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RUTGERS
Center for
GREENBUILDING



Final Report

Investigating Opportunities for Improving Building Performance through Simulation of Occupant and Operator Behavior

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Executive Summary

This is the final report for a project funded in part by the U.S. Green Building Council's Green Building Research Fund in 2009. The research investigates opportunities for improving building performance and occupant satisfaction through an iterative process of empirical fieldwork in green buildings and computer simulation modeling.

The fieldwork took place in commercial buildings in the Greater Philadelphia area owned by Liberty Property Trust and the New Jersey Economic Development Authority. It consists of building performance evaluations that document energy usage and system functionality, plus post-occupancy evaluations that document occupant perceptions and behaviors by means of walk-throughs, interviews, surveys, and building-management logs.

The computer simulation work employs an agent-based modeling approach that implements the Belief-Desire-Intention framework used in the artificial intelligence community to represent human decision making. This work is executed using newly-authored Java programming, the *NetLogo* modeling environment, and hot-linked engineering design packages including, most recently, *EnergyPlus*. Data collected during the fieldwork provides a basis for calibrating and validating the models.

This project demonstrates that the simulation modeling framework is feasible and useful. It shows the value of tailoring building designs to accommodate heterogeneous users who have diverse comfort preferences and respond to indoor environmental conditions in a variety of ways. It allows architects and engineers to perform what-if experiments regarding the usability of specific building design features.

Additionally, this project has generated a variety of important empirical insights about how social and organizational factors affect occupant behavior, and thereby affect the efficacy of specific green building strategies. *Locus of control* is a particularly problematic area, wherein control over building systems often does not map well onto social structures and organizational hierarchies. This is also a source of confusion over the respective roles of building operators and occupants. *Lack of coordination* between core and shell designs and those for interior fit-out of tenant spaces is another, better recognized problem in the same vein.

The notable contributions of this project are to demonstrate an innovative approach for simulating occupant behavior using agent-based modeling techniques, and to provide a solid grounding for the modeling work by linking it directly to detailed empirical observations within case study buildings. Recommended next steps include strengthening and disseminating the simulation-modeling framework, extending it and the field research to address more fully the operator-occupant nexus and similar social and organizational factors, and advancing consideration of *usability* metrics within the LEED framework.

Project Overview

This project – *Investigating Opportunities for Improving Building Performance through Simulation of Occupant and Operator Behavior* – was developed with two goals: (1) improve the usability of green buildings, and (2) improve our ability to model human-technology interactions.

As noted in our original proposal, architectural design is based on assumptions about how a building and its systems will be used. Sometimes, though, those assumptions do not match actual usage. Buildings may fail to perform as planned, because operators do not—or cannot—operate the buildings as intended, and because occupants sometimes behave differently than designers expect.

Post-occupancy evaluation, included as an IEQ credit in LEED-NC 2.2, can provide valuable feedback on an existing building’s usability and human effects, but its influence on future designs is often indirect (Wener, 1989; Zimmerman and Martin 2001). Needed is a more direct means to help practicing architects and engineers incorporate realistic behavioral expectations into building design. Thus, this project was conceived to advance the practice of *behaviorally-robust green design* by linking empirical research with computer simulation modeling and subsequent engagement with practicing architects and engineers to provide a basis for *evidence-based design* as an approach to green buildings.

The empirical foundation for advancing the goals of this project has been a set of case studies of LEED certified commercial buildings drawn from the portfolio of Rutgers Green Building Benefits Consortium members Liberty Property Trust (<http://www.libertyproperty.com>) and the New Jersey Economic Development Authority (<http://www.njeda.com>). The case studies took place between 2009 and 2012 in the greater Philadelphia-New Jersey region, as did the associated modeling work.

Primary authors of this report include MaryAnn Sorensen Allacci, Clinton Andrews, Jennifer Senick, Jennifer Souder and Richard Wener. Deborah Plotkin and Pallavi Shinde provided invaluable production assistance.

Methods and Data

The completed case study research has utilized a multidisciplinary building performance evaluation protocol that includes both user-oriented post-occupancy evaluation (POE) and engineering evaluation. These data, in turn, are used to validate and calibrate the simulation model of occupant behavior and building performance outcomes.

The purpose of a building performance evaluation is to develop objective, quantitative measures of resource use and indoor conditions for comparison with performance benchmarks, which may complement subjective measures of occupant perceptions. A summary of this set of building performance evaluations is included as an **appendix** to this report.

POE refers to study of the operation, status, and usability of a physical setting at some point after construction is completed and users move in (Wener, 2002)¹, and is intended to complete otherwise missing aspects of feedback

¹ Wener, R. (2002). “Post Occupancy Evaluation,” in *The Encyclopedia of Psychological Assessment*, Rocio Fernandez-Ballesteros (ed.) Thousand Oaks: Sage Publications.

loops that check how well the building's operation fits initial intentions, goals, program and design. Key findings of these POEs are included in an **appendix** to this report.

To address these issues data were collected using a variety of methods, involving the use of sources for providing both qualitative and quantitative information. The data collection techniques that were employed included walk-through interviews /observations of the space, reviews of plans, photo documentation, where permitted, interviews with building managers and planners/designers, reviews of archival data, individual and focus group interviews, and the distribution of questionnaires containing most closed-ended questions.

Our engineering evaluations focus on how well the building meets its energy performance goals as well as the role of human agency in mediating these outcomes. Utility and benchmarking analyses have been completed for each of the subject buildings.

The simulation-modeling framework was developed by programming computer code that implements a theory of human behavior based on the Belief-Desire-Intention framework from artificial intelligence. We have been iteratively developing more sophisticated and testable models, because this incremental approach ensures that we understand each model's dynamics. The next steps are to calibrate each model using survey and interview data from individual building occupants, plus building-wide performance data for one or more buildings. We validate each model by using it to predict outcomes (expressed as usability metrics) for an additional building.

Outreach to Practitioner Organizations

Throughout this project and especially over the last several months, we have shared results with a number of key practitioner organizations thereby gaining valuable feedback in the iterative process of developing the simulation models and empirical insights. Selections from the full set of presentations are included as an **appendix** to this report.

We have made presentations and convened a LEED focused sustainability workshop at the 43rd *Environmental Design Research Association* conference in May-June, 2012. Our presentations explored the "Context & Prediction of Building Efficiency & Behavioral Outcomes in Green Buildings" and the workshop (Developing a Research Agenda for The Sustainable Planning, Design, and Behavior Network) established an on-going interest in addressing how the green building community and LEED can better support the mutual goals of occupant satisfaction and building performance.

In June of 2012, we also presented at the *International Association People-Environment Studies - IAPS22 - Human Experience in the Natural and Built Environment: Implications for Research, Policy, and Practice* conference in a session entitled, "Case Studies of Post Occupancy Evaluations in Green Buildings," while also attending a sustainability network session in order to insert green building POE and simulation modeling into its agenda. (Note that IAPS is a sister organization of EDRA and that Jennifer Senick and Rich Wener, project investigators, are co-chairs of the EDRA Sustainable Planning, Design and Behavior Network).

Most recently, we presented the study results to our grant partner – Liberty Property Trust – in a meeting forum that included the Project Architect (LEED AP), Operator and Property Manager of the subject buildings as well as

many members of Liberty executive staff. Many of these same people have been involved since the beginning of the project and also participated activity at the Project Scoping meeting when the project commenced. Similarly, we have maintained communication with the NJ EDA across the project timeline, especially with the Project Architect (LEED AP) for the subject building who has served as our main point of contact. Lastly, it should be mentioned that project partners from both organizations have made presentations of their own based on the project data the Rutgers team has developed and that both Liberty Property Trust and the Rutgers Center for Green Building will be presenting project results at Greenbuild 2012 (in separate sessions).

Additional practitioner communities with whom we have had the benefit of sharing/iterating our project findings include the NJ Chapter of the USGBC (we developed a standalone case study of the NJ EDA building with data that goes beyond this project scope) and the US Department of Energy (US DOE) Greater Philadelphia Innovation Cluster, recently renamed the US DOE Energy Efficient Buildings Hub (to whom we submitted a case study that focused more narrowly on energy efficient behaviors in two of the subject buildings). These additional audiences contain many LEED APs and have been helpful in advancing the discussion about how programs and policies can influence building performance and occupant well being.

Simulation Modeling

This section provides further details on the computer simulation modeling undertaken for the project. Computer simulation models that characterize complex systems in order to inform better decision making originated in the 1960s and are now widely used in construction-related fields. Detailed engineering systems-analysis tools are widely used in designing HVAC, lighting, building siting, building envelope, and structural systems. They are used much less often for plumbing, with choices limited to equipment sizing calculators, public utility-scale tools for water and wastewater, and simple CAD-based estimating tools. Whole-building, integrated design tools are mostly confined to spreadsheet models developed idiosyncratically by engineers for their own use, and proprietary simulation tools such as Autodesk Revit that allow architects to understand better the implications of broad design choices.

The most powerful of these tools provide extremely detailed engineering estimates of system performance and equipment needs but they suffer from simplistic representations of occupant behavior. For example, most models assume homogeneous building occupants who like the same temperature set-points, lighting levels, and appliance loads, in spite of the fact that survey data and observations reveal great heterogeneity. Likewise, most models represent occupants as static objects that emit heat but otherwise do not actively engage with building systems. Building managers know that real occupants are anything but passive.

Microsimulation models of commercial building energy demand and more recent agent-based models of various human behaviors have blazed pathways for improving these representations of behavior but they have just begun to appear in building-level models. The most significant advances have been in studies of emergency building evacuations, where models now have rich detail and usability. By contrast, HVAC and lighting applications are limited to research-level models of highly stylized 1-2 room buildings. Part of the agenda for this project is to advance this marriage of engineering analysis and behavioral analysis.

With the current funding from the USGBC, prior and continuing funding from NSF and Liberty Property Trust, and new funding from USDOE, this project has developed a research-level, computer-based, simulation-modeling

framework that portrays how building systems and occupants interact. Models developed using this framework represent the dynamics of occupant behavior and the operation of building systems in existing case study buildings. These models also allow the prospective study of design tradeoffs in hypothetical buildings that more fully pursue green objectives. Especially important, the modeling framework enhances modeling of the human factors, using a multi-agent simulation approach to represent occupant behavior more realistically than current building information modeling practice allows.

The modeling framework is advancing incrementally by integrating standard, packaged engineering models (EnergyPlus, Radiance, and others) with new human factors models created using the Netlogo agent-based modeling framework. The agent-based models are linked to these engineering models using a common set of input and output files and a suite of Java-based shell programs.

The modeling framework was inspired by that of Fujii and Tanimoto (2003) but it has been considerably advanced during this project. Andrews et al (2011) summarizes the framework and its theoretical underpinnings. It represents human and environmental interactions within a computational structure that contains (1) a building simulation submodel (that points to the external engineering models), (2) a human action simulation submodel (containing a representation of agency), and (3) a mediating submodel that tracks the state of the building's controllable components and links the building and its human occupant(s). Submodel #1 manages a set of standard engineering calculations to determine the state of the architectural environment, that is, such things as indoor air temperature and humidity levels, indoor air quality, and wastewater characteristics, as functions of the building's technical state and occupant behavior.

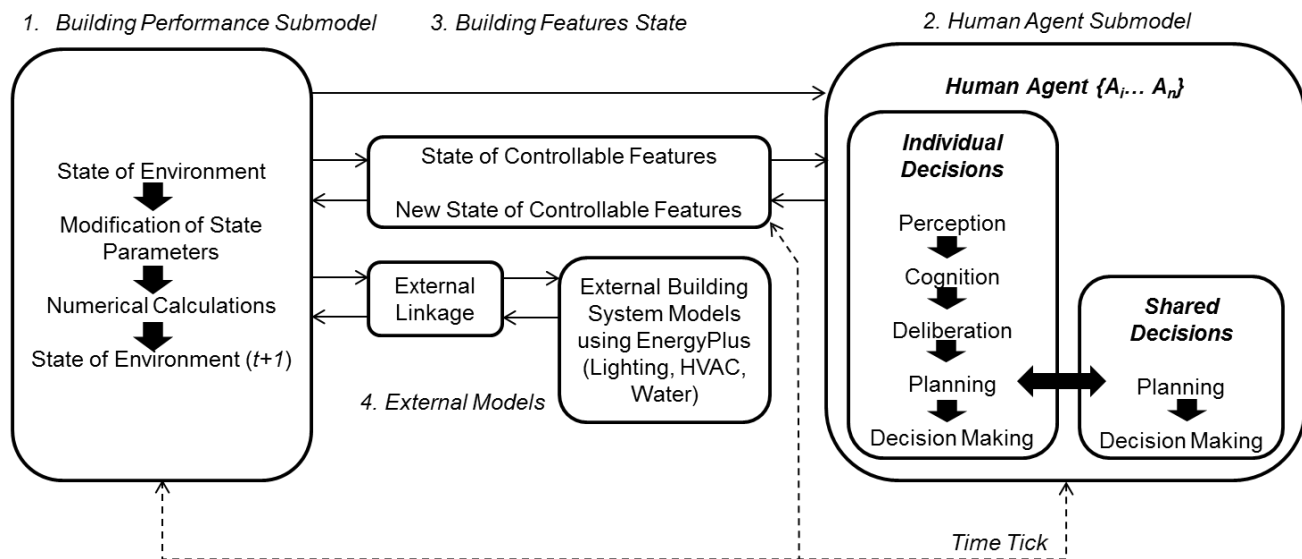


Figure 1: Computer-based simulation modeling framework

Source: Adapted from Andrews *et al* 2011

Submodel #3 describes the building's technical state, as a function of occupant behavior and the state of the building's environment, that is, it describes things like windows and faucets and whether they are open or shut. In submodel #2, the human agents respond to the states of the architectural environmental conditions and design through chained processes of sensation, cognition, desire, planning, and action that lead to changes in the states of

the building's controllable features and in its performance. Humans are heterogeneous in their sensations, perceptions, desires, causal beliefs, and prescriptive/planning beliefs, hence they act heterogeneously given similar stimuli. This modeling framework allows *in silico* tests of behavior modification proposals, as well as tests of the efficacy of technical innovations such as occupancy sensors.

Modeling Work Completed with this Grant

The simulation framework described above was initially developed off-budget as part of the NSF-funded project. For this USGBC-funded project, the model was calibrated for selected aspects of commercial buildings using data from one of the case study buildings in this project. It was then validated against one of the remaining case study buildings. The results have been published in Andrews *et al* (2011), which is attached as an **appendix** to this report.

The alternation between fieldwork and modeling has been a particularly rewarding aspect of this project. Each activity generates insights that spur creative thinking about the other. This mode of “grounded theorizing” treats modeling as the formal expression of a theory of occupant behavior, which then suggests hypotheses that warrant testing during the empirical field visits to buildings. An example of this process has been published in Andrews, Senick and Wener (2012), which is attached as an **appendix** to this report.

To date, we have completed and posted online complete models of occupant behavior relevant to residential lighting and water system design, and commercial building lighting design. Sample models are freely downloadable at **greenbuilding.rutgers.edu**.

A preliminary model for heating, ventilating, air conditioning, and indoor air quality (HVAC & IAQ) design for residential and commercial buildings has been completed and it is summarized in a Powerpoint presentation included as an **appendix** to this report. Development is still underway with continuing funding from NSF, USDOE, and Liberty Property Trust. Some of the fieldwork to collect data for calibrating and validating these models was performed under the current grant and USGBC will be acknowledged when these next models are completed. We note that model development is to some extent an open-ended process with each version of the published model incorporating additional features and operating more effectively.

Continuing Modeling Work

The HVAC & IAQ models upon which we are currently focusing are particularly ambitious. We have re-written the computer code to allow an arbitrary building geometry and we have successfully hot-linked the human behavior model to *EnergyPlus*. We have been able to input building design parameters using the public-domain *OpenStudio* software that serves as a front end to both *EnergyPlus* and *Radiance*, indeed, its developers at NREL are implementing new software features for HVAC and lighting systems at our request. The HVAC & IAQ models are currently undergoing calibration and validation against data from commercial buildings in the Philadelphia area, with funding from the USDOE Energy Efficient Buildings Hub. Specifically, we are refining the models to better reflect installed equipment in these buildings, and we are calibrating and validating them against utility bills, BMS logs, and occupant surveys.

An important new feature of the evolving modeling framework is the ability to model hierarchical and other social structures such as supervisor-employee, building operator-building occupant, and parent-child relationships. Such relationships strongly affect the adaptive responses of building occupants to changing conditions. This is especially true in commercial buildings with shared thermostats and light switches, and mixes of centrally- and locally-controlled systems. As discussed elsewhere, this is an important theme in our empirical research too.

Our long-term vision for this modeling framework is to develop a standard occupant behavior model for general use by designers. In order to achieve this vision, we are continuing to refine the behavioral theories underlying the model—for example, by distinguishing between habitual and reasoned behaviors—and we are developing a database of “typical” building occupants that can be dropped into models of as-yet un-built buildings.

Lessons Learned

Research thus far is beginning to provide a more complete profile of the challenges and possibilities of integrating green building innovations effectively into commercial office space environments. Building performance is a function of how sometimes complex physical and social components of the workplace operate synergistically to create the day-to-day office environment. Among these systems are the building systems themselves, the spatial layout in which they are inserted, and the layered social organizations of the people for whom they must operate. Good building and technology design and operation can help mediate the effective integration of many of these different components; other solutions will require a dynamic, ongoing iterative adjustment and coordination between centralized and local control of workspaces.

The following discussion is based on findings and recommendations of post-occupancy evaluation (POE) research conducted on three LEED certified multi-tenanted buildings, including building performance evaluations (BPE) of all three. POE evaluation offers a critical assessment of how buildings perform after they are occupied and can be used to assess the quality of building environment from occupants’ perspectives; compare the performance of the building from independent and archival data with standardized parameters; evaluate how a building meets or deviates from programmed objectives; and project expanded building design and programming, among other uses. The studies took place between 2009 and 2012 with building owners operating in the greater Philadelphia-New Jersey region. The studies together focus on buildings owned by Liberty Property Trust, owner and developer of single and multi-tenant commercial office buildings in the United States and the United Kingdom (<http://www.libertyproperty.com>) and the New Jersey Economic Development Authority (<http://www.njeda.com>). Data from our findings have been broadly disseminated throughout practitioner communities, including at two conferences of Environmental Design and Behavior, within the NJ Chapter of the USGBC, and the US DOE Energy Efficiency Buildings Hub project (formerly known as the US DOE Greater Philadelphia Innovation Cluster).

Methodological Lessons

Methods of post-occupancy evaluation provide opportunities for holistic study of built environments, generally considering occupant responses relevant to building characteristics and specifically varying with the objectives of

the evaluation and the type of building. In the cases referenced, the POEs involved research team walk-throughs of the sites to make independent observations and brief orienting / intercept interviews with occupants, and on-line surveys of occupants to improve understanding of respondents' experience and satisfaction with the buildings and potential effects on health and performance. Building performance evaluation (BPE) of building energy performance on the basis of archival data in the form of utility bills and facility logs were completed to provide projections of these data and energy performance benchmark analysis. In two of these buildings the study was also able to draw on surveys conducted by the building owner. Interviews were also completed with building owners and managers, designers, and tenant representatives. The POE method is highly suitable for building analysis: It has the advantage of incorporating qualitative and quantitative data in a rigorous and responsive process to develop explanatory richness from different slices of data. As a multidisciplinary process, it is particularly effective for developing a "triangulation" of understanding using various tools.

Lessons Concerning Research Objectives

The importance of post-occupancy evaluation for identifying areas of success, areas needing improvement, and noteworthy patterns of operation cannot be overstated. Overall goals of the studies collectively are to improve the usability of green buildings through the development of evidence-based design, and to improve our understanding of building-user interactions influencing both occupant well-being, performance, and building performance. The key findings from these studies have been organized in a way that offers a succinct system of guidelines for practicing designers based on two primary areas: diffusion of green design strategies and building performance measures. The summary of findings below offers points of reference for designers and policy makers in efforts to expand and improve upon green building market diffusion:

Challenges to and possibilities for diffusion of energy efficient and green building design objectives and operations in commercial office spaces

The following aspects of commercial office work environments have emerged in the sponsored research as central to the success of green building technology in the commercial office space:

MULTI-TENANTED BUILDINGS CREATE MORE COMPLEX CHALLENGES

This research has highlighted the unique characteristics of multi-tenanted buildings that call for enhanced focus on tenant-relevant activities and needs as they affect, especially, building energy and other aspects of building performance. For example, the increasingly popular trend for health care facilities to decentralize and lease space in office buildings, for example, can skew building energy performance measures due to energy-intensive technologies that are often part of their function. Technology development labs can have similarly diverse energy demands. Communicating, reaffirming, and enforcing building owner objectives for green building operations can be much more difficult to implement across multi-tenanted than single-tenanted buildings, even when building owners provide operating handbooks and regular email updates to tenants, as did the commercial real estate developer in our study. A further complicating factor is that often the tenants in these buildings are regional or local offices of a company whose headquarters are situated in a more distant place. Based on our research, this often means that the on-site office is less or unfamiliar with things like energy use for the office (does not

see the bill or pro rata charge) thus widening the incentive gap for increased energy conservation. The practice of green leasing is gaining more attention for this purpose, and progress in this area will rely on building owners working closely with tenants (at various organizational levels) to define reasonable terms and determine what is possible given tenants' needs and abilities.

CORRESPONDENCE BETWEEN CORE AND SHELL DESIGN AND INTERIOR FIT-OUT

Our findings suggest a reoccurring disconnect between building shell design and construction and interior design, or fit-out. As is typical in speculative commercial buildings, the core and shell of buildings included in the study have been constructed first, and the tenant fit-out of interior spaces has followed as tenants sign leases. The core and shell systems, therefore, have a great deal of flexibility designed into them, which sometimes limits their achievable energy efficiency but has value because the tenant's needs, and even their fit-out requirements and connections to central systems, may diverge from the original design program. At times these conflicts seem unanticipated in spite of efforts to project the effects of the building envelope on the interiors, as in the example when daylighting is maximized and delivered deep into the space via skylights, atria, or perimeter windows and the problem of glare results. Even sometimes when the glare is anticipated, methods of prediction are not reliable or readily transferrable between building types, making guidelines difficult to implement in the early stages of design.² In other situations, the divisions result from intentional modifications, wherein changes are made post-occupancy by building owners or occupants to curb unintended glare or address privacy concerns which can be associated with daylighting strategies. Similarly, preferences of occupants for window vistas can drive design with generous glazing on "cold" sides of building (e.g., on the northern exposure in the northeast) affecting the heating load and the thermal comfort of occupants. Further, changes that tenants and occupants make unilaterally can conflict with original design intentions, even when there have been attempts by the owner and tenant to coordinate core and shell construction with interior layout. Preference for floor plan design, partition heights, and privacy and acoustic needs related to these features can be diverse across tenants and affect the distribution of daylighting as well as the proper operation of HVAC circulation of the original design.

In spite of LEED efforts to create complementary but separate standards for Core and Shell and Commercial Interior certification, market trends warranting changes in both building owner and tenant operations can overpower even concerted efforts by building owner/developers to coordinate fit-outs for effective integration with building facade and systems. A new two-pronged approach is needed to promote a more unified attempt to integrate core and shell with fit-out design. The first can be in the form of LEED guidelines that offer substantial credits for producing evidence based "patterns" of interior-fit - building solutions. These patterns would contribute to building operations that also correspond to occupant well-being associated with indoor environmental quality, such as lighting control and optimal temperature. The importance attributed by LEED to these criteria would signal to the owner/developer the need for an integrated design process that brings focus to the mediating role that tenants and occupants have in building performance. As the second part of this initiative to encourage greater

² Osterhaus, W. Design guidelines for glare-free day-lit work environments, 2009. Aarhus School of Engineering (IHA), Architectural and Civil Engineering, Lighting Design Research and Development Laboratory, Aarhus, Denmark, E-Mail: wos@iha.dk

integration of interiors and building design, negotiated green leases as well as subsidies and incentives are potential tools to gain support from tenants for performance objectives.

OCCUPANT RELATIONSHIPS WITH WORKPLACE DESIGN AND LOCUS OF CONTROL

Occupants have a pivotal role in determining how buildings perform because of their dynamic relationship with the physical environment. Research on several LEED and non-LEED buildings illustrate how buildings affect occupant comfort and ability to perform work tasks as well as how occupants influence building performance by changing aspects of their workspace. The work environment includes both physical and social aspects, specifically the interactions between the physical environment, social relationships, and organizational objectives and mandates. This research underscores the relevance of a number of related and interacting themes that advance our understanding of occupants' responses to building innovations and their adoption of energy efficient and other building system technologies.³ These themes include:

THE RELATIVE COMPATIBILITY AND ADVANTAGE FOR OCCUPANTS TO MEET ORGANIZATIONAL AND PERSONAL OBJECTIVES IN THE WORKSPACE.

Adequate environmental fitness of occupants (in its scientific usage that denotes compatibility within an ecological niche) in a physical work environment can encourage a sense of competency, wellness, confidence, and productivity. Environmental fitness suggests a match between the physical environment and occupants that affords occupants the materials and processes that they perceive essential for completing their objectives. The quality of self-relevant objects essential for successful task completion as defined by the employer and the occupant can either support or frustrate the process of task completion. Individuals and organizations will judge the adoptability of innovations depending on the likelihood the engagement with objects will result in better work outcomes, will accommodate diverse user styles and abilities, and offers an element of control or perceived control for critical areas affecting comfort and performance. The incorporation of new systems and technologies will continue to rely on post-occupancy evaluation as a means of feedback on conflicts or negative effects for occupants and building performance and examples of successful integration. In addition, while lighting and HVAC installations typically aim to achieve a universal 'standard' for space categories, (e.g., office lighting of 400 lux or temperatures within a narrow band around 21 C), study participants frequently reported lighting that was "too bright", temperatures that were "too hot" or "too cold", or air movement that was inadequate. Ranges of system performance may be more acceptable to occupants and appropriate for their activities. Some of these findings also suggest realizable energy savings through avoidance of excessive air conditioning in the cooling season and excessive heating in the cold months. Further, the important role of air movement for cooling could offset the higher costs of lower temperature levels.

LOCUS OF CONTROL

As with most commercial spaces, control of decisions over operations and to some extent design is diffused among property management and occupant functions. The locus of control is clear in some situations, such as when repairs are needed to the building structure or management of central heating and ventilation systems, or an occupant's ability to adjust blinds or window treatments to management daylighting levels. Many other space management functions, however, are less clear, as with who can manage temperature settings in individual workspaces or suites or how lighting settings might be

³ Rogers, E.M.. *Diffusion of innovations*, 4th ed. NY: Free Press, 1995.

changed. This confusion can increase with technological innovations that are complicated and unfamiliar to local users (operators and occupants included). Our research findings demonstrate how this diffusion-and-confusion scenario can have negative effects on building performance and indoor environmental conditions for users. Where thermostats existed in office suites, they were often confusing to operate or deceiving as to whether or not they permitted local adjustment. Difficulties associated with occupants' inability to access or understand technical control systems and the negative effects on thermal comfort are not unique to the present study. Adaptive responses by occupants include the use of portable fans and heaters, and removal of lighting fixture lamps, among other actions that may be implemented to overcome a usability challenge. Social conflict among co-workers and other building occupants may also arise when individuals have different needs for local conditions to support work tasks while design of control systems does not afford an ability to manage those conditions. Not all buildings are suited to providing occupants the level of local control required to achieve LEED credit in this area, however, and context-relevant assessment of more nuanced levels of local control should be explored to consider where local control is most compatible with occupant and building system needs. A clear negotiation between central and local control opportunities can help address some of these disconnects and might include those already being promoted in the LEED online community:

- Ongoing occupant education and support on use of technologies,
- Overrides on local systems that are crucial for occupant comfort,
- Flexible lighting controls and ballasts that correspond to daylighting conditions, and
- Occupant access to operable HVAC diffuser vent systems.

These are examples of fixes that could go a long way in limiting the need for occupants to implement adaptations to unsatisfactory conditions.

COMPATIBILITY AND COMPLEXITY OF TECHNOLOGY INTEGRATION WITH SOCIAL AND ORGANIZATIONAL STRUCTURES

As noted earlier, ongoing training, education, and communications are essential for integrated design not only for individual occupant understanding of their role in green building design and operations but also for changes in workplace characteristics that seem more fluid in current economic times (e.g., employee / tenant / owner turnover, operations modifications, department reorganization). Systems that worked well under some layout conditions, for example, may not perform equally well with changes in activities, fit-out, work schedules, or forms of organizational or occupant communications. In some offices examined, banks of lighting over clusters of unoccupied cubicles and connected to a single switch were not be responsive to trends of the flexible workplace where some occupants spend less time in the office, and where cubicle re-design resulted in work surfaces that were no longer located below the needed lighting. Office culture can vary considerably in terms of policies specifying responsive green practices and social hierarchy for resolving office concerns, and building owners and operators may not care to reveal many aspects of their operations to tenants. Interviews with tenants and occupants elicited comments about being too busy to contact the building owner for (lighting) changes or not wanting to bother the property management even when owners in the present studies were rated as very responsive. On the other hand, building owners were sometimes surprised about the feedback provided as evidence of tenant office conditions. Periodic on-site walk-throughs may very well be the communication level that is needed to

reinforce green policies, offer specialist assessments on the quality of systems integrations, and provide the additional responsiveness that gives green building owners the added edge in a competitive market.

Building performance measures as part of building life

The studies document how building performance is affected not only by the as-built structure and operation of the building but also by decisions made by owners, tenants, and occupants over the life cycle of the structure. Building designers and owners, and policy makers alike can benefit from the insights gained through research to consider how long term building performance can be improved for occupant well-being and performance as well as energy efficiency.

Thus, building performance might be considered as a product of structure and design, systems operations, and occupant behavior combined. Each of these categories has a series of interconnected dimensions that produce the most favorable results when they are integrated and work together, less so when each area works in silos. For example, structural and technological design must be fine-tuned to achieve optimal effects, which will typically require ongoing feedback to help identify any unanticipated results in performance. In one study site, heating of a large, glass curtain wall was controlled based on the outside air temperature even during evening / off-hours, resulting in unnecessary energy consumption. A retrofit was being devised by management subsequent to the study to resolve this conflict. As work schedules and spatial configurations change, these modifications may also warrant adjustment. The design and operation of systems as exclusive, independent building components may gross a substantial resource gain on the board but net a meaningful loss when there is a disconnect with ongoing occupied workspace conditions.

Similarly, individual behaviors are an integral part of the performance web, both as they are affected by building performance and as they influence building performance outcomes. Just as interior decisions are made organizationally that affect the intended effects of core and shell, individuals will take adaptive steps they perceive to be available to them to improve conditions they determine to be unsatisfactory and not conducive to their workplace objectives. Some of these adaptive behaviors can alter building performance, as when several individuals on a floor or building section employ portable electric heaters to increase thermal comfort.

Computer simulation modeling is underway to help include occupant-relevant factors in projections of building performance. Calibrated for specific aspects of commercial building office environments using data from the case studies performed, the simulation modeling focuses on human-technology matrices that are known to be problematic for occupants and management, including building management systems for HVAC; indoor air quality; daylighting and window treatments; lighting; and recycling and composting practices. Guidelines for application will assist building developers and owners in incorporating factors that are likely to affect building function and occupant well-being and productivity.

BENCHMARKING

The studies also highlight the relative advantages and disadvantages of benchmarking. Increasingly, suburban office buildings incorporate a highly diverse mix of tenants, each with varying building performance, work schedule and other needs. The risk is that comparison of specific site performance indicators to centralized or universal benchmarking standards, particularly in cases of high-load facilities, could be based on unrealistic or inappropriate use levels. Such external comparison guidelines may be more effectively made against similarly tenanted buildings in conjunction with local energy performance feedback loops. The composites of data information can offer tailored performance indicators and

education on energy and building performance where occupants have control over their energy consumption. Owners and building managers are already aware of the need to be cautious when using universal benchmarking tools and would benefit from more site-relevant strategies.

In addition, health care tenants provide examples of competing interests between core services and energy efficiency. A common theme among a number of stakeholders interviewed the reliance on many high-energy devices in this industry means that energy efficiency objectives are not a top priority. When benchmarking analysis is conducted, high-energy uses are typically treated as outliers, which continue to distance these industries from energy efficiency objectives. Better benchmarking strategies are needed to recognize the reality of mixed uses and energy loads.

SITE VS. SOURCE ENERGY

A related topic to benchmarking is site versus source energy in evaluating building energy and atmospheric performance. The buildings studies here represent a growing trend towards all or mostly electric buildings combined with high-performance design that emphasizes a tight envelope, daylighting strategies and efficient mechanical equipment. Even while these buildings may perform well in terms of their site energy, their source energy remains high. Alternative approaches would incorporate more renewable energy and advanced energy systems such as solar and geothermal on-site. Additionally, these same systems could help to balance variable energy loads. However, the first costs associated with these systems discourage their incorporation into building projects, as was confirmed by our interviews of members of these buildings' developer/owner team and others like them. This is a well-studied problem in policy circles that nevertheless continues to be a barrier to greater dissemination of energy efficiency and sustainability features, technologies and, to a lesser extent, practices

Recommendations for future work

Empirical investigations of how organizational factors interact with the built environment

Research on integrating innovative technology into the social matrix of organizational and personal needs will continue to be important as commercial organizations change. An important related and emerging area in this matrix is social network analysis, which can look more closely at how departments and sub-department groups communicate and operate in context of the physical workplace. Much work can be done on the role of Human Resource departments in sustainable workplace operations and might include incentives to employees and development of effective communications toward building performance objectives. Data on occupants' relationships with their workspace, especially features associated with green design can contribute to more textured understanding of how social and physical features combine to affect satisfaction and productivity. As part of a feedback loop, gaps between organizational objectives and performance indicators can be identified and objectives for green design can be highlighted.

Next steps for the simulation modeling framework

The simulation modeling work has demonstrated that incorporating occupants explicitly within building information modeling is feasible and valuable. Building designs optimized for occupant usability are different than those designed for traditional objectives such as energy efficiency or low construction cost. Needed next steps include the following:

1. Validate the agent-based approach developed in the current project more widely, with a greater range of building and occupant types.
2. Develop a "typical" building population that can be dropped into simulation models of buildings that have not yet been built. This generic set of occupants should exhibit the heterogeneity found in our case study buildings regarding preferences for temperature, humidity, IAQ, and lighting. It should also capture the range of adaptive responses that building occupants perform.
3. Work with building energy and lighting modelers to improve the efficiency of the combined building-system/occupant-behavior computing framework. The current research-level framework requires long run times.
4. Extend the modeling framework to incorporate more detailed social relationships, especially those that are hierarchal including building operator vs. building occupant, boss vs. employee, and remotely-located colleague vs. proximate colleague. This will be especially useful for matching the control strategies for building systems with the control needs of building occupants in specific social and organizational contexts.
5. Extend the modeling framework to incorporate behavioral strategies for managing occupants during operation of a building. Examples include training tenants on how to operate windows or how to use a building's recycling systems, or providing occupants with dashboards to allow them to self-monitor plug loads. Building operators will want to know how effective such behavioral strategies are likely to be before rolling them out in specific contexts.
6. Translate the usability metrics encapsulated in the simulation-modeling framework into a scorable LEED point so that user-friendly designs get rewarded and green building practice places increased emphasis on the user experience.
7. Take advantage of emerging "big data" opportunities provided by ubiquitous sensors and smart building data networks to characterize occupant and operator behavior more robustly. Current monitoring systems will be to be augmented so that they capture human responses to and satisfaction with changing environmental stimuli.
8. For applications to building operational management, incorporate a feedback process through which changes such as shifts in building population and operating trends, or disconnects between users and technology can be picked up and incorporated.

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Attachments

Appendix 1: Building Performance Evaluation. This piece details our energy studies of three subject buildings and satisfies the engineering studies component of the project scope.

Appendix 2: Environmental Design & Occupant Response: Report of Post Occupancy Evaluation of Green Buildings. This paper examines issues of occupant satisfaction and productivity and how building usability impacts occupants and ultimately building performance and satisfies our POE requirement.

Appendix 3: Simulation Model Overview: Andrews, C.J., D. Yi, U. Krogmann, J.A. Senick, and R.E. Wener, "Designing Buildings for Real Occupants: An Agent-Based Approach," *IEEE Transactions on Systems, Man, and Cybernetics--Part A: Systems and Humans* November 2011, 41(6): 1077-1091.

Appendix 4: Simulation/Fieldwork Iterative Learning: Andrews, C.J., J.A. Senick, R.E. Wener, "Incorporating occupant perceptions and behavior into BIM," chapter 20 (pp. 234-46) in Shauna Mallory- Hill, Wolfgang F.E. Preiser & Chris Watson, eds., *Enhancing Building Performance*, Oxford: Blackwell, 2012.

Appendix 5: Outreach Materials: This includes a selection of recent presentations made to industry groups about this project. The presentations draw from the following events:

Invited Lectures to Practitioners 2009-12: Berkeley, CA; Birmingham, UK; Guildford, UK; Graz, Austria; Lisbon, Portugal; Nanjing, China; New Brunswick, NJ; New London, NH; New York, NY; Newark, NJ; Toronto, Canada; White Plains, NY; and Zurich, Switzerland.

Environmental Design Research Association 43rd annual conference: Emergent Placemaking, May 30-June 2, 2012, Renaissance Seattle Hotel, Seattle, Washington

Session: Context & Prediction of Building Efficiency & Behavioral Outcomes in Green Buildings

Jennifer Senick: User Response to Green Design in Premium Office Space

Clinton Andrews: Evaluation of a Green Luxury Rental High-Rise Apartment Building

MaryAnn Sorensen Allacci: Life with EnergyStar: Health Impacts of Affordable & Green Multiple-Dwelling Residences

Richard Wener: Green Buildings and Their Users

Session: Developing a Research Agenda for The Sustainable Planning, Design, and Behavior Network
Jennifer Senick And Richard Wener

International Association People-Environment Studies 22nd annual conference: Human Experience in the Natural and Built Environment: Implications for Research, Policy, and Practice. Glasgow, Scotland, June 24 - 29, 2012

Session: Case Studies of Post Occupancy Evaluations in Green Buildings

Jennifer Senick: Occupant Behavior in Multi-tenanted Office Buildings and Impacts on Energy Efficiency

Clinton Andrews: Evaluating a Green Luxury Rental High-Rise Apartment Building

Richard Wener: Expanding the Definition of Green- Impacts of Green and Active Living Design on Health in Low Income Housing

Presented at Liberty Property Trust Headquarters, Philadelphia, PA, July 27, 2012

Investigating Opportunities for Improving Building Performance through Simulation of Occupant and Operator Behavior: Update on USGBC Collaborative Study with Liberty Property Trust

USGBC Grant Project Status and Findings:

Jennifer Senick: Occupant Behavior Impacts on Building Performance

Richard Wener: Productivity and Environmental Design

Clinton Andrews: Building Simulation of Occupant Behavior/Building Performance