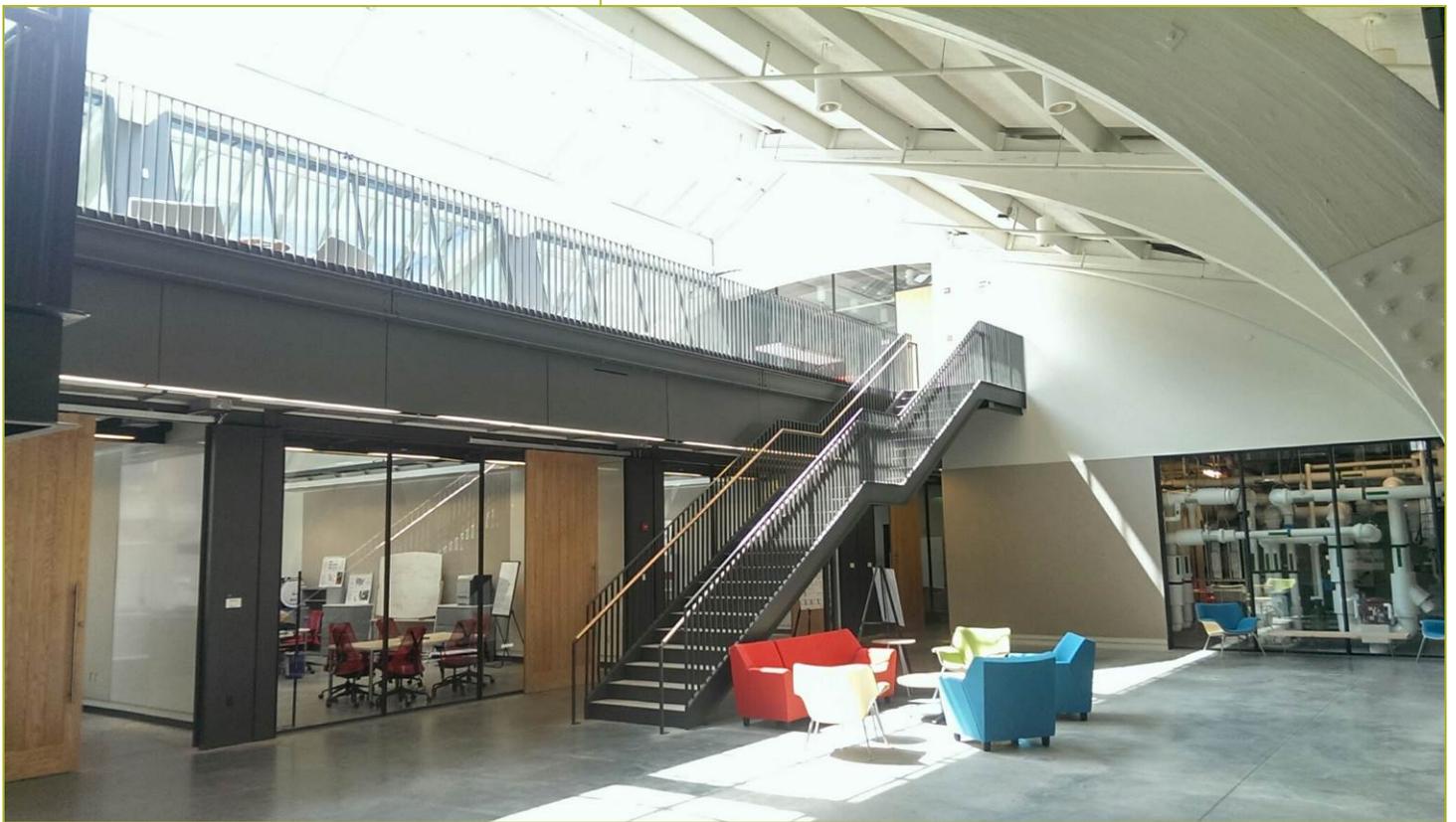


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Report Abstract

This research investigates opportunities for improving building performance and occupant satisfaction through an iterative process of empirical fieldwork in green buildings and computer simulation modeling. This project demonstrates that the simulation-modeling framework is feasible and useful. Additionally, this project has generated a variety of important empirical insights about how the usability of building-level green features and social and organizational factors affect occupant and operator behavior.

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Investigating Building Performance Through Simulation of Occupant Behavior

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ABSTRACT: This research investigates opportunities for improving building performance and occupant satisfaction through an iterative process of empirical fieldwork in green buildings and computer simulation modeling. This project demonstrates that the simulation-modeling framework is feasible and useful. Additionally, this project has generated a variety of important empirical insights about how the usability of building-level green features and social and organizational factors affect occupant and operator behavior. 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.

(Keywords: green, occupants, behavior, simulation, commercial buildings, post-occupancy evaluation, design, lighting)

Introduction

The findings and recommendations in this report are the product of a project funded in part by the U.S. Green Building Council's Green Building Research Fund in 2009. The research investigates opportunities for (1) improving building performance and occupant satisfaction through an iterative process of empirical fieldwork in green buildings and (2) computer simulation modeling for tailoring green building design to address the needs of heterogeneous occupants. The fieldwork took place in three LEED certified multi-tenanted commercial office buildings in the Northeast between 2010 and 2012 and consisted of post-occupancy (POE) evaluations of occupant perceptions and behaviors and building performance evaluations (BPE) documenting energy usage and system functionality. The resulting POE and BPE data were used to validate and calibrate a simulated model of occupant behavior and building performance outcomes.

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.

Methods And Data

This research drew on three broad methods to accomplish its objectives. These included a multidisciplinary user-oriented post-occupancy evaluation (POE), an engineering building performance evaluation (BPE) and simulation modeling.

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 [1], and is intended to complete otherwise missing aspects of feedback loops that check how well the building's operation fits initial intentions, goals, program and design.

The purpose of a BPE is to develop objective, quantitative measures of resource use and indoor conditions for comparison with performance benchmarks [2], which may complement subjective measures of occupant perceptions.

To address these issues, data were collected using a variety of methods that provided both qualitative and quantitative information. These data collection techniques 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 focused on how well each building meets its energy performance goals as well as the role of human agency in mediating these outcomes. Utility and benchmarking analyses were 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. We 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.

Building Research Sites

The three case study buildings are multi-tenanted Class A office space. Built in 2005, Building 1 was initiated as a sustainable, speculative multi-tenant office development of 76,350 square feet. It achieved LEED Platinum Certification – Core and Shell v 1.0 pilot in 2006. Built by the same organization, Building 2 was constructed in 2009 as a 95,621 square foot sustainable, speculative multi-tenant office development that achieved LEED Gold Certification – Core and Shell v 1.2 in 2009. Building 3, which was completed in 2006, was designed as a speculative 5-storied 98,225 square foot, multi-tenant facility and achieved LEED-CI Gold certification, a first for its kind for a publicly-owned facility. An interesting commonality among all three buildings is their relatively high energy-load profiles, reliance on mainly electricity over natural gas, and use of heat or energy recovery ventilation systems. Two of the buildings include healthcare tenants and one includes laboratory facilities. In one of the buildings the healthcare tenant makes up more than 50% of the energy load. The three buildings are located near to one another in a Mid-Atlantic metro area and also share a number of design features, including an emphasis on daylighting and views, occupancy sensors and daylight harvesting, and a mix of centralized and local occupant control.

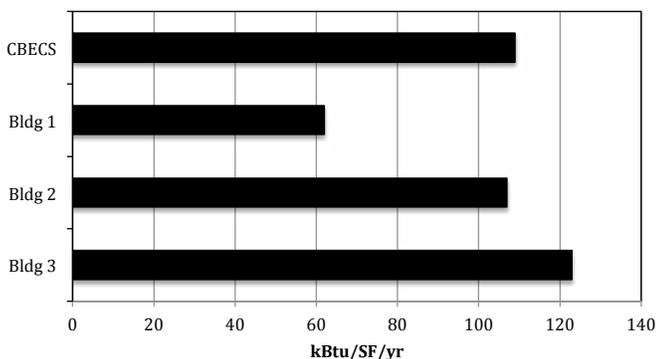


Figure 1: Site Energy Intensity Comparison.

Results And Discussion

This section summarizes highlights of more detailed analyses that have been reported elsewhere [3, 4].

Building Performance Metrics

A number of building performance analyses were performed on the three case study buildings. These included utility and benchmarking analyses as well as evaluations of building sensor and complaint logs and review of building archival data.

Figure 1 shows a comparison based on site energy intensity. In order to make comparisons across the buildings, we employed the U.S. Department of Energy's Commercial Buildings Energy Consumption Survey (CBECS) 2003, which surveyed a sample of 5,215 U.S. commercial buildings about their design characteristics and measured energy consumption [5]. The CBECS data set was used in two ways in this analysis. First, the average electricity and natural gas energy intensities (energy use/square foot-year) of office and healthcare buildings located in the Mid-Atlantic region were used to synthesize a comparable building for each of the three case study buildings (we assumed that healthcare as a principal activity is a reasonable proxy for laboratory, which is not included as a CBECS category). The second way we used CBECS data was to adjust the modeled energy intensity estimates for missing plug loads. The Site Energy Intensity for the CBECS-based comparable building is 109 kBtu/sq.ft/yr.

Based on this approach, Building 1 performs approximately at or better than the CBECS 2003 benchmarks for office and healthcare buildings. Specifically, its Site Energy Intensity is 62 kBtu/sq.ft/yr and it achieves an Energy Star Performance rating of 79.

Building 2 did not perform as well, achieving a Site Energy Intensity of 107 kBtu/sq.ft/yr with all tenants included, which would have earned an Energy Star Performance rating of 22. With the main healthcare tenant removed, Building 2's Site Energy Intensity is 77 kBtu/sq.ft/yr with an Energy Star Performance rating of 78.

Building 3 energy data required adjustments to account for irregularities in the utility billing record, but we estimated its Site Energy Intensity to be 123 kBtu/Sq.ft./yr., well above that of the CBECS benchmark and the other buildings. Building 3 outperforms a typical code building but falls short of its intended level of performance. The results of the energy analysis suggest that Building 3 consumes 25% more natural gas and about the same amount of electricity as would be expected based on the LEED design case modeled results (i.e., the LEED submittal), which we have adjusted for discrepancies in heating and cooling degree days (and the existence of an electric pre heater. It is important to note that electricity cost comprises 85% of annual energy costs for this building; thus, relatively better electric performance has more economic value.

Occupant Perceptions and Responses to Green Building Features

The focus of this analysis was on ways occupants perceive and respond to building features and conditions, based on an

understanding that critical outcomes (energy efficiency, productivity, job satisfaction) are significantly determined by these responses. Seventy-five (75) occupants across three buildings responded to our user survey. In addition we conducted detailed interviews with individuals and groups and conducted walk-throughs of the sites. Overall, the perceptions of these facilities were highly positive. These were seen as good working environments, and managers perceived them to be supportive of work productivity, both in terms of how their employees felt and worked and positive responses from clients and customers. Occupants recognized and appreciated the green quality of Buildings 1 and 2, though were less aware of these qualities in Building 3.

The quality of windows, including extensive daylight and broad views, were among the most favored qualities among occupants. Response to electric lighting was also positive, although there were some concerns about lighting being sometimes too bright (potentially causing glare) or too dim. There were also concerns about lack of understanding of or control over ways to adjust lighting, limiting ability to bring lighting levels or quality in line with changing needs or conditions. Similarly, while thermal comfort was generally adequate, there were some problems with temperature, especially being too cool in the heating months.

Concerns about how and how much occupants could modulate temperature and other conditions in their work spaces led them to take a number of adaptive responses. For example, most occupants responded to fluctuations in temperature by adjusting their clothing. Ratings of the general design and appearance, cleanliness, furnishing & fixtures were positive. These results point to significant benefits from the sustainable design of these facilities, and to greater benefits that might accrue, particularly if operators (and designers of future buildings) address usability issues and make building systems easier to adjust.

Illustrative Simulation Model

This section provides an overview of results from an illustrative simulation model of how occupants interact with a building's lighting features—scored against a set of usability metrics. See [6, 7] for details. As mentioned earlier, this is an agent-based model of occupant behaviour that can be hot-linked to various building information modelling (BIM) tools including *Radiance* for lighting, and *EnergyPlus* for thermal comfort simulations. Figure 2 summarizes the modelling logic.

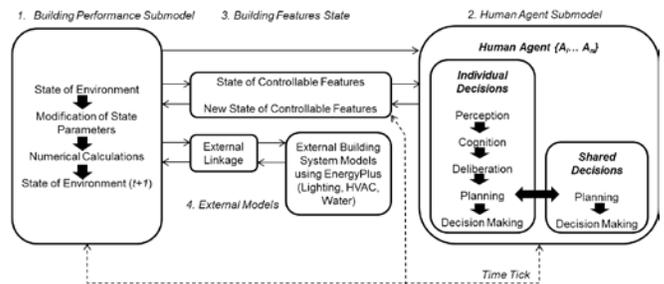


Figure 2: Simulation Modeling Framework (adapted from [7])

The simulations summarized here are calibrated to the design details and occupant survey responses for one of the tenant spaces in Building 1, which is represented as a multi-zone space with north, south, west, and interior exposures. Private offices line the south and west walls, and the north exposure is a floor-to-ceiling window wall serving cubicles. In addition to daylight, the spaces also receive illumination from indirect pendant fixtures that are switched by a time clock in the cubicle area and by manual switches in the private offices. These two conditions are summarized by cases A and B in Table 1. Simulation A suggests that the west-facing offices cause much discomfort for their occupants during the late afternoon hours, and this discomfort encourages the occupants to expend much effort to adjust blinds and light switches, and yet they often do not achieve target lighting levels, yielding poor effectiveness. Simulation B shows that the north-facing window wall provides a much more satisfying and energy-efficient experience for the cubicle dwellers.

Scenarios C and D explore hypothetical cases that vary the lighting control strategy and allow the tenant to pre-test alternative retrofit concepts for the cubicle area. Scenario C pursues greater automation in the form of occupancy and brightness sensors. Scenario D instead devolves lighting control to the cubicle occupants, giving each a manually switched task light.

Scenario C, which preserves central control but attempts to make it smarter, uses about the same amount of lighting energy and causes about the same amount of discomfort as the current time clock system for this set of occupants (who mostly adhere to traditional work hours). Scenario D, which decentralizes lighting control, reduces discomfort but at a cost in both greater occupant effort and more lighting energy consumption. A more conscientious set of occupants that regularly turned off their task lights might have a different outcome.

Table 1: Modeling Results for Lighting Performance in Tenant Space (adapted from [6]).

	A. Private Offices (base case)	B. Cubicles (base case)	C. Cubicles (more automation)	D. Cubicles (more local control)
Glazing Orientation	West	North, some south & interior	North, some south & interior	North, some south & interior
Lighting	Indirect Pendant	Indirect Pendant	Indirect Pendant	Task lights
Automation	Manual	Time clock	Occupancy & brightness sensors	Manual
Results				
Effectiveness	57%	95%	84%	90%
Efficiency				
Lighting energy use (kWh/SF-yr)	6.2	2.2	2.3	6.4
Occupant effort (ordinal)	1129	0	0	37
Satisfaction				
Discomfort (ordinal)	12	3	4	1

Note: Mean values for 20 simulations of each case are shown. All differences in values shown are significant at the 95 percent level.

This example illustrates the potential importance of incorporating occupant perceptions and behaviour into decision making about the design and operation of buildings. It also suggests that it is important to calibrate simulation tools using real behavioural data, because people differ widely from one another in both their perceptions and behavioural responses.

Design as a Game

Once a robust database of occupant behaviour surveys has been acquired, the model can become a useful new design tool. For educational purposes, we have developed the *Hit the Bullseye* design game [8]. The player's goal is to design a lighting (or other) system that is less costly, less polluting, requires less effort to operate, and causes less discomfort than alternative designs. The player uses the computer model to simulate how different designs perform. The model has been pre-calibrated for a generic population of building occupants. The player uses a radar or target chart to keep score.

In the example shown in Figure 3, Design B performs better than design A, that is, it is closer to the center of the target. Design B costs less, pollutes less, requires less effort, and causes less discomfort than Design A. A design tool incorporating principles from this game could eventually find practical use as part of a BIM suite.

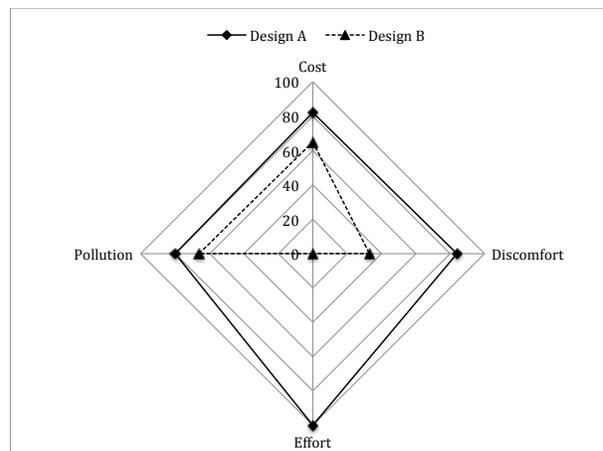


Figure 3: Using Simulation to Understand Design Trade-offs Affecting Occupants (adapted from [8]).

Conclusions And Recommendations

Diverse Energy Use in Multi-Tenanted Buildings; Core and Shell and Fit-out Consideration

There are a variety of possible inferences to draw from the building performance analyses of the three case study buildings. First, it is reasonable to assume that the buildings' design balances energy efficiency with other factors such as overall appearance and spectacular views, which may offer tenants a higher quality experience than in a typical office building. In our interviews with building management teams, we also learned that they have faced a number of challenges in energy management that are common to multi-tenanted buildings including construction problems such as the value-engineering of certain control sequences which were written but not implemented, start-up issues such as incorrect commissioning of VAV boxes, and partial tenancy and thereby partial load conditions.

Most important, the fact that all three buildings have tenants who are large energy users seems to have a significant impact on overall energy performance, particularly in the case of Building 2 where one healthcare tenant uses up to 50% of the building's energy. Benchmarking of building performance becomes challenging in the multi-tenanted case because actual tenants' energy use profiles often diverge from those assumed during design. Also, most of the energy operations of the healthcare tenant in Building 2 are not directly controlled by the building manager thereby presenting a real challenge for meeting energy efficient objectives of this building.

In typical speculative commercial buildings like these, the core and shell has been constructed first, and the tenant fit-out of interior spaces has followed as tenants signed leases. The core and shell systems, therefore, tended to have a great deal of flexibility designed into them, which sometimes limits their achievable energy efficiency. Yet, this flexibility 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.

In a competitive market, attracting and keeping diverse commercial tenants are also balanced with energy performance and other green objectives. The aesthetic objective of having large amounts of window area to provide occupants with daylighting and access to views can also have energy intensifying effects. Our research also highlighted the great extent to which disconnects can occur between core and shell design objectives and tenant fit-out solutions as when partitions and floor plans obstruct daylighting, programmed ventilation, or are not in sync with existing lighting fixtures. This is an area that the LEED practitioner is already paying attention to and hopefully a combination of revised programmatic advice and organizational solutions (such as better coordination through green leases) is emerging.

Locus of Control, Effects of Local and Central Management of Energy Use

Our research has highlighted the pivotal role of locus of control in both energy management and occupant satisfaction and related outcomes. As the LEED guidelines recognize, not all buildings are suited to providing occupants the level of local control required to achieve LEED credits in this area, 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.

Simulation Tools Incorporating Occupant Behavior; Data Needs and Algorithmic Development

The models introduced here demonstrate a feasible approach for incorporating the consideration of occupant concerns and behaviors more fully into the design process. Much work is still needed to extend these tools beyond proof of concept and into everyday use.

A high priority is to develop a generic population of building occupants for use in pursuing behaviourally-robust designs. This can be done by accumulating post-occupancy evaluation microdata from a wide variety of buildings and locations within one database that incorporates building conditions and occupant perceptions, behaviors, adaptive responses, and demographics.

Software development should focus on extending the model from lighting to other systems that are important for green building designers, including water use, thermal comfort, and indoor air quality. It should also incorporate social decisionmaking considerations that influence how occupants actually operate shared building controls such as thermostats and light switches. Also important will be efforts to make simulations more speedy, efficient, and user-friendly. See [9] for further details.

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