room air temperature and relative humidity) for the occupancy model. Both occupancy and building model are coupled with the context model, which supplies them with relevant information on external (weather) conditions around the building. The overall computational framework generates thus building performance data (e.g., thermal conditions indoors, heating and cooling loads, systems' energy use, etc.) under dynamic and concurrent (coupled) consideration of occupancy, building, and context states.

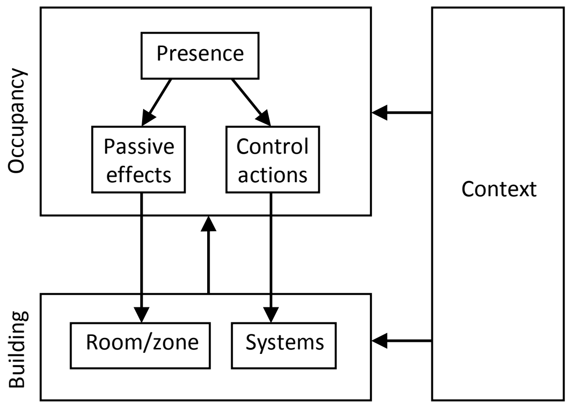

Figure 8 Schematic illustration of coupled models for performance simulation including occupancy, building, and context information (Mahdavi 2011)

PERFORMANCE FOR PEOPLE

People's relevance to computational building performance modeling is not restricted to either tool usability concerns or input models for user presence and actions in buildings. Arguably, the most essential utility of building performance simulation is provision of a reliable quantitative basis toward evaluating projected buildings in view of their suitability for human occupancy, or, in the human ecological parlance, their "habitability" (Mahdavi 1998c). Performance simulation results deliver values for a large class of building performance indicators relevant to people's requirements and expectations. However, this central utility of performance simulation, much like the proverbial elephant in the room, is seldom addressed in the performance simulation discourse in an explicit and systematic manner. Hence, a brief discussion of related questions may be beneficial, even at the ostensible risk of stating – at times – the obvious.

Human requirements

Interestingly enough, the link between performance simulation results and human requirements is not always obvious. For example, while computing heating and cooling demand of a building, or assessing the surface condensation risk on a construction, specialists may be primarily concerned with the sizing of mechanical equipment or evaluating building integrity risks, rather than pondering on immediate occupancy-related functional and performance requirements of buildings and spaces.

Previously, we discussed a general classification scheme for the multiple dimensions of building performance simulation results (see Table 1). It would be interesting to contemplate a further classification of performance simulation results in view of their relevance for occupancy-related (habitability-related) evaluation processes. Such requirements are multi-faceted and the applicable classification schemes can be quite complex. For the purposes of the present discussion, it may be sufficient to assume that occupancy-related performance variables generally relate to: *i)* health and safety, *ii)* comfort, *iii)* satisfaction, and *iv)* productivity. In our classification, we would like to specifically inquire if a performance indicator is phenomenally relevant, i.e., if it represents a correlate to some salient aspect of human perception.

Relevance for occupancy and perception

Given the wide range of occupancy-related building performance criteria, we consider a differentiation (see Table 3) between three kinds of performance simulation results (Mahdavi 2004b):

a) Some performance simulation results do not appear to have any bearing on the habitability of buildings and spaces. For example, a building with very high heating and cooling loads (and correspondingly high fuel consumption, CO_2 emission, and energy cost) may be operated in a manner that results in thermally comfortable spaces. In other words, poor energy performance must not imply poor thermal comfort conditions. However, even while focusing on obtaining load information from simulation runs, considerations of human requirements are implicit in the simulation process. For example, heating and cooling loads (and derivative predicted energy use levels) are computed under certain assumptions regarding target indoor climate conditions as captured in terms of variables such as air temperature, operative temperature, and relative humidity. Respective set points for acceptable indoor environmental conditions are typically derived from thermal comfort considerations.

b) Certain simulation results such as task illuminance levels or room air CO_2 concentrations are relevant to the quality of spaces in view of human occupancy requirements (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.

c) Some performance simulation results pertain to indicators 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).

Table 3
Classification of building performance results in view of their relevance to occupancy and phenomenal experience

Type	Relevance to occupancy	Relevance to phenomenal experience	Illustrative instances
a	No	No	Annual heating load
b	Yes	No	Task illuminance level; indoor CO_2 concentration
c	Yes	Yes	Air temperature; luminance; sound level

Sensing the results

More recently, building performance simulation has acquired the potential to circumvent numeric representations altogether, providing instead a virtual version of the simulated phenomenon. Instead of merely generating numeric values for selected performance variables, simulation-based visualization and auralization of architectural spaces can deliver images and sounds virtually indistinguishable from those resulting from the real spaces. Simulation-powered virtual buildings can trigger immediate impressions of spaces, supporting thus relevant evaluative processes. Instead of just making sense of numeric simulation results, one could literally sense the simulations' outcome.

As soon as computational rendering of architectural scenes acquired some level of maturity, suggestions were made that such renderings – being factually indistinguishable from photographic images – could substitute traditional numerically-based assessment and evaluation methods in lighting. Likewise, one saw in computational "auralization" the potential to render conventional evaluation approaches in statistical room acoustics obsolete. In fact, there is some evidence of the postulated evaluative equivalency of virtual and actual spaces in view of their phenomenal implications. Simulated images of and sounds in spaces were shown to elicit from test participants verbal evaluations congruent with those pertaining to real spaces (Mahdavi and Eissa 2002, Mahdavi et al. 2005b). Digital surrogates of real buildings have been indeed rapidly improving, and immersive environments seemed to be the next logical step in this evolution. Presumably, next to visual and acoustical sensations, other types of phenomenal experience (say sensation of radiative heat or olfactory and haptic stimuli) may be induced by digitally reproduced trigger.

Here is, however, caution in order. There are principal and practical reasons why such expectation should be moderated. Perception of real spaces is a complex multi-sensory process. Generation of comprehensive phenomenally effective emulations would require resources and technologies beyond the means and possibilities of all but few members of the design community. Moreover, building evaluation formats required for accountability in the design decision support process can hardly rely on perceptual snapshots. Building evaluation processes frequently necessitate high-level performance indicators, whose values are typically aggregated over time and space (e.g., whole building annual energy performance indicators). Such aggregations over time, location, and viewpoints would further increase the overhead challenge associated with evaluative processes that require real-time multi-aspect virtual building models. Moreover, even if a simulation-powered virtual realization of building designs could eventually provide hi-fidelity sensory stimuli of design models in an efficient and reliable manner, the subjective component of the perceptual experience would pose the same kinds of challenges that occupants' often divergent evaluation of real spaces do.

Human ecology of performance evaluation

This latest observation offers a fitting passage to a concluding reflection on the constituent determinants of human experience. In building performance simulation, we are primarily concerned with getting the predictions of buildings' behavior right. In a sense, performance simulation can be thought as a virtual monitoring system operating in a virtual building. Thereby, virtual sensors for indoor environmental conditions would be the ones that deliver relevant data to people's sensations and perceptions. Let us assume, for the sake of argument, that simulation can provide us with reliable numeric predictions (or even realistic emulations) of buildings' indoor environments. We would still need to derive, from values of physical variables, information relevant to people's experience. In other words, a gap may be postulated between the sensory basis of a perceptual situation and the actual evaluative judgment that arises from such situation.

To converge on occupants' evaluation of the thermal, visual, acoustical quality of built spaces, simulations of buildings' physical behavior must be supplied with knowledge and models pertaining to human physiology (consider the thermal comfort case), psychology, and even sociology. The latter step requires, both in view of method selection and in terms of levels of uncertainty, a change in perspective. Methods that serve us well while doing the physics of buildings would fall short of capturing the nature and variability of human perception.

To better understand this point, a classical dichotomy from the human ecology discourse may be useful. In human ecology, the relationships between people and their surrounding environment is thought to exhibit two aspects: one related to matter and energy, and the other related to information (Knötig 1992, Mahdavi 1998c). Thereby, the notion of information is understood in the broad sense of a structure (pattern, configuration) that can be associated with (attributed to) matter and energy. Pivotal for the present discussion is the following, seemingly trivial observation: People's evaluative processes of circumstances and events are not only affected by the matter and energy-related aspect of environmental relations, but also – and in many instances decisively – by the information-related aspect. Specifically, the variance in people's information-centered attitudinal and experiential standpoint vis-à-vis the very same (energetically identical) circumstance, event, or exposure situation may result in considerably different evaluative outcomes.

This circumstance can be vividly illustrated via a number of classical studies and observations in the domain of environmental acoustics:

- In one experiment, two demographically similar groups of participants provided significantly different assessments of the same acoustical event (recorded white noise). Participants in the first group, who were told the recording was of a waterfall, judged it much more favorably than the second group, who was told the recording was of a factory. People's attitude toward the alleged source of an acoustical event clearly influenced their evaluation of the exposure, despite the absence of any objective difference in the nature of the event (Mahdavi 2004b).
- In another experiment (Schönpflug 1981), participants were exposed to white noise of different intensity while performing certain tasks (time estimations). The participants who received positive feedback about their performance ranked the same acoustical exposure as less annoying than those who received negative feedback concerning their performance. But the feedback messages were manipulated and did not reflect the true performance. Hence, their effect on participants' subjective evaluation of the noise exposure situation cannot be explained in terms of an acoustically induced impairment. The explanation lies rather in the nature of the information processing that was triggered by the combined effect of acoustical exposure and negative feedback. The degree of annoyance due to noise was apparently higher, once it was identified as the reason for one's (alleged) failure.
- A comparative study of the effectiveness of different traffic noise control strategies (Kastka 1981) concluded that the evaluation processes under exposure situations cannot be captured via purely energetic indicators. The study explored the annoyance level of inhabitants before and after installation of noise barriers and traffic quieting measures in two locations in Germany. The annoyance reduction effect of the barriers was not found to be as large as their "objective" noise level reduction effect (in average about 8 dB). The traffic quietening measures showed, in contrast, a considerable positive change in the evaluation of the acoustical exposure situation, although, in this case, the sound level reduction was insignificant (in average about one dB). The traffic quietening measures reduced the annoyance level primarily not through noise level reduction, but rather through the changes in the negative attribution (meaning) of the traffic for the inhabitants. Apparently, the quietening measures effectively reduced the dominance of the negatively viewed environmental factor "traffic" in the inhabitants' view of their environment.

One might argue that such variance in evaluative processing of energetically identical "stimuli" might be a phenomenon specific to short-term exposure situations or just one domain (e.g., acoustical environment). Yet even in the thermal comfort domain, we no longer believe that there is a "predefined set of environmental conditions" (a common thermal energy field as it were) that, if maintained, would assure the comfort and satisfaction of the inhabitants. Indeed thermal comfort research has continuously pursued a deeper understanding of the processes involved in people's thermal sensation and evaluation, given the evidence collected in the field and given the fundamental complexity, variance, and dynamism of the relationship between people and their surrounding environment (see, for example, Mahdavi and Kumar 1996, McIntyre 1982, Busch 1992, de Dear et al. 1991, Schiller et al. 1988, Auliciems 1981).

The information-related aspect of people's interrelationships with their surrounding environment may explain at least some of the contributing factors to predictive limitations of a comfort theory that is limited to basic physical and physiological considerations. Thereby, the relevance of this information-related aspect can be approached in two ways. On the one hand, information can be viewed as corrresponding to experience of differences. On the other hand, the process of recognizing and evaluating a circumstance or an event depends on the infromational state of the observer, including prior experiences, expectations, and attitudes. These two approaches could be perhaps more conveniently communicated if we consider the notions of the "thermal pleasantness" and the "forgiveness factor":

- The view of information as messages of difference is implicit in treatments that contrast thermal comfort (in the sense of thermal neutrality) with thermal pleasantness. Experiencing an environmental state as positive is preceded by information in the sense of perceptual change (difference). Kuno (1995), for example, suggests that the experience of thermal pleasantness results from body's physiological inertia in dealing with quick (or discontinuous) changes in ambient conditions that are initially experienced as uncomfortable. As a consequence, one must experience the "uncomfortable zone" before entering into the "pleasant zone". Hypothetesized physilogical underpinnings of adaptive models of thermal comfort theory point in a similar direction, when they quote the potential of an energetically identical thermal field to trigger diverse sensations, given the variance in individuals' internal states (de Dear 2009).
- A number of post occupancy studies suggest that allegedly intangible factors such and people's lifestyle and environmental consiousness can effectively lead to an extention of the thermal comfort zone. This phenomenon is occasionally coined as the "forgiveness factor". It suggests that, given certain informational (attitudinal) states in occupants of the so-called "green buildings", shortcomings of the thermal environment (i.e. deviations of the indoor conditions from the conventionally defined comfort ranges) may be acceptated (Deuble and de Dear 2010, Leaman and Bordass 2007).

Building performance simulation typically provides predictions for the energetically relevant features of the indoor environment. Subjective evaluations, however, are not at all fully determined by energetic descriptors of the so-called environmental exposure. Rather, such evaluations emerge through the complex workings of the information processing in human minds.

CONCLUSION

The exploratory shift of focus toward the human dimension of building performance simulation proves to be both enlightening and inspiring. It opens up a broad and promising landscape of research and development opportunities. In our brief excursion in this landscape, we took up three vantage points, viewing people as tool users, as modeled entities, and as beneficiaries of predicted building performance information relevant to human occupancy:

- Viewing people as users of simulation applications, we were reminded of the many ways tools could be enhanced (interfaces, data processing and visualization features, integration and interoperability), of how the level of competence in tool usage could be elevated (education, training), and of how boundary conditions for tool deployment could be improved (processes, policies, incentives).
- Viewing people as modeled agents in building performance simulation environments, we were reminded on the paucity of reliable empirical data concerning observations of people's presence and behavior in buildings, and the need for rigorous model development efforts and scrupulous model validation studies.
- Viewing people as the ultimate addressees of simulation-based information on indoor environmental quality, we recognized the vital need to improve our currently rather fragmentary understanding of the complex processes that affect people's perception and evaluation of their surrounding environments.

In short, for all those equipped with intellectual curiosity and vested interest in the sustainability and habitability of the built environment, the building performance simulation domain continues to offer a fertile field of inquiry that is both challenging and rewarding.

REFERENCES

Augenbroe G. 2011. The role of simulation in performance based design. In: Building performance simulation for design and operation (Hensen JLM and Lamberts R, editors). Spon Press. ISBN13: 978-0-415-47414-6.

Augenbroe G. 2003. Developments in interoperability. In: Advanced building simulation (Malkawi AM and Augenbroe G, editors). Spon Press. ISBN 0-415-32122-0.

Auliciems A. 1981. Toward a psycho-physiological model of thermal perceptions. *International Journal of Biometeorology*, 25: 109-122.

Bazjanac V. 2001. Acquisition of building geometry in the simulation of energy performance. Proceedings of the seventh IBPSA Conference. Rio de Janeiro, Brazil. pp. 305 – 311.

Bourgeois D. 2005. Detailed occupancy prediction, occupancy-sensing control and advanced behavioral modeling within whole-building energy simulation. PhD Thesis. Université Laval, Quebec, Canada.

Boyce, P. 1980. Observations of the manual switching of lighting. *Lighting Research & Technology*, 12(4): 195-205.

Busch, J. 1992. A tale of Two Populations: Thermal Comfort in Air-Conditioned and Naturally

Ventilated Offices in Thailand. Energy and Buildings, Vol. 18, pp. 235-249.

Chang S and Mahdavi A. 2002. A hybrid system for daylight responsive lighting control. *Journal of the Illuminating Engineering Society*, 31(1): 147- 157.

de Dear R. 2009. Towards a theory of adaptive thermal comfort – the pleasure principle. Proceedings of Healthy Buildings 2009, Syracuse, New York.

de Dear RJ, Leow KG, Foo SC. 1991. Thermal Comfort in the Humid Tropics: Field Experiments in Air Conditioned and Naturally Ventilated Buildings in Singapore. International Journal of Biometeorology, Vol. 34, pp. 259-265.

De Wilde P. 2004. Computational Support for the Selection of Energy Saving Building Components. Doctoral thesis. Delft University Press. ISBN 90-407-2476-8.

Deuble M and de Dear R. 2010. Green Occupants for Green Buildings: The Missing Link?' Proceedings of Conference: *Adapting to Change: New Thinking on Comfort*, 9-11 April 2010, London, UK.

Diaper, G. 1990. The Hawthorne Effect: a fresh examination. Educational Studies. Volume 16, Issue 3, 1990, pp. 261 – 267.

Fenn J and Raskino M. 2008. Mastering the hype cycle:how to choose the right innovation at the right time. Harvard Business Press.

Fritsch R, Kohler, A, Nygard-Ferguson M, Scartezzini JL. 1990. A stochastic model of user behaviour regarding ventilation. *Building and Environment*, 25(2): 173-181.

Haldi F, Robinson D, Pröglhöf C, Mahdavi A. 2010. A partial double blind Evaluation of a comprehensive Window Opening Model. In: "BauSim 2010 - Building Performance Simulation in a Changing Environment" (Mahdavi A and Martens B: editors), ISBN: 978-3-85437-317-9. pp. 331 - 336.

Hensen JLM and Lamberts R. 2011. Introduction to building performance simulation. From: Building performance simulation for design and operation (Hensen JLM and Lamberts R, editors). Spon Press. ISBN13: 978-0-415-47414-6.

Herkel S, Knapp, U, Pfafferott J. 2005. A preliminary model of user behavior regarding the manual control of windows in office buildings. *Proceedings of The Ninth International IBPSA Conference, Building Simulation 2005*. Montréal, Canada. pp. 403-410.

Hobbs D, Morbitzer C, Spires B, Strachan P, Webster J. 2003. Experience of using Building Simulation within the Design Process of an Architectural Practice. Proceedings of the 8th IBPSA Conference. Eindhoven.

Humphreys, M.A. and Nicol J.F. (1998) "Understanding the adaptive approach to thermal comfort", *ASHRAE Transactions* 104(1): 991-1004.

Hunt D. 1979. The use of artificial lighting in relation to daylight levels and occupancy. *Building and Environment*, 14: 21-33.

IFC 2011. URL: http://buildingsmart.com/ (visited July 2011).

Inoue T, Kawase T, Ibamoto T, Takakusa S, Matsuo Y. 1988. The development of an optimal control system for window shading devices based on investigations in office buildings. *ASHRAE Transaction*, 94: 1034-1049.

Liao C, Lin Y, Barooah P. 2011. Agent-based and graphical modelling of building occupancy. Journal of Building Performance Simulation. doi: 10.1080/1940493.2010.531143.

Kastka J. 1981. Psychologische Indikatoren der Verkehrslärmbelästigung. In: Akustik zwischen Physik und Psychologie. SCHICK, A. (Editor). Stuttgart (Klett-Cotta).

Knötig, H. 1992. Some Essentials of the Vienna School of Human Ecology. Proceedings of the 1992 Birmingham Symposium: Austrian and British Efforts in Human Ecology (ARCHIVUM OECOLOGIAE HOMINIS), Vienna, Austria.

Kuno, S. 1995. Comfort and Pleasantness. Pan Pacific Symposium on Building and Urban Environmental Conditioning in Asia, Nagoya, Japan. Vol. 2, Part 2, pp. 383-392.

Lam KP, Wong NH, Feriady H. 1999. A study of the use of performance-based simulation tools for building design and evaluation in Singapore. Proceedings of the sixth IBPSA conference. Kyoto, Japan. pp. 675 – 682.

Leaman A and Bordass B. 2007. Are users more tolerant of 'green' buildings?' Building. Research & Information, 35: 6, 662 — 673.

Lindelöf D and Morel N. 2006. A field investigation of the intermediate light switching by users. *Energy and Buildings*, 38: 790-801.

Love JA. 1998. Manual switching patterns observed in private offices. *Lighting Research & Technology*, 30(1): 45-50.

Madjidi M and Bauer M. 1995. How to overcome the HVAC Simulation Obstacles. Proceedings of the fourth IBPSA conference. Madison, Wisconsin, USA. pp.34 – 41.

Mahdavi A, Mathew P. 1995. Synchronous Generation of Homologous Representation in an Active, Multi-Aspect Design Environment. Proceedings of IBPSA Conference. Madison, Wisconsin. pp. 522 - 528.

Mahdavi A and Kumar S. 1996. Implications of Indoor Climate Control for Comfort, Energy, and Environment. Energy and Buildings 24. pp. 167 - 177.

Mahdavi A, Mathew P, Wong NH. 1997. A Homology-based Mapping Approach to Concurrent Multi-domain Performance Evaluation. Proceedings of the The Second Conference on Computer Aided Architectural Design Research in Asia: CAADRIA '97. Taiwan. (ISBN 957-575-057-8) pp. 237 - 246.

Mahdavi A. 1998a. Computational Decision Support and the Building Delivery Process: A Necessary Dialogue. Automation in Construction 7, pp. 205 - 211.

Mahdavi A. 1998b. A Middle Way to Integration. Proceedings of the 4th Design and Decision Support Systems in Architecture and Urban Planning Conference. Maastricht, The Netherlands.

Mahdavi A. 1998c. Steps to a General Theory of Habitability. Human Ecology Review. Summer 1998, Volume 5, Number 1. pp. 23 - 30.

Mahdavi A, Wong NH. 1998. From Building Design Representations to Simulation Domain Representations: An Automated Mapping Solution for Complex Geometries. Computing in Civil Engineering; Proceedings of the International Computing Congress, ASCE Annual Convention. pp. 1-10.

Mahdavi A. 1999. A comprehensive computational environment for performance based reasoning in building design and evaluation. Automation in Construction 8 (1999) pp. 427 – 435.

Mahdavi A, Ilal ME, Mathew P, Ries R, Suter G, Brahme R. 1999. The architecture of S2. Proceedings of Building Simulation ’99. Sixth International IBPSA Conference. Kyoto, Japan. Vol. III. ISBN 4-931416-03-9. pp. 1219 - 1226.

Mahdavi A, Brahme R, Gupta S. 2001. Performance-based computational design via differential modeling and two-staged mapping. Proceedings of the CAAD Futures Conference. Eindhoven, The Netherlands. pp. 667 – 680.

Mahdavi A and Eissa H. 2002. Subjective evaluation of architectural lighting via computationally rendered images. Journal of the Illuminating Engineering Society. Volume 31. Number 2. Summer 2002. pp. 11 - 20.

Mahdavi A, Feurer S, Redlein A, Suter G. 2003. An inquiry into the building performance simulation tools usage by architects in Austria. Proceedings of the Eight International IBPSA Conference (Eindhoven, Netherlands). Augenbroe, G. – Hensen, J. (eds). ISBN 90 386 1566 3. Vol. 2. pp. 777-784.

Mahdavi A. 2004a. Notes on representation in computer-aided architectural design. GCAD Symposium Proceedings. Pittsburgh, PA, USA.

Mahdavi A. 2004b. Reflections on computational building models. Building and Environment. Volume 39, Issue 8, August 2004. ISSN 0360-1323. pp. 913 – 925.

Mahdavi A and El-Bellahy S. 2005. Effort and effectiveness considerations in computational design evaluation: a case study. Building and Environment, 40 (2005), pp. 1651 - 1664.

Mahdavi A, Bachinger J, Suter G. 2005a. Toward a unified information space for the specification of building performance simulation results. In: Building Simulation 2005, Ninth International IBPSA Conference. Montreal, Canada (Beausoleil-Morrison I, M. Bernier, M.: Editors). pp. 671 - 676.

Mahdavi A, Becker G, Lechleitner J. 2005b. An empirical examination of the evaluative utility of design auralization; in: "Building Simulation 2005, Ninth International IBPSA Conference, August 15-18, Montreal, Canada", I. Beausoleil-Morrison, M. Bernier (Editors). pp. 677 - 684.

Mahdavi A and Pröglhöf C. 2008. User-System interaction models in the context of building automation. In Zarli AS and Scherer R. (eds) *Proceedings of ECPPM 2008 - eWork and eBusiness in Architecture, Engineering and Construction*, Sophia-Antipolis, France, pp: 389-396.

Mahdavi A, Mohammadi A, Kabir E, Lambeva L. 2008a. Occupants' operation of lighting and shading systems in office buildings. *Journal of Building Performance Simulation*, 1(1): 57-65.

Mahdavi A, Kabir, E, Mohammadi A, Pröglhöf C. 2008b. User-based window operation in an office building. In: Olesen, B., Strom-Tejsen P and Wargocki P. (eds) *Proceedings of Indoor Air 2008 - The 11th International Conference on indoor Air Quality and Climate*, Copenhagen, paper 177.

Mahdavi A. 2011. People in building performance simulation. In: Building performance simulation for design and operation (Hensen JLM and

Lamberts R, editors). Spon Press. ISBN13: 978-0-415-47414-6.

Mcdonald I, Strachan P. 2001. Practical application of uncertainty analysis. Energy and Buildings. 33: 219 – 227.

McIntyre DA. 1982. Chamber Studies — Reductio Ad Absurdum? Energy and Buildings. Vol. 5, pp. 89-96.

Morbitzer C, Strachan P, Webster J, Spires B, Cafferty D. 2001. Integration of Building Simulation into the Design Process of an Architecture Practice. Proceedings of the 7th IBPSA Conference. Rio de Janeiro.

Nicol JF 2001. Characterising occupant behavior in buildings: Towards a stochastic model of occupant use of windows, lights, blinds, heaters, and fans. *Proceedings of The Seventh International IBPSA Conference, Building Simulation 2001*, Rio de Janeiro, Brazil, pp: 1073-1078.

Norretranders T. 1999. The User Illusion: Cutting Consciousness Down to Size. Penguin Press Science. ISBN-10: 0140230122.

Pessenlehner W, Mahdavi A. 2003. Building morphology, transparence, and energy performance. Proceedings of the Eight International IBPSA Conference (Eindhoven, Netherlands). Augenbroe, G. – Hensen, J. (eds). ISBN 90 386 1566 3. Vol. 3. pp. 1025-1032.

Pont U, Sommer B, Mahdavi A. 2010. Ein Vergleich der Ergebnisse von stationärer und instationärer Berechnung von thermischen Energiekennzahlen anhand bestehender Objekte in Wien. In: "BauSim 2010 - Building Performance Simulation in a Changing Environment" (Mahdavi A and Martens B: editors), ISBN: 978-3-85437-317-9. pp. 515 - 522.

Rea MS 1984. Window blind occlusion: a pilot study" *Building and Environment*, 19(2): 133-137.

Reinhart C. 2001. Daylight availability and manual lighting control in office buildings - simulation studies and analysis of measurements. PhD thesis. University of Karlsruhe, Germany.

Reinhart C 2004. LIGHTSWITCH-2002: A Model for Manual Control of Electric Lighting and Blinds. *Solar Energy*, 77: 15-28.

Rijal HB, Tuohy P, Humphreys, MA, Nicol JF, Samuel A, Clarke J. 2007. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. *Energy and Buildings*. 39: 823-836.

Schiller G, Arens EA, Bauman PE, Benton C, Fountain M, Doherty T. 1988. Thermal Environments and Comfort in Office Buildings. ASHRAE Transactions, Vol. 94, Part 2, pp. 280-308.

Schönpflug W. 1981. Acht Gründe für die Lästigkeit von Schallen und die Lautheitsregel. From Akustik zwischen Physik und Psychologie. In SCHICK, A. (Ed.), Akustik zwischen Physik und Psychologie. Stuttgart (Klett-Cotta).

Wang C, Yan D, Jiang Y. 2011. A novel approach for building occupancy simulation. Building Simulation: An International Journal. Vol. 4, No. 2. ISSN 1996-3599. pp. 149 – 167.

Watts D. 2011. Everything is obvious: once you know the answer. Crown Publishing Group, Random House, N.Y. eISBN: 978-0-385-53169-6.