DREXEL UNIVERSITY YEAR 1: GPIC POLICY, MARKETS, AND BEHAVIOR RESEARCH

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EXECUTIVE SUMMARY

Drexel conducted interviews with office workers in the GPIC region that addressed both energy use and comfort. Key results include:

- Occupants’ comfort is strongly correlated with their ability to adapt their environment to their personal needs and preferences. Adaptive options can range from personal behavior, such as allowing appropriate adjustments to clothing to building-level adjustments, such as allowing occupants greater control over heating and cooling.

- Providing better occupant control may actually save energy in some cases, since 52% of occupants report being too warm in the winter and 40% report being too cool in the summer.

- Energy efficiency is not a primary motivator for office occupants; just 27% of occupants indicated energy concerns influence adaptive actions.

- Adaptations to warm discomfort are generally reported to be less viable/effective than for cold.

- Occupants widely use adaptive measures that may significantly impact overall building energy use; 40% of occupants use personal heaters; 38% use fans.

- Energy education programs for office occupants are scarce in the sample interviewed, but enthusiasm for them is high; occupants prefer that initial education on the use of new technologies be conducted up front in person, and the majority of respondents also believe that some sort of feedback over time is necessary to ensure effective use.

Drexel also conducted interviews with participants in the building retrofit decision making process. Important results include:

- First cost and uncertainty in the cost savings achieved by a technology are key barriers to the adoption of energy conservation measures. Local examples of success are seen as the best way to address this barrier. These local examples of success must include clear and convincing information on the payback achieved by energy conservation measures.

- A majority of stakeholders forgo complex metrics and instead use simple payback to evaluate investment decisions. The average acceptable payback period reported was 3.9 years (with a standard deviation of 1.6 years).

- The cost of sophisticated computer modeling may represent a disproportionately large percentage of the total retrofit budget for a single-building retrofit. Thus economies of
scale may be preventing the adoption of newer technologies by smaller, single-retrofit projects. This also suggests a need for simpler, more intuitive modeling tools.

- The ability of energy-efficiency investments to reduce exposure to energy price volatility is widely perceived to be an important benefit of these technologies. However, respondents do not have tools available to them to value this aspect of energy-efficiency investments.

Drexel worked closely with United Technologies Corporation to develop a series of 28 EnergyPlus models that represent both existing energy use and the impacts of various combinations of energy conservation measure that may be undertaken. Results from these simulations served as a key technical input to a regional building energy use model developed by UTC. This model can be used to evaluation the impact of different policies on the adoption of energy conservation measures and total building energy use across the GPIC region.
# TABLE OF CONTENTS

INTRODUCTION .................................................................................................................................... 11

CHAPTER I ............................................................................................................................................... 13

1. Introduction ..................................................................................................................................... 14
2. Objective ........................................................................................................................................... 14
3. Materials/Methods .......................................................................................................................... 14
4. Results ............................................................................................................................................... 16
   4.1. Environmental Satisfaction .................................................................................................... 17
   4.2. Temperature Discomfort and Associated Adaptations ...................................................... 19
   4.3. Occupant Perspectives on Energy Conservation ................................................................. 24
   4.4. Case Comparison: Deep Retrofit vs. Non-Retrofit Offices ................................................ 29
5. Discussion ......................................................................................................................................... 31
6. References ......................................................................................................................................... 34

CHAPTER II .............................................................................................................................................. 35

1. Introduction ..................................................................................................................................... 36
2. Objective ........................................................................................................................................... 36
3. Materials/Methods .......................................................................................................................... 36
   3.1. Semi-Structured Interview Format ....................................................................................... 37
4. Results ............................................................................................................................................... 38
   4.1. Triggers for Small Building Retrofits .................................................................................... 38
   4.2. Potential Barriers to Performing Energy-Efficient Building Retrofits .................................. 39
   4.3. Major Design Decisions During the Retrofit Process ......................................................... 40
   4.4. Energy Conservation Measures Targeted First ................................................................... 41
4.5. Most Responsible Parties .......................................................... 42
4.7. Factors Affecting Decision to Adopt New or Nonstandard Technologies .......... 43
4.8. Metrics Used to Make Decisions About Building Retrofit Investments ........ 44
4.9. Value of Metrics ........................................................................ 44
4.10. Primary Sources of Uncertainty .................................................. 45
4.11. How Uncertainties Are Considered ............................................. 45
4.13. Summary of Results ................................................................. 46
5. Discussion...................................................................................... 47
6. References..................................................................................... 48

CHAPTER III ..................................................................................... 49
1. Introduction .................................................................................. 50
2. EnergyPlus Modeling ..................................................................... 50
   2.1. Relevant Building Stocks and Studies ........................................... 51
   2.2. Baseline Model Construction....................................................... 53
   2.3. ECMs Upgrades for Baseline Models .......................................... 58
   2.4. Preliminary EnergyPlus Models and Results ............................... 60
3. Alteration of EnergyPlus Modeling Results .................................... 63
   3.1. Transformation/Alteration of EnergyPlus Results .......................... 64
4. GPIC Building Energy Profiles ...................................................... 66
   4.1. Presentation of Annual Energy Use Histogram ............................. 67
   4.2. Interpretation of Annual Energy Use Histogram ............................. 69
5. Discussion...................................................................................... 69
6. References................................................................................................................................................... 69

CONCLUSIONS...................................................................................................................................................71

APPENDIX............................................................................................................................................................73
LIST OF FIGURES

Figure I-1  Environmental condition evaluation across the full sample of occupants .................. 18

Figure I-2  Season during which “too warm” and “too cold” conditions are reported to occur by occupants ................................................................................................................................................... 18

Figure I-3  Preferred temperature sensations by season for the full sample of occupants (N=32). .................................................................................................................................................................... 20

Figure I-4  Primary drivers of adaptive action for the full sample (left) and the sample split between those working in open areas (upper right) and private offices (lower right) .................. 25

Figure I-5  Percentage of occupants in buildings not already implementing given Energy Conservation Measure (ECM) that are at least somewhat knowledgeable about the ECM, and source of knowledge ........................................................................................................................................................................... 26

Figure I-6  Occupant suggestions regarding the integration of new technologies that involve some degree of user control into an office setting ............................................................................................................................................................................. 28

Figure I-7  Comparison of deep-retrofit and non-retrofit building occupants in terms of environmental satisfaction and energy knowledge level ........................................................................................................................................................................ 30

Figure I-8  Source of information attached to occupant responses of “somewhat knowledgeable” or above for pooled ECM list, compared by deep-retrofit and non-retrofit group ........................................................................................................ 30

Figure II-1. Breakdown of respondent type ................................................................................ 37

Figure II-2. Triggers for small building retrofits .......................................................................... 39

Figure II-3. Barriers to energy-efficient retrofits .......................................................................... 39

Figure II-4. Major decisions during the retrofit process .................................................................. 41

Figure II-5. Energy conservation measures targeted first ................................................................. 41

Figure II-6. Primary responsibility for retrofit decisions ................................................................. 42

Figure II-7. Estimating the performance of new technologies ........................................................ 42

Figure II-8. Factors affecting the decision to adopt new or non-standard technologies ............... 43

Figure II-9. Metrics used to make decisions about retrofit investments ....................................... 44

Figure II-10. Metrics used to make decisions about retrofit investments ..................................... 45
Figure II-11. Use formal methods .......................................................................................................... 45
Figure II-12. Use formal methods to evaluate value of ECMs with regards to volatility .............. 46
Figure II-13. Perceive ECMs as a hedge against future energy price volatility......................... 46
Figure III-1. NREL Baseline in OpenStudio Plug-in ........................................................................... 54
Figure III-2. Scaling NREL Baseline ...................................................................................................... 54
Figure III-3. Visualization of Baseline 1 (Left) and Baseline 2 (Right) .............................................. 55
Figure III-4. Model Schedules (Liu et al., 2009).................................................................................... 56
Figure III-5. Baseline 1 (left) and Baseline 2 (right) CAV System Schematics ................................. 57
Figure III-6. Baseline 1 (left) and Baseline 2 (right) VAV System Schematics ................................. 59
Figure III-7. VAV/Central Chiller Upgrade (left) and DOAS System (right) ................................. 60
Figure III-8. Total Site Energy Consumption By Model Run .............................................................. 62
Figure III-9. Transformed Total Site Energy Consumption By Model Run ..................................... 64
Figure III-10. Total Site Energy Consumption for 198 Models ....................................................... 68
LIST OF TABLES

Table I-1. Spearman correlations between general comfort and individual environmental variables.....................................................................................................................................................17

Table I-2. Composite frequency and effectiveness scores for both warm and cold adaptive actions.......................................................................................................................................................23

Table I-3. Composite priority scores for both warm and cold adaptive actions...........................................24

Table III-1. Baseline Model Internal and External Gains........................................................................55

Table III-2. Baseline Model System Sizing............................................................................................58

Table III-3. Twenty-Eight Model Descriptions.....................................................................................61

Table III-4. Energy End-Use by Run (MWh/Year)..................................................................................63

Table III-5. Transformed Energy End-Use by Run (MWh/Year)............................................................65

Table III-6. Transformed Energy End-Use, Percentage of Original....................................................66

APPENDIX:

Table 0-1. Model Internal Gain Inputs.................................................................................................114

Table 0-2. Model Air Handler Specifications.......................................................................................115

Table 0-3. Model Heating and Cooling Inputs....................................................................................116

Table 0-4. Run Identifiers and Descriptions for 198 Models............................................................117
INTRODUCTION

The primary goals of the Greater Philadelphia Innovation Cluster (GPIC) are to stimulate private investment in energy-efficient measures in new and existing buildings in the GPIC region in order to reduce carbon emissions and create a market environment that incentivizes such investment. The Task 4 team has been charged with determining policy, market, and behavioral (PMB) barriers preventing the adoption of energy efficient building system technologies and how these barriers may be surmounted by modifying the existing financial, policy, and regulatory framework.

As laid out by GPIC, specific Task 4 goals include the following:

- Explore the role of occupant behavior in building energy efficiency including the effects on building energy management of real-time feedback to occupants of energy usage information via dashboards, static and mobile IT devices, and other media.
- Analyze roles and activities of organizations and individuals participating in policy networks spanning local, state, and national government levels influencing integrated energy efficient retrofit of average size commercial and multi-family residential buildings.
- Analyze the costs and benefits of energy efficient building retrofits addressing factors such as occupant health, safety and security, community wellbeing, and worker productivity, creativity and innovation, as well as reduced energy consumption.

This report presents research performed by Drexel University in Year One that targeted the above areas of inquiry. The report chapters are broken down as follows:

Chapter I summarizes findings from a series of semi-structured interviews conducted with office building occupants in the GPIC region in order to better characterize how individual behaviors may facilitate or hinder energy efficiency in office buildings. Here, behavior is examined alongside one's personal comfort, workplace productivity, and perceived ability to control the interior environment. Several individual behavioral adaptations to various environmental conditions are described in terms of their availability to occupants, frequency of use, and effectiveness when used. Occupant knowledge of and enthusiasm for behavioral intervention/education programs is also assessed, and recommendations for how to effectively involve employees in workplace technology integration are provided.

Chapter II examines the decision-making processes of stakeholders (building owners, developers, property managers, architects, engineers, and others) and how they view investment in energy efficient building retrofits. Simple payback analyses are identified as a common evaluation method with a most decision makers requiring a relatively short payback time (<4). The greater use of lifecycle performance metrics is identified as a goal that could be facilitated by the development of improved performance evaluations tools, particularly tools
that can be applied to small projects with limited budgets for performance modeling. In addition, this chapter highlights how uncertainty in financial performance is a barrier to the adoption of new technologies and how local examples of successes have a great ability to reduce decision makers’ uncertainty and facilitate the adoption of new technologies.

Finally, Chapter III presents the results of computer modeling that simulates the effects of various energy-efficient technologies in different types of medium office buildings. Findings are based on the use of both engineering judgment and EnergyPlus modeling of 28 building models. Data from these 28 building models is extrapolated and transformed to represent approximately 198 characteristic medium office buildings that may be present within the GPIC region in order to inform a larger, macroscopic, PMB model.

Major findings from this initial effort are discussed in the report’s conclusions section. This is discussed in the report’s concluding section. The results of this research will guide subsequent research in GPIC’s second year and beyond.
CHAPTER I

Surveying Behavior of Office Occupants in the GPIC Region

Chapter Highlights:

• 32 semi-structured interviews are conducted with office occupants in the GPIC region to examine key adaptive behaviors in the workplace as well as occupant perspectives on Energy Conservation Measures (ECMs).
• Occupants’ general evaluation of environmental comfort is strongly correlated to level of satisfaction with adaptive ability.
• 52% of occupants report being too warm in the winter and 40% report being too cool in the summer, suggesting the provision of temperature control to occupants may save energy in some cases.
• Adaptations to warm discomfort are generally reported to be less viable/effective than for cold.
• A clear hierarchy of adaptive actions is observed and relates to the ease/effectiveness of each available adaptive option.
• Adaptive actions are tied primarily to personal comfort in private offices, while social influences play a more dominant role in open plan settings; just 27% of occupants indicated energy concerns influence adaptive actions.
• 40% of occupants use personal heaters; 38% use fans, adding unexpected electricity loads to overall building energy consumption.
• Energy education programs for office occupants are scarce in the sample interviewed, but enthusiasm for them is high.
• Lighting retrofits are most familiar to those who work in a building that has not already undergone this ECM, and HVAC retrofits are least familiar.
• Occupants prefer that initial education on the use of new technologies be conducted up front in person; the majority of respondents also believe that some sort of feedback over time is necessary to ensure effective use.
1. INTRODUCTION

The primary goal of the GPIC consortium is to demonstrate “...how buildings can achieve operational energy savings of 50% in a scalable, repeatable, and cost effective manner across a broad building stock, while preserving workplace quality [italics added].” [1] The latter part of this statement suggests that various efficient technologies and practices are prioritized in service of the consortium’s general 50% energy reduction goal, it is imperative that the characteristics, preferences, and behaviors of the ultimate users of these efficiency measures – the building occupants – be factored in. Indeed, occupant behavior has been suggested in the literature to be a crucially important “wildcard” variable to efficiency upgrades, and numerous studies have shown that inadequate consideration of occupant well-being and satisfaction as part of the building design and retrofit processes can result in higher annual energy consumption and costly maintenance issues [2,3,4; (see Appendix A.1.3 for a full literature review)]. Accordingly, it is important that the influence of occupant behavior on commercial building energy consumption be assessed as part of the ongoing GPIC research efforts.

2. OBJECTIVE

A series of semi-structured interviews were conducted with office building occupants from around the GPIC region with the goal of examining key behavioral tendencies in the workplace and the relationship of these tendencies to outcomes of individual comfort, productivity, and whole building energy use.

As noted in [5], semi-structured interviews are employed in situations where the researcher knows what they want to find out, but wishes to remain “free to follow new leads”. Because each of these interviews takes some time, they typically only engage a small sample of subjects, and follow up efforts such as large sample structured surveys are generally necessary to more precisely quantify observed response frequencies. Nevertheless, the semi-structured approach is useful within the context of occupant behavior research because it can identify aspects of behavior that are not yet well known or understood and provide a rich context for interpreting responses.

3. MATERIALS/METHODS

The interview methods and results reported here constitute a preliminary stage of occupant behavior surveying as part of GPIC. In this stage, the open ended semi-structured format is used to gain a general understanding of key occupant behavior issues for office buildings in the GPIC region as well as which behavioral tendencies warrant further study in the second stage. Office buildings are chosen for this preliminary research because they represent a focus within the commercial building sector for GPIC study during Year One of the five-year project.

A total of 32 office employees from 7 buildings were interviewed over the course of roughly one month. Each of the buildings is located either within the Philadelphia metropolitan region or
the surrounding suburban areas. The specific breakdown of occupants by building/location is as follows:

- 10 occupants from a mid-sized office building in downtown Philadelphia that underwent a deep retrofit in 2008
- 9 occupants working in two similar mid-sized office buildings that were older and had not undergone a recent retrofit (one of which was recently torn down)
- 5 occupants working in a small office in South Philadelphia
- 3 occupants working in mid-sized office building in Cherry Hill, NJ
- 5 occupants working in small to mid-sized office buildings in the suburban PA areas outside of Philadelphia.

The 7 buildings recruited for this research are intended to engage as broad a spectrum of GPIC-region office environments as possible to ensure that multiple perspectives are represented in the results. Thus, the recently renovated offices can be contrasted to the aging offices; the smaller offices present a different social dynamic than did the larger ones; and the low-density context of the suburban offices runs counter to the high density of the urban locations. Recruitment of employees at these locations typically proceeded through an office manager who was able to notify small groups of the employees about the research.

The majority of interviews took place face-to-face in the field with a few others conducted remotely via phone. Each of the 32 interviews was conducted by one of two GPIC researchers and typically ran 30-45 minutes. With the permission of the respondents, the interviews were also recorded and stored as .mp3 audio files. The following areas of general questioning guided the conversation (see Appendix A.1.1 for full protocol):

I) Background Information
- Includes questions about how long individual has worked in the building; how much time they spend there; and what type of office they work in.

II) Environmental Quality, Comfort, and Adaptability Assessment
- Includes questions about general comfort level within the office; specific sources of discomfort; behaviors that are taken to manage discomfort; and the effect of various sources of discomfort on workplace productivity.

III) Energy Consumption
- Includes questions about who pays energy bills for the building; energy education efforts within the building; opportunities for energy saving; knowledge of various Energy Conservation Measures (ECMs); and recommendations for effective integration of new technologies that involve some element of building occupant control.

To ensure that the results of the interviews could be summarized systematically, a set of rules was developed for scoring the various response items that were covered by the audio recordings. A brief summary of key scoring rules follows:
• **General comfort level**: 1=Generally very uncomfortable; 2=Generally somewhat uncomfortable; 3=Generally neutral; 4=Generally pretty comfortable; 5=Generally very comfortable

• **Frequency of discomfort and effect on productivity (queried by source)**: 1=Never; 2=Occasionally; 3=Sometimes; 4=Most of time; 5=Always

• **Frequency of behavioral action/effectiveness of action in response to discomfort (queried by action)**: 1=Never; 2=Occasionally; 3=Sometimes; 4=Most of time; 5=Always

• **Priority of behavioral actions**: 1=Do this first; 2=2nd; and so on as necessary

• **Satisfaction with layout characteristics**: 1=Dissatisfied; 2=OK; 3=Satisfied

• **Satisfaction with adaptive ability**: 1=Very dissatisfied; 2=Somewhat dissatisfied; 3=Neutral; 4=Somewhat satisfied; 5=Very satisfied

• **Adaptive stimulus other than own comfort**: 1=Social influences; 2=Energy concerns; 3=Combination of 1&2; 4=Other; 5=None (Only own comfort)

• **Who Pays Bills**: 1=Building owner; 2=Building tenant; 3=Don’t know; 4=other

• **Energy Saving Ideas**: 1=HVAC/set points; 2=Lighting; 3=Envelope; 4=Renewables; 5=Smart Grid; 6=Energy Audits; 7=Occupant/Manager Education; 8=Recycling/compost; 9=Plug loads; 10=Other; and scoring rules for responses with more than one of these options added as necessary

• **Already doing Energy Conservation Measure (ECM)**? 1=Yes; 2=No; 3=Don’t know

• **ECM Knowledge Level**: 1=Very knowledgeable; 2=Somewhat knowledgeable (has heard of); 3=No knowledge of ECM

• **ECM Knowledge Source**: 1=Own building; 2=Residential context; 3=Other commercial context; 4=Knows specialist; 5=Media; 6=Other

• **Technology Integration Recommendation**: 1=Educate in person up front; 2=Education via e-mail up front; 3=Feedback in person; 4=Feedback via e-mail; 5=Advanced discussions; 6=Offer direct/indirect incentives; and scoring rules for responses with more than one of these options added as necessary

Two researchers scored each interview response. In many cases, one researcher scored the interview as it happened and another checked the results after the fact; for instances where scoring at the time of the interview was not possible, the interview audio file was reviewed and scored by both researchers after the fact. In all cases, the same researcher was assigned the final judgment call for scoring to ensure consistency across the variety of responses yielded.

### 4. RESULTS

Of the 32 interview respondents reported on here, 20 are female and 12 male, and all work in office buildings that are air-conditioned in the summer and fully heated in the winter. The strong majority are full-time employees, with only 2 of the respondents considering their job part-time and 3 more reporting a situation in between full and part time. About 2/3 of the respondents had worked in their respective buildings for over 1 year, with the remaining 1/3 split between having worked there for less than 6 months and for between 6 months and 1 year.
44% of the respondents work in a cubicle; 24% work in either a public area or open plan desk; and the remaining 32% work in a private office.

### 4.1. Environmental Satisfaction

In general, problems with general comfort do exist in the sample interviewed, with 41% of respondents at or below the “sometimes comfortable” threshold. Poor ratings of general comfort are tied most significantly to the interior environment being frequently “too hot” across the year (as shown by the correlation in Error! Reference source not found. – the more frequently the occupants are too hot, the less favorably they evaluate their general comfort to be) and to lower levels of satisfaction with adaptive ability. The correlation between general comfort rating and frequency of warm discomfort becomes even stronger if the sample is filtered down to those who were only too hot in the summer ($r = -0.854$, $p < 0.001$). Regarding adaptive ability, occupants expressed a greater tolerance for occasional discomfort if they generally felt able to manage that discomfort when it arose. When this was not the case, it was possible to “cope” or “get used to” the poor conditions, but general comfort evaluations suffered.

<table>
<thead>
<tr>
<th>Table I-1. Spearman correlations between general comfort and individual environmental variables.</th>
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<tbody>
<tr>
<td>General Comfort Level</td>
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<td>Too Hot</td>
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<td>Too Cold</td>
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<tr>
<td>Too Humid</td>
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<tr>
<td>Too Dry</td>
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<td>Too Drafty</td>
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<td>Too Stuffy</td>
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A closer examination of occupant comments surrounding their adaptive ability suggests that those who are not satisfied with their ability to manage discomfort would greatly appreciate more effective control of temperature, either directly through a local thermostat or indirectly through a responsive and accessible management staff that could make adjustments on their behalf. As one occupant put it: “My main wish is just that it was cooler and that I could adjust temperature or have a clear scenario for requesting that the temperature be adjusted”. These sentiments are supported quantitatively by a strong positive Pearson correlation of $0.878$ ($p < 0.001$) between the reported effectiveness of available thermostat adjustments when too hot and evaluations of general adaptive ability—the strongest such correlation between any individual adaptive action and the general adaptability assessment. That thermostat control matters most to occupants when too warm is a reflection of the paucity of other viable adaptive options under such conditions. It is also important to note that the reported frequency of thermostat adjustments when too warm does not correlate significantly with occupants’ overall adaptability assessments, suggesting that simply providing thermostat control to occupants would not be enough to improve their perceived adaptability if the control does not effectively regulate temperature.

Figure I-1 indicates which sources of discomfort occur most frequently across the occupant sample interviewed. Of the ten individual discomfort sources surveyed, poor acoustics, hot temperatures and cold temperatures are the three most frequent problems, while excessive humidity, dryness, foul odors, and poor light levels are the four least frequent. Regarding thermal discomfort, Figure I-2 shows that a substantial portion of respondents mentions feeling
too warm in the winter (52%) and too cold in the summer (40%). This suggests that improving occupants’ ability to personally tune the interior environment by adjusting temperature set points (either through a manager or by themselves) would in some cases save energy by enabling warmer indoor temperatures in the summer and cooler temperatures in the winter.

Figure I-1 Environmental condition evaluation across the full sample of occupants.

Figure I-2 Season during which “too warm” and “too cold” conditions are reported to occur by occupants.
In the case of poor acoustics, 78% of the sample reported coworker proximity to be the root of the problem, a statistic that includes some individuals who work alone in private offices (“The walls were very thin”). Acoustics also has the greatest average perceived effect on productivity when uncomfortable, yielding a mean score of 3.00 or “sometimes has an effect” (N=27, σ=1.49) compared to a score of 2.92 for conditions being too hot (N=25, σ=1.29) and 2.33 for conditions being too cold (N=24, σ=1.41). The effect of cold conditions on productivity was often not assessed as severely as for warm conditions because something could easily be done about the cold (“It’s not really a distraction because I can just put on a sweater and that does the trick”). It should be noted, however, that none of these three mean productivity scores could be statistically distinguished from one another.

Given the clear prevalence of acoustic problems in these offices and their effect on workplace productivity, it seems surprising that the rated frequency of acoustic issues does not significantly correlate with general ratings of comfort. Upon closer examination of the supporting audio, however, it becomes clear that while issues of loud coworker conversations and lack of acoustic privacy are certainly common in the workplace, they are also expected of an office environment (as one cubicle employee explained: “Acoustics? That’s always going to be a problem in cube world”). This degree of expectation seems to temper the influence of poor acoustics on the general comfort rating, especially when compared to another condition like temperature that is generally not expected to be outside of certain ranges. Moreover, in many cases the benefits of increased connectivity with coworkers outweigh associated acoustical drawbacks. One occupant, for example, expressed his feeling that “…constant communication is required. The layout could possibly be better but what we have now works well for our style.”

In the absence of a significant relationship between acoustics and general comfort, the following section places a focus on the issue of temperature discomfort and associated adaptive responses. As has been shown in Figure I-1, issues with the interior environment being too warm or cold are both significant relative to the other sources of discomfort surveyed. Furthermore, a greater variety of actions can usually be taken in response to temperature in an office than for any other single environmental variable, making temperature adaptation a valuable marker for the more general process of environmental adaptation in office buildings.

### 4.2. Temperature Discomfort and Associated Adaptations

Figure I-1 above reveals that warm discomfort occurs about as frequently as does cold discomfort across the sample interviewed. Furthermore, respondents’ preferred thermal sensations in the warmer summer months mirrored thermal preferences for cold winter months: as Figure I-3 demonstrates, the same number of respondents expressed a preference for colder than neutral sensations in the summer as expressed a preference for warmer than neutral sensations in the winter (14 respondents in both cases). The Figure further reveals that most occupants do tend to prefer the central three categories of “neutral”, “slightly warm”, and
“slightly cool” that are typically associated with thermal comfort. The 2 occupants who said they would prefer moderate/slightly cool conditions in the winter both indicated a desire to save energy, while 2 of the 3 occupants who said they prefer moderate/slightly warm conditions in the summer were afraid of overcooling and the third said they wished to save energy.

In general, it seems that occupants express more frustration with warm discomfort because it cannot be managed as effectively as can cold discomfort - particularly when it occurs in the summer. In large part, this is tied to the limits of clothing adaptation in warm summer conditions when compared to cold conditions: while many occupants reported bringing in layers and adding or subtracting clothing as conditions became too cold throughout the year, people typically dress for work in as little clothing as possible in the summer and thus have no further opportunity to reduce layers during the day when conditions run warm. As one respondent lamented, “You can’t take off more layers of skin when you are too hot in the summer time”. This inability to manage warm discomfort in the summer could significantly impact one’s ability to work effectively, especially with other employees:

Being too hot would definitely make me more aggressive than I already am, and more pissed off at the whole world. If you are too hot, you are going to be much more irritated. If I ever got in a fight with someone, it was in the summer, because...physically I could take the heat, but mentally and mood-wise, I could not.

The negative impact of the inability to adjust clothing in the summer is compounded by the fact that there typically are not many other viable adaptive options available to occupants when
warm: just 38% use fans, 47% have access to operable windows, and 40% have access to thermostats. Of the 47% with access to windows, 1/3 never use them when it is warm during the summer because doing so would actually make the conditions worse; similarly, 46% of those with access to a thermostat never use it in warm conditions because they either don’t know how it works or have determined it has no appreciable effect on the environment: “We have a thermostat in our space, but it didn't seem to control anything, so we never use it.”

Regarding the use of fans, roughly 50% of occupants who have one use it more than “occasionally”, and the action is regarded on average to be effective “some of the time” but not by itself an ideal solution to frequently warm conditions. Interestingly, there is a strong negative correlation between the reported effectiveness of fans and the frequency that conditions are reported to be warm ($r=-.796$, $p<.001$). Supporting audio suggests that those who have a fan and only experience infrequent warm discomfort can effectively use this adaptation to make it through brief problem periods, while those who experience more prolonged warm discomfort periods feel fans are really only effective to a certain extent. The account of one occupant in a building with sporadic warm periods helps to illustrate the short-term effectiveness of fans:

Most of the time I bike to work. When I first come in in the summer, I might be kind of hot – so I have a little fan behind my desk and I will normally turn that on for about 5 minutes until I cool down. That fan for a couple of minutes cools me down.

Another account provides a typical perspective of someone working in an office with significant summer overheating issues:

The fan was moderately effective: it wasn't the same as having an air-conditioner pointed at you, but it could be the difference between being uncomfortable and comfortable.

Other than clothing, fans, windows, and thermostats, reporting to management is another option available to most occupants when too hot, but this is also not particularly effective: only 52% of respondents said they report warm conditions at least “occasionally”, and this action is on average between “occasionally” and “sometimes” effective when taken. It is furthermore noted that there is a strong correlation between the frequency of reporting warm conditions and the frequency that the warm conditions affect productivity ($r=.732$, $p<.001$); based on occupant comments, this relationship seems to be self-reinforcing: most respondents will only report being too hot if they “can no longer function” in the workplace, but the very act of reporting also serves to detract further from their ability to work effectively.

When conditions are too cold, the ability to effectively add layers of clothing proves to be invaluable in tempering occupant assessments of both the severity of the conditions and the effect these conditions have on their work. Indeed, the reported effectiveness of clothing adaptations correlates significantly with both the frequency that cold conditions were reported to occur ($r=-.424$, $p<.05$) and the effect that cold conditions have on productivity ($r=-.701$, $p<.001$). Regarding the latter of these correlations, one occupant explained it best:
Cold doesn’t affect me too much unless it is extreme. Once, the heat had broken and it was 55 degrees in here. My fingers were frozen on the keyboard and I was wearing a jacket all day long. At 2 or 3 o’clock, I think we all just went home.

This mention of typing problems – that cold would only affect productivity if it got to the point where fingers were numbed – is common, and in fact some occupants had purchased typing gloves to prevent the issue. The key thing to note about the response, however, is the suggestion that productivity quickly degrades under cold conditions once clothing adjustments are no longer possible or effective, as is the case for warm discomfort. Of course there are other options aside from clothing for adapting to the cold, but these are again not available to all occupants: 40% of occupants use a personal heater, and as before only 40% have control over a thermostat. Unlike fans, however, personal heaters are on average evaluated to be “mostly” effective, and 85% of those who have one use it more than “occasionally” when cold. In most cases, those who do not think the personal heater is very effective are not indicating this from a comfort perspective, but because they run into power issues when using the heater. As one occupant explained:

Clothing was the only thing I could do unless I wanted to take everyone out with me. I purchased a personal heater once and tried it after hours because it usually got cold after the sun went down. So there was really nobody there in the offices and I thought ‘Oh, this shouldn’t be a very big load’. But I forgot that I am on the same circuit as one of the labs. And there were a lot of pissed off students.

The amount of people who have control over a thermostat in cold conditions but never use it is comparable to the result seen earlier for warm conditions (42% never use in cold and 46% never use in warm). In addition to personal heaters and thermostats, drinking warm fluids is an adaptive action that a substantial portion of occupants reported using (40%, compared to 20% who drink cool fluids in response to warm temperatures) and is on average “mostly effective”, adding to the sense that cold can be managed more effectively by occupants than the heat. The discrepancy between the use of warm vs. cool fluids as a temperature adaptation is tied to the fact that few respondents who do drink water frequently view it as a direct adaptation to warm discomfort; rather, this is something that they might do anyway throughout the day to stay hydrated.

As in the case of warm conditions, the frequency with which cold conditions were reported to management correlates strongly with the frequency that the conditions negatively affected productivity (r=.885, p<.001). However, the act of reporting problems with cold is perceived on average to be more effective than is the act of reporting problems with heat (between “sometimes” and “mostly” effective for the cold vs. between “occasionally” and “sometimes” effective for the heat).

Table I-2 summarizes the average occupant frequency-of-use and effectiveness ratings for each of the warm and cold adaptive options surveyed. It is observed that on average, warm adaptations are taken less frequently and are less effective than cold adaptations (note that the shaded cells have not been included in calculation of these statistics due to small sample size).
In addition to the above conclusions about the frequency of adaptive actions and their effectiveness, the interview results provide an understanding of the sequence in which temperature adaptations were taken. This information is summarized in Table I-3, which shows the average priority with which each adaptive action was reported to be taken by occupants when too hot or cold (1=Do this 1st, 2=2nd, 3=3rd, etc.)

Overall, it is clear that actions immediately accessible to occupants are taken first, while actions that involve more effort and/or contain a social element are taken later. Thus, when warm, occupants first adapt their clothing, turn on their fan, and open their door (if possible); if these things do not work, the occupant will then mention the problem to coworkers and adjust the thermostat/open the window; and if this still does not work they might report the problem or leave the office. Similarly, when conditions are cold, occupants adjust clothing, turn on their heater, and drink warm fluids first; then mention the problem to coworkers and adjust the thermostat if these initial actions are not effective; and finally report the problem if the conditions persist. Note that a few occupants reported the action of opening/closing blinds as a first response – but to lighting conditions, not temperature. Thus, blinds are not included in Table I-3 as a type of temperature adaptation.

Note that in Table I-3 the act of “leaving” is differently positioned within the warm and cold adaptive processes. While there is some uncertainty around this item due to the small number of occupants having reported doing it, those who did mention leaving when too cold see it as a more immediate response to “get the blood pumping”, while those who leave when too warm indicated that they do this out of frustration when nothing else is working (i.e., as a last resort).

Care should also be taken in interpreting the relation between adjusting the thermostat and opening the window when too warm. In fact, only 2 of the respondents actually have both options available to them. For the first, the window will be opened if she is warm in the summer and perceives it to be cooler outside than inside, and will subsequently be closed in favor of a thermostat adjustment if conditions continue to get warmer. For the second, the window will be opened if he is warm in the winter and has already adjusted the thermostat but the space has
not yet cooled down. Judging by these two examples, the sequence of opening a window and adjusting a thermostat when too warm seems to depend on the season, with the window being opened first in the summer if it is not too hot outside and second in the winter as a way to cool down the space more quickly. No other occupants in this sample reported having done the latter, however, and a larger number of respondents with control over both windows and a thermostat would be needed to explore this particular subset of the adaptive hierarchy further.

Finally, Figure I-4 examines whether factors other than personal comfort are playing a role in occupant adaptations (to temperature or otherwise). When analyzing the full sample of occupant responses to this question (left hand side of the figure), it does appear that there are other things to consider: 55% of the respondents said that social influence, energy concerns, or a combination of the two significantly factor into their daily adaptive choices (note, however, that only 27% say energy concerns influence their adaptive behaviors). Breaking this result down by office type, however, a much different picture emerges: for those with private offices, personal comfort is overwhelmingly the only factor driving adaptations (80% of this sub-sample); for those in open office areas (cubicle, open desk, public section), social influences play a more dominant role (42%) and concern for personal comfort alone is more muted (26%). Intuitively, this result makes sense: those who work in private offices tend to have more individual control over adaptive options like operable windows and thermostats that are typically managed collectively in open-office scenarios.

### 4.3. Occupant Perspectives on Energy Conservation

Most office occupants have little financial incentive to save energy because they do not see the energy bill. The results of these interviews further demonstrate that most occupants do not know how energy actually is paid for in their buildings – half of the respondents fall into this category. This seems to be more of an issue in larger office environments – in the smallest office interviewed, 4 of the 5 respondents were able to comment on how energy was paid for, while in the mid-sized office building that had undergone a deep retrofit, only 4 of the 10 respondents were able to comment, in spite of the building’s clear culture of energy savings.

Moreover, few office occupants outside of the retrofitted office are aware of any kind of occupant or building manager energy education programs being implemented in their buildings: 72% of the respondents interviewed said that no such programs are in place, and of
the 28% of occupants who said there is a program, 78% are from the deeply retrofitted office, where the management offers tours and displays to educate occupants about the building’s energy saving

features and regularly send out e-mails regarding window opening habits and new technology integration. Even so, 30% of occupants interviewed from the retrofitted office still do not believe that a dedicated energy education program has been established.

Despite the fact that existing energy education programs are scarce, the idea of educating building managers and occupants about energy use was evaluated quite positively by the sample of respondents. Of the 29 occupants who were able to offer an opinion on the issue, 66% feel that an occupant/manager energy education program would be “very effective”, and 31% more indicated that it might be effective depending on how it is orchestrated.

Occupant knowledge about energy education programs as well as 7 other Energy Conservation Measures (ECMs) was gaged as part of the latter half of the interview. Figure I-5 shows the percentage of occupants who are at least “somewhat knowledgeable” about each ECM (i.e. have

Figure I-4 Primary drivers of adaptive action for the full sample (left) and the sample split between those working in open areas (upper right) and private offices (lower right)
at least heard of it) in buildings where that ECM has not yet been implemented (note: the ECM of shutting down computers is excluded from the Figure). For this sub-sample of respondents, the 3 least well-known ECMs are occupant/manager education, improving HVAC equipment efficiency, and implementing so called “smart grid” approaches involving real-time electricity usage and pricing information. Figure I-5 further demonstrates that those respondents who are at least somewhat familiar with occupant/manager education and HVAC measures get their information from previous experiences in commercial buildings and residential settings, respectively, while the source of information about smart grid approaches is more evenly distributed across multiple options.

Among the remaining 4 ECMs shown, residents who do not already have the ECM in their building are most familiar with lighting retrofits (84%), followed by conducting energy audits (72%), renewable energy sources (64%), and envelope upgrades (60%). Most residents who are familiar with energy audits and envelope upgrades gain their information from a residential context, indicating that they have either personally pursued these ECMs for their own home or know someone who has pursued them. For lighting retrofits, the prime source of occupant familiarity is previous office experiences, where occupancy sensors in particular were a common implementation. Where a residential context was mentioned as the source of knowledge.
familiarity for lighting retrofits, it was often in regard to more efficient fluorescent or LED bulbs that the respondent had personally chosen for use in their own home; few respondents had direct knowledge about how these efficient lighting types are specifically implemented in an office setting. Finally, knowledge about renewable energy for those who do not have direct experience with it in their office is split amongst multiple options, much in the way of the smart grid ECM. Note as well that the media is a more significant source of occupant familiarity with renewables than it is for any of the other ECMs covered by the interview.

As already noted, the ECM of shutting down a computer at the end of the day is not shown in Figure I-5 because too few occupants directly commented on how much they knew about this practice. However, half of the 18 people who were questioned about this ECM reported they do not shut down their computer, primarily because leaving it on enables remote desktop when away and quicker start-up on the following day of work.

Regarding the introduction of new efficient technologies that offer some degree of occupant control, over 80% of occupants indicated that at minimum a building manager should hold an upfront meeting in-person with office employees to ensure that they know what the technology does and how they should properly use it (Figure I-6). The occupant emphasis on in person meetings to educate is significant, as less than 10% believe that attempts to educate upfront via e-mail would be successful. Indeed, up front e-mails are not evaluated as positive approaches for occupant engagement because inboxes are already saturated and most will not spend the time to read material that doesn’t directly pertain to their workday. An additional 10% of occupants recommended that before a manager even decides to implement a technology and educate occupants about it, he or she should investigate whether the occupants would actually be eager and willing to effectively use the technology (the “advance discussions” bar on Figure 6).

Roughly 60% of occupants indicated that in addition to holding meetings up front to educate about a new technology, managers should provide some sort of feedback to occupants over time about how effectively the technology is being used, including tips where necessary about how to adjust their usage to save more energy. Here again, the majority of occupants who recommended feedback also recommended that it occur in person through regular integration into weekly/monthly meetings or office events. It is noted, however, that a full 1/3 of those who recommended feedback believe that e-mails/online engagement would be sufficient. Thus, while most respondents do not feel that the Internet is a particularly effective way to engage people up front, some think it could work as an education tool once occupants are familiarized with a technology and expecting this form of follow up regarding its use over time. However, none of the occupants who specifically recommended feedback via e-mail want it on anything more than a monthly basis, again expressing concern about over-saturated inboxes and the possibility that daily or weekly provision of energy use information in this way would become a distraction.

While almost 40% of occupants mentioned the provision of direct or indirect incentives for the effective use of a new technology, there is general apprehension in the responses surrounding
the idea of direct cash rewards for reducing energy use. Take the following exchange, for example:

(Interviewer): How would you feel about having rewards or incentives for having people use energy more efficiently?

(Occupant): I don’t know. I hate thinking that it’s tied to a monetary thing. I know it would work for people but it’s unfortunate that you have to do things like that. I think people want to do the right thing.

Instead, suggested incentives are typically non-financial, and include placing a focus on being environmentally responsible, creating competitions between occupant groups regarding who can use the least amount of energy, and associating energy saving behaviors with improvements in physical comfort and workplace morale. Where financial incentives are mentioned, it is in an indirect sense: for example a few employees suggested that energy savings be presented as a savings to their organization’s annual operating budget, which would in turn free up more funding for employee salaries and benefits.

Figure I-6 Occupant suggestions regarding the integration of new technologies that involve some degree of user control into an office setting.
4.4. Case Comparison: Deep Retrofit vs. Non-Retrofit Offices

Within the total set of occupant responses, two response sub-samples offer an interesting opportunity for comparison: on one hand, the 10 occupants from the mid-sized office building that had undergone a deep retrofit provide a “best case” perspective, as their building has been extensively updated with multiple ECMs; on the other, the 9 occupants from the two older mid-sized office buildings that had not undergone any significant retrofits provide a “worst case” perspective.

Figure I-7 compares these two sub-samples of responses across each of the environmental satisfaction items covered in the interviews as well as a pooled ECM knowledge item. In general, the occupants of the deep-retrofit office are more satisfied with environmental conditions and their ability to manage discomfort than are non-retrofit occupants – just 11% of the non-retrofit occupants are at least “pretty satisfied” with their adaptive ability, compared to 80% of the deep-retrofit occupants; and just 33% of non-retrofit occupants said conditions are generally at least “pretty comfortable”, again compared to 80% from deep retrofit offices (given the small sample size, the former comparison of proportions is the only to achieve significance in a chi-square test of independence, p<.001). Again, there appears to be a relationship between one’s overall assessment of adaptive ability and the reported effectiveness of individual adaptive options: while occupants from the non-retrofit building appear to have marginally greater access to key temperature adaptations (here, control over clothing; personal heaters/fans; windows; thermostats; and warm fluids) and use these options marginally more frequently than do occupants from the deep-retrofit offices, the actions taken by occupants in the deep-retrofit office are on the whole perceived as more effective than in the non-retrofit office (63% of actions taken to manage temperature in the deep retrofit office are reported to be at least “pretty effective” compared to 40% in the non-retrofit office; the difference between these proportions is nearly significant at a p value of .07).

Deep retrofit occupants are also more satisfied than non-retrofit occupants with 4 of the 5 individual areas of environmental satisfaction queried, with the one exception being lighting, where over 90% of lighting satisfaction responses were positive in both these office environments. Keeping a focus on the 5 individual satisfaction items, the largest discrepancy between deep-retrofit and non-retrofit occupant responses is for temperature: 68% of deep-retrofit responses to temperature are at or below the positive threshold of “occasionally” too warm/cold, while only 33% of non-retrofit responses are at or below this threshold (these proportions are not statistically different in a chi-square test, p<.05).

When energy knowledge scores are pooled across all of the ECMs surveyed, the deep retrofit offices again best the non-retrofit offices: 70% of the score-able knowledge responses from the deep-retrofit interviews indicate the occupant is at least “somewhat knowledgeable” about the given ECM, while 54% of the non-retrofit knowledge responses indicate this level of ECM knowledge. A chi-square test of these proportions reveals that this is not significant at a Type I error = .05 level (i.e., there is less than 5% chance that the null hypothesis of equal proportions was rejected due to random variability in the data). Not surprisingly, Figure I-8 demonstrates
that the majority of deep-retrofit occupants’ knowledge about ECMs comes from their own building, which has undertaken 4 of the 7 ECMs queried – HVAC efficiency, lighting, envelope, and renewables – and maintained an open dialogue with occupants about what was going on during the retrofit process. For non-retrofit occupants, knowledge in some cases also comes from one’s own building (13% in Figure I-8, in all cases due to small upgrades in lighting), but mostly it comes from experiences in other commercial buildings (34%) and a residential context (31%).
5. DISCUSSION

The key findings from this work are summarized as follows:

- **General environmental comfort level associates significantly with the frequency that conditions are too warm – especially for those who experience warm discomfort in the summer only - and the ability to effectively manage discomfort.** The strong relationship between general comfort rating and the frequency one is too hot in the summer reflects the difficulty of adapting to warm discomfort during this time of year, especially when compared to the winter when clothing reductions are normally possible. Occupant responses suggest that general comfort assessments can be positive even when specific instances of discomfort are reported– so long as those instances are either short lived or the occupant feels able to manage them directly through adaptive actions.

- **Satisfaction with adaptive ability is particularly tied to the effectiveness of thermostat adjustments when one is too warm.** The strength of this relation suggests two things: 1.) Installing “dummy” thermostats that do not actually regulate temperature may negatively impact an occupant’s general assessment of adaptive ability and in turn their general assessment of comfort. 2.) The effectiveness of a thermostat when warm has a pronounced relationship with one’s general assessment of adaptive ability because there are generally few other viable options for alleviating warm discomfort (especially in summer). Thermostat adjustments when cold seem to matter less to adaptive ability because there are other effective cold adaptations available to occupants.

- **Acoustics and temperature are reported as the most frequent sources of environmental discomfort.** Acoustics has the greatest average effect on productivity when an issue; however, occupants generally expect distractions from inadequate noise privacy and coworker conversations in an office setting, which seems to temper the effect that poor acoustics has on general comfort assessment.

- **Thermal sensation preferences tend towards “slightly cool” in the summer and “slightly warm” in the winter.** The distribution of preferred sensations suggests that most people do feel comfortable when “slightly cool”, “neutral”, or “slightly warm”. A few respondents reported preferring a warmer sensation in summer or cooler sensation in winter due to energy-use concerns; future work might further examine the relationship between concern for energy use and preferred thermal sensation by asking occupants what range of sensations they might be willing to tolerate in order to save more energy (especially if they were given more control over the thermal environment as part of the energy savings’ strategy).

- **Adaptations to warm discomfort are generally less viable/effective than for cold.** Clothing in particular is not as frequently adjusted when warm because people
dress in as few layers as possible in the summer in expectation of warm conditions; when available, windows are not used in the heat of the summer because they can make conditions worse; thermostats are also not used by many who have access because these individuals either do not understand how to use them or have determined they have no effect; fans offer an initial improvement in comfort but are only moderately effective as a longer term solution to heat. Cool fluids are not mentioned as a direct thermal adaptation nearly as much as are warm fluids (20% report drinking cool fluids vs. 40% who drink warm fluids). The regular provision of cool drinks to occupants by the building management may go a long way towards improving thermal comfort and general perception of adaptive ability - especially in the summer months when few other adaptations are viable.

- **Order of adaptive action reflects the accessibility and ease of each adaptive option.** For both warm and cold conditions, clothing is adjusted first, followed by other adjustments to one's personal space including fans/personal heaters (38% use fans; 40% use a personal heater), opening doors (44% have access to a door), and drinking fluids; actions that require leaving the immediate workspace or socializing with others such as opening/closing windows (47% have access to operable windows) or adjusting thermostats (40% have control over a thermostat) are taken later in the process; and reporting is taken as a last resort when nothing else has worked. The act of reporting carries a negative association with productivity for both warm and cold conditions: people will report when they feel the conditions are hindering their ability to work, but the distraction of reporting further impedes work efficiency.

- **Fans and personal heaters are both used by substantial portions of office occupants, but differ in perceived effectiveness.** While a similar percentage of occupants use fans and heaters (38% vs. 40%), heaters are evaluated to be effective on average “most of the time” while fans are on average only effective “some of the time” and are generally not regarded as a long-term solution to warm discomfort. However, the perceived effectiveness of heaters is diminished somewhat by their potential to cause electrical problems. Indeed, though fans and personal heaters offer more personal control over comfort, neither is accounted for in the design of these buildings’ conditioning systems and their use is likely leading to unexpectedly high electricity consumption. Future research should aim to quantify the energy impacts of such personal heating/cooling technologies and examine ways to build them into the strategy for conditioning office spaces.

- **Personal comfort predominantly drives adaptive actions in private offices, while social influence plays a larger role in open plan/cubicle settings.** People in open plan offices must consider the effect of adaptations such as adjusting the thermostat or opening the window on others in the space; in many cases one will accordingly try to gauge others’ comfort levels through mentioning their own discomfort before engaging in these particular adaptations. This associated
process of gaining others’ approval helps explain why such adaptations are used less frequently than those that are more immediate and do not require the consent of others (clothing, personal heaters/fans, etc.)

- **Occupant/manager energy education programs are scarce in the sample interviewed, but enthusiasm for them is high.** Though less than half the occupants not already participating in an energy education program are familiar with such programs, the majority wishes to know more about how much energy they use and how this consumption can be reduced.

- **Lighting retrofits are most familiar to those who work in a building that has not already undergone this ECM, and HVAC retrofits are least familiar.** Source of occupant knowledge about lighting retrofits is predominantly experiences in other commercial buildings. For other ECMs such as energy audits and envelope upgrades, the primary source of familiarity is their own home or a home of an acquaintance. This carries implications for how information about energy conservation measures is presented to occupants. For example, programs geared towards educating occupants about the outcome of energy audits in commercial buildings might first discuss the relationship between commercial audits and the residential audit process that is more familiar to occupants.

- **New technologies that involve occupants should be integrated through occupant education up front in person; the majority of respondents also believe that some sort of feedback over time is necessary to ensure effective use.** While the clear majority of occupants wants an initial explanation of the technology’s benefits and operation done face-to-face and not via e-mail, 1/3 of those who recommended feedback believe it can occur online, though e-mail follow-ups are not desirable on anything more frequent than a monthly basis. The remaining 2/3 believe regular face-to-face feedback is most effective. Occupants are apprehensive about direct cash incentives, though some believe that explaining the indirect financial benefits of lowering operating costs would be helpful.

- **Keeping occupants abreast of a commercial retrofit process can have benefits in both energy conservation knowledge and comfort tolerance down the line.** Occupants from the extensively retrofitted building are generally more knowledgeable about energy conservation measures and satisfied with comfort and adaptive ability than are occupants from two buildings that have not been retrofitted and have no connectivity between building managers and occupants about energy use. For the retrofitted offices, the source of most occupants’ knowledge is their own building, which reflects the active efforts of the building management to inform occupants about the new technologies being installed as part of the retrofit. Knowing more about such technologies and their benefits from an energy use and environmental perspective promotes greater occupant tolerance of inevitable hiccups in operation and associated periods of discomfort. As one occupant of the retrofitted offices related:

  I am happy to deal with a few days of discomfort a year in return for having a geothermal system – it is a totally fine tradeoff for me.
The above findings will be further explored and refined in the future using a structured survey instrument that is administered to a larger sample of office building occupants. This survey instrument will allow the more precise quantification of important trends observed here, such as the relationship between the effectiveness of adaptive actions and overall assessment of adaptive ability; the impact of the frequency of individual environmental conditions on general comfort evaluation; and the hierarchy of adaptive actions. Responses to the structured instrument can be paired with corresponding measurements of environmental conditions to yield a more comprehensive understanding of the mechanisms driving adaptive occupant behaviors in the built environment; the effects of these behaviors on comfort and productivity; and the potential for focusing on behavioral phenomena as a low hanging fruit in the larger GPIC effort to substantially reduce commercial building energy consumption.

6. REFERENCES


CHAPTER II
Surveying Stakeholder Decision Processes in the GPIC Region

Chapter Highlights:

- 16 semi-structured interviews are conducted with stakeholders (building owners, architects, engineers, consultants, contractors, and others) regarding adoption, development, and prioritization of energy-efficient technologies during building retrofits.
- Results suggest that while many stakeholders view first cost as an important barrier to investment in energy efficient retrofits, uncertainty regarding both the operations and the cost savings from a retrofit greatly contribute to this decision.
- A majority of stakeholders forgo complex metrics and instead use simple payback to evaluate investment decisions. The average acceptable payback period reported was 3.9 years (with a standard deviation of 1.6 years)
- While computer modeling is widely-employed by stakeholders as an initial step in the retrofit decision-making process, stakeholders place more weight on actually seeing the technology in operation, thus reinforcing the importance of demonstration projects and local examples of success.
- To be convincing to other potential adopters, a demonstration project must not only show operational success but cost-benefit success as well. This emphasizes a need for transparency in cost data regarding building performance.
- The cost of sophisticated computer modeling may represent a disproportionately large percentage of the total retrofit budget for a single-building retrofit. Thus economies of scale may be preventing the adoption of newer technologies by smaller, single-retrofit projects. This also suggests a need for simpler, more intuitive modeling tools.
- One noteworthy type of operational uncertainty comes from compatibility issues between different pieces of equipment where “ripple effects” of newer equipment on existing equipment is difficult to predict. As a consequence, contractors may be avoiding certain retrofit measures due to compatibility concerns.
1. INTRODUCTION

Economic theory suggests that technologies with a positive net present value will be adopted by rational entities in order to maximize profits – but energy conservation measures (ECMs) do not seem to follow this model. [1] Potential barriers to adoption of ECMs may be real, such as inability to obtain the capital required, timing issues, and legal or zoning ordinances – or perceived, such as a general lack of understanding or familiarity with the technology being considered. The decisions made by stakeholders (building owners, architects, engineers, consultants, contractors, and others) regarding adoption, development, and prioritization of energy-efficient technologies must be better understood in order to achieve the substantial energy reduction goals set forth by GPIC. There are many reasons why these decision-makers may or may not choose to spend money on energy-saving measures but the relative importance of these different reasons is not well understood. Furthermore, different stakeholders likely have very different views on which factors are most important, complicating the process. [2] In order to better characterize the decision-making process, it is imperative that the specific factors that most influence key decisions on commercial building retrofits as well as differences between stakeholder groups be assessed as part of the ongoing GPIC research efforts.

2. OBJECTIVE

To better characterize the key factors that contribute to decisions regarding the energy retrofit of commercial office space, a series of semi-structured interviews were conducted with key stakeholders from office buildings around the GPIC region. This series of interviews covered the first of two planned stages of stakeholder surveying: in the first stage, the semi-structured interviews allowed for open-ended responses from the subjects which can bring out factors that might be overlooked by a more rigid interview format. In the second stage a structured survey will be conducted to more precisely quantify the frequency of different attitudes and practices identified during the first stage. The interviews examined the key factors that influence decisions regarding the use of energy-saving measures, their relative weight in the decision-making process, and how these factors may or may not differ across stakeholder groups (i.e., building owners vs. architects). The results of the first round interviews provide an understanding of the contributing factors that warrant further study in the second stage.

3. MATERIALS/METHODS

A semi-structured interview was administered to 16 stakeholders from 15 different organizations over the course of approximately six weeks. Each of the organizations is located either within the Philadelphia metropolitan region or the surrounding suburban areas. Interview subjects were recruited through email and by word of mouth. Respondents included building owners and managers, architects, engineers, developers, and consultants. The specific breakdown of stakeholders by role is shown in Figure II-1.
3.1. Semi-Structured Interview Format

The interviews were administered in person or by phone and lasted between 30 minutes and 1.5 hours per respondent. The interview consisted of two primary sections:

I) Background Information
Includes questions about the individual’s role in the building design/development/retrofit process, what type of buildings they typically work with, and the area in which their buildings are located.

II) Factors Affecting the Decision to Invest in Energy-saving Measures
Includes questions about specific triggers for building retrofits, the barriers that must be considered, what types of efficiency measures are targeted, and what metrics or models are used to assist in making the decisions. Where possible, specific target values were elicited for the various metrics. Questions covered the following general areas regarding building retrofit decisions:

- Triggers for building retrofits.
- Barriers to performing building retrofits.
- Specific energy conservation measures typically targeted first as part of a retrofit.
- Designation of primary responsibility for key design decisions during the retrofit process.
- Factors affecting the choice of a new or non-standard technology in the retrofit process.
- How the performance of new technologies is estimated prior to installation.
- Metrics used in making decisions about retrofits (both financial and non-financial).
- Acceptable or target values for these metrics.
- Primary areas of uncertainty in decisions regarding building retrofits and how this uncertainty is considered in the process.
- The perceived importance of possible volatility in future energy prices to decisions regarding the retrofit process.

Following subject approval, responses to these questions were recorded with a digital audio device. In cases where subjects preferred not to have their responses recorded, notes were taken and interviews were scored during or immediately following the conversation. The full survey instrument is shown in Appendix A.2. Responses to each question were scored and tabulated into a single database for analysis.
4. RESULTS

While it is impossible to completely characterize every factor in the retrofit investment decisions, it is possible to describe what a typical set of decision processes might look like for a simple, single-project retrofit:

- A building owner decides to perform a building retrofit because of a change in the tenants’ usage/programming requirement or because of mandatory maintenance following failure of equipment (typically mechanical equipment such as HVAC).
- As part of this retrofit, the owner must decide how much to invest in energy efficient measures (since the initial cost may be greater than more traditional measures). The owner assesses the presence and availability of internal capital for the project.
- The owner interfaces with an architect/engineer/consultant to develop some ideas based on the experience of the A/E/C firm as well as case studies and technical literature.
- For projects of a certain scale, computer modeling is used to estimate the cost/energy savings. Economies of scale do not support extensive modeling for single-project retrofits on office buildings smaller than 100,000 square feet so in some cases this may result in less comprehensive results.
- If possible, the owner talks to others that have already adopted and begun using this technology. Such referrals may be made any number of ways and do not necessarily come from the vendor or the A/E/C firm. Where local examples of success do not exist, some owners may decide to do small-scale pilot testing.
- The owner re-assesses the presence and availability of capital for the project.
- Based on the results of the computer modeling, conversation with other people, and the recommendations of the technical firm, the owner decides whether or not to proceed.
- At this point, obtaining authorization to proceed varies greatly by the type of institution, but in many cases there may be a period of debate before approval is granted.

This initial round of semi-structured interviews has yielded a coarse understanding of how various factors contribute to decisions to invest in energy-retrofit measures for commercial office buildings and which of these factors should be focused upon in a longer structured survey that will be administered during Year Two of the GPIC project. Specific findings from the surveys in Year One are discussed below.

4.1. Triggers for Small Building Retrofits

Across all respondent types, the most commonly reported trigger for conducting a building retrofit is a modification in utilization by the building owner or tenant (shown in Figure II-2). This is essentially an umbrella category that captures all the operational changes required to conduct business on a day-to-day basis. Such changes may include turnover in the tenants occupying the space or alterations in programming needs for an existing tenant.
Results also show that facility maintenance is an important trigger for performing a building retrofit. Additionally, maintenance may often dictate when the retrofit occurs, essentially serving as justification to invest money in energy conservation measures conjointly with the maintenance work. The occupant variables category, which includes improvements in comfort and productivity, was the third most-cited trigger category despite only being ranked first by two respondents.

It should be noted that among triggers ranked as second most important, energy efficiency was second only to owner/tenant needs. This indicates that while energy-efficiency is not often the primary driver of a retrofit, it is very frequently given consideration. Overall, energy efficiency was the fourth most-cited trigger for building retrofits. This suggests that energy efficiency by itself may be sufficient motivation for some retrofits, and that energy efficiency is not always relegated to “piggy-backed” on a retrofit that is taking place for some other reason. One example, provided by an interview subject, is lighting upgrades, which can be motivated solely by an interest in energy-efficiency as they do not disrupt occupant activities and have favorable economic returns even when undertaken as standalone measures.

Although none of the respondents cited code as the primary trigger for a retrofit, it was given secondary or tertiary importance by 4 respondents.

### 4.2. Potential Barriers to Performing Energy-Efficient Building Retrofits

As shown in Figure II-3, initial cost was overwhelmingly perceived by stakeholders as the primary barrier to performing an energy-efficient building retrofit. Of the fourteen respondents who discussed initial cost, 13 of them ranked it as the most important barrier which must be overcome before a retrofit.
can occur. This is not surprising given the existing literature on the topic. As one property manager admitted during the interview, “[First cost] probably carries more weight than it should.”

The second most-mentioned barrier to initiating a building retrofit was the availability of capital. This was particularly important for larger organizations where internal funding is prioritized to projects with more pressing needs. It should be noted that availability of capital was only listed as a primary barrier by 3 respondents, the remainder of which listed it as second or third most important. Several respondents discussed the problems associated with obtaining financing for retrofit projects from lenders that are skeptical of the return on investment. There are several means by which this hurdle can be cleared. One possible solution utilizes innovative financing programs where the cost of the loan for the ECM is tied to the utility bill and remains with the property even after tenants change. By coupling the loan payment to the utility bill (which presumably has a low rate of default), the lender thus removes an element of risk from their investment.

An unexpected finding from the surveys was the category “uncertainty regarding outcomes of the retrofit process” manifesting itself as the third most popular barrier to energy-efficient retrofits. Moreover, when only first- and second-ranked barriers are considered, this category outstrips all other categories except for initial cost. This finding has important implications for facilitating adoption of ECMs and is discussed more in the subsequent sections.

“Timing of the retrofit process” was ranked in the top three barriers by 5 respondents, although only one respondent ranked it as the primary barrier to the retrofit process. Timing was particularly important for organizations where swing space is limited and tenants are not easily displaced.

“Design challenges” and “legal barriers” ranked at the bottom of the group. Design challenges typically related to physical limitations, such as insufficient space, or compatibility considerations, such as interfacing newer components with older systems. Legal barriers included any ordinances preventing the adoption of new technologies. None of the respondents cited “loss of revenue” as a top-three barrier to performing a retrofit. Taken together, these results may suggest that it is not actual technical or legal roadblocks preventing investment in energy-efficient retrofits, but rather questions of cost and uncertainty.

4.3. Major Design Decisions During the Retrofit Process

Consistent with responses to previous questions, the most important decisions made during the retrofit process were those made to ensure that the retrofit costs stay within budget (shown in Figure II-4). A majority of respondents ranked this as the most important type of decision to be made once a retrofit has been initiated. The importance of “being green” followed closely behind budget considerations in terms of number of times cited, while “comfort” lagged in third and was not assigned primary importance by any respondents. However, at least some stakeholders view investment in energy-efficiency as targeting all three of these areas.
One developer discussed the fact that “being green” has benefits beyond just marketing appeal – that investing in energy efficient measures have a clear track record of paying for themselves in terms of increased rent that comes with a more desirable working environment.

4.4. Energy Conservation Measures Targeted First

Lighting was ranked first the most times (22% of the responses) as being the first ECM targeted during an energy-efficient retrofit (shown in Figure II-5). “Building conditioning systems and commissioning” was cited by 31% of the responses as an ECM commonly targeted first during a retrofit; however, only about 4% of the respondents gave ranked it first. Building envelope improvements (most typically windows) was also a commonly-cited target for retrofits.

Some respondents took a functional approach to energy efficiency: “Turn it off, turn it down, fix what is broken,” is the mantra proclaimed by one property manager, commenting on the importance of making sure that existing equipment is being operated correctly before money is spent on upgrades and new technologies.

Results show that control and metering technologies are frequently overlooked as tools for energy-efficiency, yet they may represent highly effective ways to increase occupants’ satisfaction with their work environment. As discussed in Chapter I, occupants who feel they are unable to control the environmental conditions in their workspace report being less comfortable and may use energy-intensive devices like fans and space heaters to compensate for unsatisfactory conditions, thereby frustrating energy conservation efforts.
4.5. Most Responsible Parties

As shown in Figure II-6, the vast majority of respondents acknowledged that the building owner has primary responsibility for making decisions regarding building retrofits. However, depending on the circumstances, the owner’s decisions may be influenced by recommendations of the engineer, architect, or other design consultant. In many cases, the analyses performed by the engineer/architect/consultant generate the options from which the owner must pick and choose.

For this question it is also important to consider the well-documented problem of “split incentives” – where neither the owner nor the tenant are motivated to invest in ECMs because the tenant pays the energy bills but does not own the space. Such organizational obstructions must be resolved in order to facilitate greater investment in ECMs. As discussed in Section 4.2, one possible solution to this problem is to couple the retrofit loan payment to the utility bill, thus pinning the investment to the building itself and bridging the current gap between owners’ incentives and tenants’ incentives.


There was a significant amount of variation in the methods employed to estimate the performance of new or non-standard technologies (prior to installation) with no one method emerging as clearly dominant (Figure II-7). Although the owner having direct experience with the technology was ranked first by the most respondents, engineer/architect experience and vendor experience were described by more respondents as having at least some weight in the adoption decision.

Anecdotal information can be very important when choosing which technologies to adopt. This reinforces the importance that stakeholders place on local examples of success. Anecdotal information may also inform the perceived location of a
new technology on an “adoption curve,” an idea that was mentioned by several different respondents when discussing new or non-standard technologies.

Several respondents reported using EPA’s Portfolio Manager software to track consumption, performance, and cost information for their buildings. Other computer software mentioned by respondents included proprietary programs for monitoring building systems provided by Aircuity and Carrier. There was no particular type of software used by the majority of respondents.

In general, respondents had a favorable view of third-party case studies and technical literature in estimating building performance. But as with the computer software case, there was no one source that was more popular than any other. Literature sources mentioned by respondents included EnergyStar, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and the US Department of Energy. Internal data available to technical firms (architects, engineers, and consultants) were not considered to be third-party literature.

4.7. Factors Affecting Decision to Adopt New or Nonstandard Technologies

An important result from this question was the importance that stakeholders placed on local examples of success when considering new or nonstandard technologies (Figure II-8). This category was ranked by 44% of respondents as being one of the top three most important considerations. Respondents varied in the degree to which the examples of success needed to be local; however, it generally appeared that local examples were more convincing than examples that were far away because local examples likely indicated the presence of a regional support structure.

Conversely, although approximately 69% of respondents utilize some form of computer modeling, it was only ranked by 8% of respondents as being one of the top three tools affecting retrofit decisions. This may suggest that the complexity of some models allows only those with expert knowledge to capitalize on the projections afforded by these tools, or that the modeling results are used as a “point of departure” but are not in themselves sufficient to sway a major retrofit decision.

A corollary is that by virtue of their complexity to model, certain ECMs (typically more advanced measures) may be difficult to incorporate into smaller retrofit projects for one of several reasons: 1) economies of scale for small projects do not support a very extensive modeling phase prior to selecting which ECMs to adopt, making it less likely that new or non-
standard technologies will be adopted, and 2) small scale projects often do not have the support staff or in-house expertise to fully capitalize on the options afforded by these ECMs. One architect noted that this can limit the types of ECMs used in smaller-scale retrofit projects. This reinforces the notion that simpler and more inexpensive modeling methods coupled with better case literature may increase adoption by smaller or less sophisticated projects.

Coupled with the results of the previous question, these data suggest that while computer modeling is an important initial step in the retrofit decision-making process, stakeholders place more weight on actually seeing the technology in operation.

4.8. **Metrics Used to Make Decisions About Building Retrofit Investments**

Simple payback was cited by roughly 30% of respondents as the dominant metric by which retrofit investments are considered (Figure II-9). Non-financial performance metrics such as LEED or EnergyStar ratings were cited by approximately 21% of respondents as playing a role in decisions regarding retrofits, though in most cases this appears to be a secondary consideration after an acceptable payback period has been achieved.

In addition to simple payback, several respondents reported using more sophisticated financial metrics such as net present value (NPV), internal rate of return (IRR), savings-to-investment ration (SIR, mentioned by one respondent), or a combination of these metrics. Additionally, approximately 12% of respondents factored tax rebates and government incentives into their metric calculations; however, this category was most commonly given less weight than other categories.

4.9. **Value of Metrics**

For simple payback, with the exception of one outlying answer given as 20 years, the average payback period acceptable to respondents was 3.9 years with a standard deviation of 1.6 years. Assuming a lifespan of 10 years, this would correspond to an annual rate of return between 20% and 25%. It is important to note that there is a difference in acceptable payback periods between retrofit projects done in the city of Philadelphia versus those done in the surrounding areas. This is due to city labor laws which can increase the cost of labor and therefore also increase the amount of time required for payback. So while the cost of a particular ECM may
pay for itself in 3 years in a suburban location, this same ECM may require a 5 or 6 year payback within the city.

Additionally, there is some preliminary evidence that stakeholders will accept different payback periods for different technologies (for example, lighting vs. solar). The precise extent of this is unclear and will be further explored in subsequent research.

4.10. Primary Sources of Uncertainty

Respondents were asked to characterize the primary source of uncertainty in the retrofit process as cost-benefit uncertainty (“Will it cost me more than I thought?”) or operational uncertainty (“Will it work?”). Responses were fairly evenly split among the categories although more respondents ranked cost-benefit uncertainty ahead of operational uncertainty (Figure II-10). Only 13% of respondents believed that operational uncertainty was the only important type of uncertainty. This highlights the fact that demonstration projects need not only to be successful on an operational basis but also on a cost-effective basis.

One noteworthy type of operational uncertainty comes from compatibility issues between different pieces of equipment. One contractor noted that, “…a large amount of uncertainty comes from the interactions between components in a system when only one component is upgraded.” This is particularly relevant to retrofit projects where existing equipment may be decades old and it is not immediately apparent what types of ripple effects newer equipment will have on the systems already in place. As a consequence, the contractor will typically only recommend upgrades that they have already done successfully in other projects.

4.11. How Uncertainties Are Considered

An overwhelming majority of respondents (approximately 82%) only considered these sources of uncertainty through informal methods (Figure II-11). Few respondents claimed to use formal techniques such as sensitivity analysis or Monte Carlo methods to evaluate this uncertainty, and among those that did, the work was typically outsourced to a consultant. Such an uneven breakdown between the use of informal and formal methods presents an opportunity for user-friendly tools to be made accessible to decision-makers.
4.12. Do Decision-Makers View Energy Efficient Retrofits as Hedge Against Price Volatility?

Approximately 82% of respondents said they view investment in energy conservation measures as a hedge against future volatility in energy pricing (Figure II-13). At the same time, only 18% of respondents said they use formal methods to evaluate the value of these ECMs in reference to energy price volatility (Figure II-12). These disproportionate results are consistent with data from previous questions and again may represent a need for better modeling tools to facilitate such projections.

![Figure II-13. Perceive ECMs as a hedge against future energy price volatility.](image)

![Figure II-12. Use formal methods to evaluate value of ECMs with regards to volatility.](image)

4.13. Summary of Results

The results can be summarized as follows:

- **Triggers for retrofits**: The most common trigger is a change in usage or programming requirements by the owner/tenant followed by mandatory maintenance upgrades. Energy-efficiency was commonly ranked second in this category.
- **Barriers to energy-efficient retrofits**: Initial cost and availability of capital are the most frequently-mentioned barriers to investment in ECMs; however, uncertainty regarding the operational and cost-benefit performance of the technologies also emerged as an important factor.
- **Energy conservation measures targeted first**: Lighting was ranked first the most times (22% of the responses) as being the first ECM targeted during an energy-
efficient retrofit. “Building conditioning systems and commissioning” was cited by 31% of the responses as an ECM commonly targeted first during a retrofit; however, only about 4% of the respondents gave ranked it first. Building envelope improvements (most typically windows) was also a commonly-cited target for retrofits.

- **Primary responsibility for retrofit decisions**: The building owner has primary responsibility for making decisions regarding building retrofits but these decisions may be influenced by recommendations of the engineer, architect, or other design consultant. The problem of “split incentives” remains an important one.
- **Estimating the performance of new technologies**: Many different methods are employed to estimate technology performance with no one method dominating the others. Owner experience, engineer/architect/vendor experience and computer modeling were described by respondents as having at least some weight in the adoption decision.
- **Factors affecting the decision to adopt new or nonstandard technologies**: Local examples of success carry the most weight when new or nonstandard technologies are being considered. These examples are even more persuasive when cost effectiveness is demonstrated.
- **Metrics used in making retrofit decisions**: Simple payback was cited by roughly 30% of respondents as the dominant metric by which retrofit investments are considered. Non-financial metrics such as LEED or EnergyStar ratings were cited by approximately 21% of respondents as playing a role in decisions regarding retrofits, though in most cases this was of a secondary nature.
- **Acceptable values of metrics used in making retrofit decisions**: For simple payback, with the exception of one outlying answer given as 20 years, the average payback period acceptable to respondents was 3.9 years with a standard deviation of 1.6 years. Assuming a lifespan of 10 years, this would correspond to an annual rate of return between 20% and 25%.
- **Uncertainty regarding outcomes**: There is slightly more uncertainty regarding cost-effectiveness than operation of ECMs. This highlights the need for demonstration projects to be successful not only on an operational basis but also on a cost-effective basis.
- **Managing uncertainty**: Only a small minority of stakeholders use formal methods to quantify uncertainty during the retrofit decision-making process.

5. **DISCUSSION**

Overall, these interviews have confirmed key findings from previous work while further clarifying several points:

- **The importance of examples of success**: Many stakeholders emphasized the importance of local success stories to convince them that the ECM in question would work as claimed. Several stakeholders also mentioned that they will conduct small-scale pilot testing on new products before deciding to invest on a larger scale. Many
of these same respondents expressed concern that vendors’ claims of technology performance could potentially be inaccurate in some situations. Together these statements suggest that a third-party database of case studies categorized by ECM type may facilitate the diffusion of new or non-standard technologies by connecting potential adopters with those that have already adopted them. To be truly convincing, it is important that such case studies include cost data in addition to operational performance data.

- **Economies of scale in computer modeling:** Sophisticated computer modeling requires extensive data collection and analysis, the cost of which may be a disproportionately large percentage of the total retrofit budget for a single-building retrofit. Only for larger buildings or multi-building retrofits does this modeling become economical. This may suggest that simpler and cheaper approaches to modeling may be beneficial to smaller scale retrofit projects. The same is also true for performance tracking software. One respondent noted that while they use proprietary software to track building performance, the organization simply does not have the in-house expertise to capitalize on the functionality of the systems in use.

- **The role of uncertainty in the retrofit process:** Although nearly all of the respondents indicated that cost-benefit variables and operational variables both generate an element of uncertainty in the retrofit decision-making process, cost-benefit uncertainty was judged to be more important. These results show that case studies must demonstrate success not only on an operational level but also in terms of cost-effectiveness, a finding which supports the need for financial transparency in building performance.

The results of these interviews have identified key factors in the investment decisions regarding energy-efficient retrofits. Future work will focus on better characterizing the relative weights of these factors and their impact on the overall decision-making process.

6. REFERENCES


CHAPTER III

Building Stock Modeling and Energy Use

Chapter Highlights:

- 28 EnergyPlus models were created to represent various mid-sized office buildings which may be found within the GPIC region. Characterization data for these models was gathered from industry and academic research as well as collaboration with other GPIC coordinators and participants.
- Key buildings and properties have been identified within the GPIC region for the purposes of validations and verification of energy models.
- Energy use results supported work by the UTC team to understand regional effects of policy on energy use in mid-sized office buildings by extending the results of 28 models to represent 173 other building types within the region.
1. INTRODUCTION

For the Greater Philadelphia Innovation Cluster (GPIC) region, there is an identified need to develop a stock of energy models that represent the current population of mid-sized office buildings found in the GPIC area (from now on referred to as the target building stock) in order to understand regional energy use, as well as the potential gains in efficiency that might be realized through retrofits. The first step to developing this target stock is identifying a baseline, or “least efficient” building (one with the most potential for upgrade). After identifying the baseline, a second set of energy models is needed to represent renovations or upgrades to this baseline in the form of energy conservation measures (ECMs) which have already been implemented in the target building stock. Finally a set of models is needed to represent ECMs that may be adopted in the future. The models developed in this manner can then be weighted to reflect their frequency in the target population, and the aggregate energy saving of retrofits that move a portion of the building stock from one state to another can be forecast. A description of the forecasting model is provided elsewhere (Otto et al., 2012). This chapter describes the development of the building energy simulation models.

2. ENERGYPLUS MODELING

Currently there is little specific characterization data for the target building stock. However, from what is known based on statistical data (Otto et al., 2012), the baseline (representing typical, less-efficient buildings in this region) buildings can be described as:

- geographically based in Philadelphia, PA
- having 3 stories, with a cumulative area of 60,000 square feet
- being open 7 am – 7 pm on weekdays
- being open 9 am – 1 pm on Saturdays
- having single pane windows
- having two elevators

Two general types of buildings, termed Baseline 1 and Baseline 2 that are used to represent the mid-sized office buildings in the region. In addition to the characteristic above, the buildings can be described as:

- Baseline 1 – masonry exterior walls, 20% glazing
  - 1 constant air volume (CAV) system per floor, hot water (HW) main heat and reheat, direct expansion (DX) cooling
  - Based on ASHRAE 90.1-1989 code requirements
- Baseline 2 – steel frame exterior walls, 60% glazing
  - 1 roof top unit (RTU) per floor, natural gas (NG) main heat and electric reheat, DX cooling
  - Based on ASHRAE 90.1-1989 code requirements

The general modeling approach is to begin with these two baseline energy models. Then ECM packages are applied to the baseline buildings to represent potential upgrades which represent
other current or future buildings that could exist in the region. This modeling approach does not consider all possible combinations of ECMs. Instead it recognizes that the ECMs that are easier to implement and offer the most favorable immediate returns will be undertaken first while others that require more costly investments and longer payback times would be undertaken only as part of a package that included the more immediately favorable investments as well. For example, lighting upgrades generally require limited capital investments and short payback periods, while envelope improvements have high upfront costs and longer payback periods. Thus, lighting improvements are considered as an individual ECM, but envelope improvements are considered only as part of a package that includes lighting improvements as well. For each of the two baseline buildings, a set of 14 ECM packages is developed for a total of 28 energy models.

EnergyPlus is the computational engine used to develop and simulate the 28 models used in this GPIC study. These 28 different models can then be adjusted to represent a wider variety of ECMs when there is an engineering basis for understanding how a particular ECM would affect building energy use without the need for a building simulation. For example, improvements in hot water heating efficiency would not be expected to affect other components of building energy use and could be simulated simply by adjusting the portion of energy use dedicated to hot water heating to reflect the energy saved by the new equipment. In contrast, improvements to lighting affect the overall heat balance of the building and require separate model simulations.

2.1. Relevant Building Stocks and Studies

The approach for this GPIC study is to take a current EnergyPlus model and modify it for use as the baseline buildings. While some studies have developed models that provide a useful starting point, available models require modification to bring them to baseline conditions. In the following section, two studies which provide useful models and information to the baseline model development are summarized.

2.1.1. National Renewable Energy Laboratory Study (NREL) (Deru et al., 2011)

The most relevant EnergyPlus building model is based on the study by Deru et al. (2011). The report details the development of reference energy models for the most common commercial buildings in the United States to serve as benchmarks for energy efficiency research. The study has developed models for three vintages, 16 building types, and 16 geographical locations for a total of 768 models. The vintages include:

- Pre-1980 (based on survey of pre-1980 buildings)
- Post-1980 (meets ASHRAE 90.1-1989 minimum requirements)
- New (meets ASHRAE 90.1-2004 minimum requirements)

The 16 buildings types are based on 2003 Commercial Building Energy Consumption Survey (CBECS) classification, and are:

- Small Office
• Medium Office
• Large Office
• Primary School
• Secondary School
• Stand-Alone Retail
• Strip Mall
• Supermarket
• Quick Service Restaurant
• Full Service Restaurant
• Small Hotel
• Large Hotel
• Hospital
• Outpatient Healthcare
• Warehouse
• Midrise Apartment

The 16 geographical locations are based on DOE and ASHRAE climate classifications (Briggs, Lucas, & Taylor, 2003), and are summarized below, with a representative city enclosed in parentheses:

• 1A (Miami, Florida)
• 2A (Houston, Texas)
• 2B (Phoenix, Arizona)
• 3A (Atlanta, Georgia)
• 3B-CA (Los Angeles, California)
• 3B-other (Las Vegas, Nevada)
• 3C (San Francisco, California)
• 4A (Baltimore, Maryland)
• 4B (Albuquerque, New Mexico)
• 4C (Seattle, Washington)
• 5A (Chicago, Illinois)
• 5B (Denver, Colorado)
• 6A (Minneapolis, Minnesota)
• 6B (Helena, Montana)
• 7 (Duluth, Minnesota)
• 8 (Fairbanks, Alaska)

The models developed for this NREL study are based on all characterization data available for the whole of the United States, and serve as a good starting point for developing baseline energy models.
2.1.2. Pacific Northwest National Laboratory Study (PNNL) (Liu, Thornton, Wang, Lane, & Rosenberg, 2009)

The purpose of the study by Liu et al. (2009) is to develop energy models for support in recommending an ECM package which reduces medium office building energy consumption by 50% over their baseline. Their baseline model is constructed based on one of the Deru et al. (2011) models with new construction, medium office model with some slight modifications and follows the ASHRAE 90.1-2004 minimum requirements. This PNNL study suggests that a radiant heating and cooling with dedicated outdoor air systems (DOAS) can reduce building energy consumption over the baseline by 57% for a 4A (Baltimore) climate. However, the study understands that the suggested system is not always a simple implementation option, and has also evaluated a high-performance variable air volume (VAV) system which reduces building energy consumption by 43% for a 4A (Baltimore) climate.

2.2. Baseline Model Construction

The two baseline models are constructed based on the Post-1980, climate 4A, medium office NREL model with modification to make them more representative of the GPIC baseline energy models. The first model will be referred to as Baseline 1 (Commissioned) and the second model will be referred to as Baseline 2 (Commissioned). The terminology “commissioned” simply denotes that the building has undergone commissioning, which typically includes balancing ductwork and ensuring that the control and sensory network is functioning within acceptable bounds.

2.2.1. Simulation Settings, Sizing, Geography, and Fabric

Since this is a series of simulations based in the GPIC area, the weather profile chosen is for northeast Philadelphia. The heating design day is based on NE Philadelphia’s 99.6% dry-bulb (DB) conditions, and the cooling design day is based on NE Philadelphia’s 0.4% wet-bulb (WB) conditions. The simulation runs on 4 time steps per hour, with a shadow calculation frequency of 5. All other pertinent weather and location data is based on the NE Philadelphia typical meteorological year (TMY) weather file.

The NREL model is scaled length-wise and width-wise by a factor of 1.057 in each direction to preserve the aspect ratio (1.5 length-to-width) and bring the total square footage to 60,000 SF, which is needed for this GPIC study.
The floor to ceiling height of the NREL model is 9 feet, with a floor to deck height of 13 feet. This ratio is preserved, but for the Baseline 1 model, the glazing height is altered from 4.255 feet (~33% glazing area) to 3.250 feet (25% glazing area). For the Baseline 2 model, the glazing height is altered to 7.800 feet (~60% glazing area). Both baseline buildings are assumed to have single pane windows installed. It is assumed that these single pane windows have a u-value of 1.0 Btu/hr-ft²-°F and a solar heat gain coefficient (SHGC) of 0.5, similar to findings by Deru et al. (2011).

According to the available characterization data, the Baseline 1 model has a masonry exterior wall construction meeting ASHRAE 90.1-1989 construction code. This masonry wall is constructed of the following materials (listed from outside layer to inner layer) and is based on the NREL, post-1980 small office building mass wall construction:

- 1 inch of stucco
- 8 inch heavy weight concrete blocks
- R-6 wall insulation
• ½ inch gypsum wall board

The Baseline 2 model has a steel frame exterior wall construction meeting ASHRAE 90.1-1989 construction code. This steel frame wall is constructed of the following materials (listed from outside layer to inner layer):

• Wood siding
• R-9.4 wall insulation
• ½ inch gypsum wall board

For both baseline models, the roofing structure is assumed to be a deck roof with insulation entirely above the deck. Vertically, this structure is metal deck, with insulation above, and decking membrane on top. Baseline 1 has a roof with R-15 insulation, and baseline 2 has a roof with R-15 insulation as well, meeting the minimum code requirements respectively. In order to visualize these buildings, Figure III-3 could be used (please note these are idealized models and do not include visualizations for mechanical systems or real fenestration objects such as doors).

![Figure III-3. Visualization of Baseline 1 (Left) and Baseline 2 (Right)](image)

Since both baseline models are assumed to have identical glazing material specifications, the building loads for Baseline 1 are expected to be less than that of Baseline 2. Baseline 1 is a heavy masonry structure with minimal glazing area, while baseline 2 is a light structure with a large glazing area.

2.2.2. Internal Gains, Exterior Equipment, and Infiltration

For all models, interior gains are important. The gains used to develop the baseline models are presented are discussed in the following section, and presented in Table 5 below.

Table III-1. Baseline Model Internal and External Gains

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population Density</td>
<td>0.005 person/sq ft</td>
<td>(Deru, et al., 2011)</td>
</tr>
<tr>
<td>Ventilation Requirement</td>
<td>26.5 CFM/person</td>
<td>(Deru, et al., 2011)</td>
</tr>
<tr>
<td>Interior Lighting Power Density</td>
<td>1.5 watts/sq ft</td>
<td>(Deru, et al., 2011)</td>
</tr>
<tr>
<td>Interior Small Plug Loads</td>
<td>1.0 watts/sq ft</td>
<td>(Deru, et al., 2011)</td>
</tr>
<tr>
<td>Elevator Power Consumption</td>
<td>32,000 watts</td>
<td>(Deru, et al., 2011)</td>
</tr>
<tr>
<td>Exterior Lighting Consumption</td>
<td>18,000 watts</td>
<td>(Deru, et al., 2011)</td>
</tr>
</tbody>
</table>
The gains specified for this model include gains from people, lights, small plug loads, elevators, and a building domestic water heater. It is assumed that the building has a population density of 0.005 people per square foot (consistent with Deru et al). Ventilation requirements are included in the population density and schedule; each person requiring 26.5 cubic feet per minute (CFM) (Deru, et al., 2011). As far as lighting, it is assumed that the baseline buildings are lit by 90% T8 lighting and 10% incandescent lighting, coming to a lighting power density (LPD) or 1.5 watts per square foot (consistent with Deru et al.). The other internal gains are kept consistent with Deru et al., having small plug loads at 1 watt per square foot, and having two elevators with an overall consumption of 32 kilowatts. Exterior equipment is summarized by exterior lighting. This is a total of 18 kilowatts for exterior lighting, and uses the astronomical clock control option in EnergyPlus. The infiltration is based on Deru et al. as well as Liu et al.; both are based on a previous commercial building study at the National Institute of Standards and Technology (Emmerich & Persily, 2005). Deru et al. reports an infiltration rate of 0.223 CFM/ft$^2$ of exterior wall area, which is consistent with NIST work. For infiltration, it is assumed that when the systems are off, infiltration is at maximum, and when the systems are on, infiltration is at 25% of maximum.

2.2.3. Schedules for Simulation

The schedules used for these simulations are consistent with those by Deru et al. (2010) and Liu et al. (2009), and are demonstrated in Figure III-4 below.

![Figure III-4. Model Schedules (Liu et al., 2009)](image-url)
2.2.4. Mechanical Systems and Definitions

Based on characterization data, Baseline 1 has 3 constant air volume (CAV) air-handling units (AHUs) – one per floor. Each AHU is equipped with a direct expansion (DX) coil, which is connected with an electric cooling source having a COP of 3. Each AHU is also equipped with a hot water heating coil. Each of the fifteen air-conditioned zones has CAV, hot water reheat terminal units with hot water reheat. Hot water is provided by a central, natural gas, hot water boiler with an efficiency of 70% (being decremented below 90.1-1989 code to account for poor management and maintenance). In EnergyPlus, this is modeled using an HVACTemplate object for a unitary system. Due to limitations of this template object, the Baseline 1 mechanical systems have been modeled as 3 unitary systems (one per floor). Each system has a DX cooling coil, as well as a NG furnace for the main heating coil. Each zone has baseboard hot water heating to represent zone reheat mechanisms, serviced by a central boiler having an efficiency of 70%.

Baseline 2 has 3 CAV packaged, rooftop units (RTUs) – one per floor. Each RTU has a main cooling coil supplied by electric cooling of COP 3 and a main heating coil supplied by a natural gas fired furnace with an efficiency of 70% (decremented as in Baseline 1). Similar to Baseline 1, each conditioned zone has a CAV terminal unit. However, these terminal units are equipped with electric resistance heat. It is assumed that the efficiency of these reheat coils is 100%. Again, these systems are modeled in EnergyPlus using a unitary system HVACTemplate object except that the reheat mechanism is electric baseboard heating.

Building sizing determined the following requirements for each of the baseline scenarios per floor (since this is how the systems are implemented). Sizing factors of 1.33 are used.

Figure III-5. Baseline 1 (left) and Baseline 2 (right) CAV System Schematics
Table III-2. Baseline Model System Sizing

<table>
<thead>
<tr>
<th></th>
<th>Baseline 1</th>
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<th>Baseline 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cooling</td>
<td>Heating</td>
<td>Airflow Required</td>
<td>Cooling</td>
</tr>
<tr>
<td></td>
<td>Load (kW)</td>
<td>Load (kW)</td>
<td>(CFM)</td>
<td>Load (kW)</td>
</tr>
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<td>94</td>
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<tr>
<td>Floor 2</td>
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<td>16,250</td>
<td>152</td>
</tr>
<tr>
<td>Floor 3</td>
<td>105</td>
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<td>16,150</td>
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</tr>
<tr>
<td>Total</td>
<td>304</td>
<td>305</td>
<td>46,960</td>
<td>444</td>
</tr>
</tbody>
</table>

2.3. ECMs Upgrades for Baseline Models

After the two baseline models were built, ECM upgrades (and their combinations) were modeled for the baseline models. The ECM upgrades that were implemented for this GPIC study are outlined in the following sections.

2.3.1. Internal Gain ECMs

In real buildings, lighting is often considered as one of the first energy conservation measure upgrades, being characterized as “low-hanging fruit.” For the baseline buildings, lighting is characterized as 90% T-8 fluorescent bulbs with 10% incandescent lighting (having an LPD of 1.5 watts per square foot). Given the lack of characterization data, the luminaire type for this lighting is assumed to be recessed. In ECM upgrades, the cheapest option is simply changing the lamp, not the fixture, and that assumption is used when modeling a lighting upgrade. The first upgrade modeled is changing the lamps to T-5 fluorescent bulbs, and is modeled by decreasing the LPD to 1 watt per square foot. The second upgrade modeled is changing the lamps to LED light tubes. This is modeled by decreasing the LPD to 0.22 watts per square foot, which is not typically achieved by products currently available on the market, but a projected future LPD that could be achieved by 2020 (Dr. Kevin Otto, GPIC contributor). It is expected that as LPD is decreased, annual cooling loads are decreased, while annual heating loads are increased. When a lighting ECM was applied to internal lighting, it was also applied to external lighting (in the same proportion that LPD was reduced).

Another internal gain ECM explored involves upgrading the elevators and their motors. The baseline models feature a two-elevator bank consuming 32 kW. Current products on the market exhibit a 50% energy savings over older elevator banks and their motors (Kone Elevators, 2012). For this reason, high efficiency elevators are modeled by consuming only 16 kW.

2.3.2. Envelope ECMs

The baseline models incorporate single pane glazing in their envelopes. The first envelope ECM modeled is upgrading to double pane glazing. This is modeled simply by altering the baseline model glazing properties (u-value of 1.0 and SHGF of 0.5) from single pane properties (Deru, et
al., 2011) to those of double pane glazing properties (u-value of 0.57 and SHGF of 0.39) as presented in ASHRAE 90.1-2004.

The second envelope ECM modeled is upgrading the roof coating from a standard asphalt coating to a white roof coating. A roof coating does little to insulate a roof as it simply alters the ratio of radiation absorbed by the roof. By default, an asphalt roof membrane has a thermal absorptance ratio of 0.9, a solar absorptance ratio of 0.7, and a visible absorptance ratio of 0.7. A white roof is modeled by reducing all of these absorptance ratios to 0.2 (Walton, 2012).

2.3.3. **Mechanical ECMs**

Mechanical ECMs take one of two forms: an efficiency upgrade, or a system upgrade. For these simulations, low efficiency cooling has a COP of 3, while high efficiency cooling has a COP of 5. Alternatively, low efficiency heating has an annual fuel utilization efficiency (AFUE) of 70%, while high efficiency heating has an AFUE of 95%.

The other form mechanical ECMs take in this GPIC study are system upgrades. The first system upgrade modeled in EnergyPlus takes out the CAV AHUs and terminal boxes, and replaces them with VAV AHUs and terminal reheat boxes. For baseline 1, this is modeled by replacing the unitary HVACTemplate object with the VAV HVACTemplate object. For baseline 2, this is modeled by using the Packaged VAV HVACTemplate. For both, terminal units are replaced to be VAV terminal units.

![Figure III-6.Baseline 1 (left) and Baseline 2 (right) VAV System Schematics](image)

Other mechanical system upgrades include centralizing cooling. Centralized cooling was modeled with a central, electric centrifugal chiller and a cooling tower with a two speed fan. This upgrade was only simulated when either a VAV system or dedicated outdoor air (DOAS) system was present. If a central chiller was modeled, the AHUs were modeled as VAV HVACTemplate objects.
The final mechanical system upgrade was modeled as a DOAS system (where AHUs are sized on outdoor air requirements instead of building load requirements) with passive heating and cooling. The zones were heated by hot water radiators, and cooled by chilled beams. The inputs for models with the DOAS system upgrade are based on the EnergyPlus example file: 5ZoneCoolBeam.idf.

2.3.4. Operation and Maintenance ECMs

One operational ECM is mean to be explored by these simulations: temperature reset. However, currently this ECM is still being explored in terms of inputs required for modeling.

![Figure III-7. VAV/Central Chiller Upgrade (left) and DOAS System (right)](image)

2.4. Preliminary EnergyPlus Models and Results

Again, there are 28 energy models that have been created under the scope of this project. The energy models are tabulated in greater detail in Appendix A.3. Error! Reference source not found. Table III-5 summarizes model construction in terms of envelope architecture and is presented in terms of model run number (reference Table III-3). Table III-6 tabulates some of the internal gains in the models, summarizing infiltration rates, lighting types and lighting power densities. Additionally, the heating and cooling setpoint and setback temperatures (in terms of degrees Celsius) are presented. Finally, the simulated model locations and TMY weather files used are also summarized in Table 0-1. Table 0-2 and Table 0-3 summarize the details of the building mechanical systems. These two tables describe the number and type of building conditioning systems simulated in each model.
Table III-3. Twenty-Eight Model Descriptions

<table>
<thead>
<tr>
<th>Run Description</th>
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</thead>
<tbody>
<tr>
<td>1. Baseline 1 (Commissioned)</td>
</tr>
<tr>
<td>2. Baseline 1 + Temp Reset Strategy</td>
</tr>
<tr>
<td>3. Baseline 1 + T-5 Lighting + Temp Reset Strategy</td>
</tr>
<tr>
<td>4. Baseline 1 + DP Windows + Temp Reset Strategy</td>
</tr>
<tr>
<td>5. Baseline 1 + HE Cooling + HE Boiler + Temp Reset Strategy</td>
</tr>
<tr>
<td>6. Baseline 1 + HE Elevators + T-5 Lighting + DP Windows + Temp Reset Strategy</td>
</tr>
<tr>
<td>7. Baseline 1 + HE Elevators + LED Lighting + DP Windows + Temp Reset Strategy</td>
</tr>
<tr>
<td>8. Baseline 1 + HE Elevators + T-5 Lighting + DP Windows + HE Cooling + HE Boiler + Temp Reset Strategy</td>
</tr>
<tr>
<td>9. Baseline 1 + VAV upgrade + HE Cooling + HE Boiler</td>
</tr>
<tr>
<td>10. Baseline 1 + VAV upgrade + HE Cooling + HE Boiler + HE Elevators + T-5 Lighting + DP Windows</td>
</tr>
<tr>
<td>11. Baseline 1 + Central chiller + HE Boiler + VAV upgrade + HE Elevators + LED Lighting + DP Windows</td>
</tr>
<tr>
<td>12. Baseline 1 + White Roof + Commissioning + Temp Reset Strategy</td>
</tr>
<tr>
<td>13. Baseline 1 + White Roof + Central chiller + HE Boiler + VAV upgrade + HE Elevators + T-5 Lighting + DP Windows</td>
</tr>
<tr>
<td>14. Baseline 1 + Chilled Beams &amp; DOAS + White Roof + Central chiller + HE Boiler + HE Elevators + T-5 Lighting + DP Windows</td>
</tr>
<tr>
<td>15. Baseline 2 (Commissioned)</td>
</tr>
<tr>
<td>16. Baseline 2 + Temp Reset Strategy</td>
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<tr>
<td>17. Baseline 2 + T-5 Lighting + Temp Reset Strategy</td>
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<td>18. Baseline 2 + DP Windows + Temp Reset Strategy</td>
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<td>20. Baseline 2 + HE Elevators + T-5 Lighting + DP Windows + Temp Reset Strategy</td>
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<td>22. Baseline 2 + HE Elevators + T-5 Lighting + DP Windows + HE Cooling + HE Boiler + Temp Reset Strategy</td>
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<td>23. Baseline 2 + VAV upgrade + HE Cooling + HE Boiler</td>
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<td>24. Baseline 2 + VAV upgrade + HE Cooling + HE Boiler + HE Elevators + T-5 Lighting + DP Windows</td>
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<tr>
<td>25. Baseline 2 + Central chiller + HE Boiler + VAV upgrade + HE Elevators + LED Lighting + DP Windows</td>
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<tr>
<td>26. Baseline 2 + White Roof + Commissioning + Temp Reset Strategy</td>
</tr>
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<td>27. Baseline 2 + White Roof + Central chiller + HE Boiler + VAV upgrade + HE Elevators + T-5 Lighting + DP Windows</td>
</tr>
<tr>
<td>28. Baseline 2 + Chilled Beams &amp; DOAS + White Roof + Central chiller + HE Boiler + HE Elevators + T-5 Lighting + DP Windows</td>
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</table>
The preliminary simulation results are presented in Figure III-8 above. Figure III-8 shows the total site energy consumed (in mega-watt hours per year, or MWh/Year) on the x-axis and the model run description on the y-axis. The blue data series summarizes data runs based on the Baseline 1 construction, while the red data series summarizes runs based on the Baseline 2 constructions. The data are presented as the summation of all end-use annual consumptions. These results are tabulated in Table III-4 below in terms of end-use.

Table III-4 summarizes annual energy consumption by end-use (and displays total) in terms of MWh/year. The end-uses for this calculation include: interior lighting, exterior lighting, heating systems, cooling systems, pumps (for heating and cooling systems), fans, elevators, and plug loads.
Table III-4. Energy End-Use by Run (MWh/Year)

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<th>Exterior Lighting</th>
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<th>Heating</th>
<th>Cooling</th>
<th>Pumps</th>
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</table>

3. ALTERATION OF ENERGYPLUS MODELING RESULTS

After review by Drexel, UTC, and other GPIC contributors, the results presented in the previous section did not appear to fully represent some of the buildings found in the GPIC region (in terms of energy end-use profiles and utility consumption). More appropriate results are required for use in the more macroscopic Policy, Market, and Behavior (PMB) model (Otto et
al., 2012). The following sections document the refinement of the original EnergyPlus results, as well as how the refined results were used to extrapolate data across all ECM packages.

### 3.1. Transformation/Alteration of EnergyPlus Results

Most of the transformations applied to the data are based on experience and engineering judgment from Drexel and UTC.

![Figure III-9. Transformed Total Site Energy Consumption By Model Run](image)

The transformed, total energy consumption is depicted in Figure III-9 (similar to Figure III-8). This transformed data is broken down by end-use in Table III-5. The percentage change for the transformed data from the untransformed data is provided in Table III-6. Typically, data are not transformed by more than 20%. One transformation includes taking 10% of heating consumption and defining it as domestic hot water consumption (an end-use not considered in preliminary modeling). Another transformation assumes that if interior lighting is upgraded from T-8 and incandescent to T-5, exterior lighting stays the same.
<table>
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<tr>
<th></th>
<th>Interior Lighting</th>
<th>Exterior Lighting</th>
<th>Hot Water</th>
<th>Heating</th>
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4. GPIC BUILDING ENERGY PROFILES

Constraints for Year One have only allowed for developing the previously defined 28 models. The medium office building stock in the GPIC region would more appropriately be characterized by additional models. Work by the UTC team analyzed the 28 models and modified them to represent another 170 combinations of potential building ECM packages. These cumulative 198 models fed the PMB model, with 99 of the models representing variations...
of the Baseline 1 building, and the other 99 models representing variations of the Baseline 2 building. While the models include some of the ECMs described in earlier sections, other ECMs captured by the 198 models include measures such as heat pumps, ice storage, photovoltaics, smart grid implementation, and even combined heating, and power which were not modeled in EnergyPlus. For some models, the Baseline 1 and Baseline 2 models from previous sections were decremented (representing an uncommissioned or poorly maintained building) effectively creating new, least efficient baseline models for analyses by UTC.

In order to aid the work of UTC in their PMB model, 3 additional models were also created: two models which took Baseline 1 and Baseline 2 and updated them to ASHRAE 90.1-2004 building code, and one model which took Baseline 1 and updated it to match as closely as possible the recommendations made by Liu et al. (2009) to reduce building energy consumption by 50% over the baseline. The results of these three models are presented in the next section.

4.1. Presentation of Annual Energy Use Histogram

Figure III-10 on the next page presents the annual site energy (in terms of MWh per year) for the above described 201 models (99 models representing variations of the Baseline 1 building model, 99 models representing variations of the Baseline 2 building, two models representing the baseline models upgraded to ASHRAE 90.1-2004 code, and one model representing the Baseline 1 building model upgraded according to the recommendations by Liu et al. (2009)). 198 of these models are based on extrapolations and interpolations of the transformed data from the 28 models which are simulated in EnergyPlus. The results for these 198 models are presented in similar fashion to Figure III-8 and Figure III-9 with run identifier on the y-axis, and annual site energy on the x-axis. Two models represent the baseline models which are brought up to ASHRAE 90.1-2004 requirements. The results for these two runs are represented by dashed lines. If Baseline 1 is upgraded to ASHRAE 90.1-2004 requirements, simulations would suggest that energy consumption would be reduced to 940 MWh per year; if Baseline 2 is upgraded to ASHRAE 90.1-2004 requirements, simulations would suggest that energy consumption would be reduced to 970 MWh per year. Finally, one model represents a baseline model which follows the recommendations of Liu et al. (2009) for reducing building energy consumption by 50%. Simulations suggest that energy consumption would be reduced to 660 MWh per year.
Figure III-10. Total Site Energy Consumption for 198 Models
The 198 models are described in Table 0-4 of Appendix A.3. It is important to note that these run identifiers and descriptions are in a different order than the models presented in previous sections. However, models that were presented in earlier sections have been bolded for reference.

### 4.2. Interpretation of Annual Energy Use Histogram

While it is difficult to verify or validate all of the results from the 198 models, the histogram can be used to identify some areas of concern or future work. For example, models 78 – 88 appear to exhibit exorbitant energy consumption compared to the first run, or least efficient model. It would appear that the common factor with these models would be the implementation of combined heating and power (CHP). The purpose of this ECM is to capture the excess heat produced by electricity generation. This would appear to stem from excessive heating consumption of the building compared to other runs, and the modeling approach needs to be revisited by UTC, Drexel, and other GPIC contributors if possible.

### 5. DISCUSSION

Year One work on creating a database of GPIC medium office buildings has delivered some interesting preliminary conclusions, highlighted needs for improvement, and suggested future work (please refer to Appendix A.4 for suggested future work). For example, identifying both the isolated and synergistic effects of ECMs could inform not only policy but also building-level decision-making for the GPIC region. The largest concern for this work is the lack of reliable verification or validation data. Collaboration with GPIC coordinators and the data management team has put actions into place to remediate this deficiency. Drexel has identified key buildings which have the potential to validate not only key model inputs but also energy consumption. Additionally, Drexel continues to research additional methods of verification and validation of model inputs and outputs.

### 6. REFERENCES


CONCLUSIONS

Consistent with the short-term goals of the GPIC Policy, Markets & Behavior Team, the research presented in this report represents a first step toward an integrated understanding of existing public policy, market, and behavioral barriers to integrated energy efficient retrofit projects. The primary findings from each research effort are summarized below.

The occupant behavior interviews revealed that one’s general assessment of comfort is heavily associated with perceived ability to adapt the environment to personal preferences. Taken together, the interview responses begin to paint a holistic picture of behavior in an office environment across the course of a year, revealing a clear difference between the availability and effectiveness of adaptive behavioral actions in the summer vs. the winter and indicating an adaptive hierarchy where actions with greater accessibility/ease and perceived effectiveness are prioritized by occupants. Greater environmental control will not necessarily increase energy costs as 40% of occupants reported being cold in summer and 52% being warm in winter. The interview results also highlight the importance of considering behavioral adaptations when trying to anticipated building-wide energy use, as 40% of occupants used fans and 38% personal heaters, both of which might add unexpected electricity peaks to overall building energy consumption patterns. Moreover, only about 1/3 of occupants indicated that energy use concerns carried any influence over their adaptive actions. Efforts to improve energy-related behaviors in an office through education - which are currently quite rare - are generally viewed quite positively by respondents. However, occupants stress the importance of engaging people up front in person when trying to introduce new efficient technologies and/or practice, and the majority believe some sort of feedback would be necessary to ensure proper use over time. Future work is warranted to quantify the behavior and energy knowledge trends observed here more precisely through formal surveys, in tune with the larger goal of constructing realistic schemes for how occupants actually use and adapt to an office environment in the field.

The semi-structured decision-maker surveys identified key factors influencing energy-efficient retrofit investment decisions. Results indicate that although energy-efficiency in itself is rarely the trigger for a retrofit, it is commonly considered as part of the decision process once a retrofit is underway. While most investments are evaluated using a simple payback metric targeting an average payback period of approximately 4 years, there is a substantial amount of uncertainty among decision-makers regarding the projected cost savings of these investments, particularly for new or non-standard technologies. Rather than analyzing this uncertainty using formal methods, decision-makers typically prefer to see a local example of success to demonstrate the merits of the ECM in question. Results also indicate the need for simpler computer modeling tools for smaller-scale retrofits. Future work will focus on better characterizing the relative weights of these factors and their impact on the overall decision-making process.
Results from the building modeling indicate that there are many potential retrofit options which can help reduce GPIC regional, commercial building energy use by changing its medium office building energy use profile. While the energy models constructed will classify some of medium office buildings within the GPIC region, stronger classification data will provide more accurate energy use profiles. Future work is aimed at expanding the database of energy models constructed, as well as finding strong sources of verification and validation for the energy models that have been constructed.

The results of this research will be used to inform how energy savings and investment decisions are simulated in a regional model of energy efficiency being developed by United Technologies, Inc. By simulating market trajectories under different policies, the model can be used to identify ways to incentivize policy, market, and behavioral changes to create a business environment that supports full-spectrum energy efficient retrofits in the GPIC region.
APPENDIX

A.1 CHAPTER I APPENDIX

A.1.1 Occupant Behavior Interview Protocol

Semi-Structured Interview for Building Occupants
Greater Philadelphia Innovation Cluster (GPIC) Task 4: Policy, Markets, and Behavior

Patrick L. Gurian¹, Jared Langevin¹

¹ Department of Civil, Architectural, and Environmental Engineering, Drexel University, Philadelphia, PA

We would like to talk to you about your level of satisfaction with the working environment and the degree to which you are able to maintain comfort in the workplace through various adaptive measures. Your responses will help to identify key opportunities for improving occupant satisfaction and productivity while reducing overall energy consumption and operating costs in small office buildings.

I. BACKGROUND INFORMATION

1. How long have you worked in this building?

Prompts

1a. If new to this building, is it similar to buildings you have worked in previously?

2. How much time do you spend in the building on a given workday?

Prompts

2a. Full/Part time?
2b. Normal 9-5 work schedule or otherwise?
3. Is the building air-conditioned in the summer? Heated in the winter?

4. Please describe the type of office space that you work in.

Prompts

4a. Private closed office?
4b. Shared closed office?
4c. Open plan office/cubicle?
4d. How many people work within the immediate vicinity (~20 feet) of your area?

II. ENVIRONMENTAL QUALITY, COMFORT, AND ADAPTABILITY ASSESSMENT

1. Please describe your impressions of this office’s interior environment in terms of overall comfort level.

Prompts

1a. When inside, how comfortable are you generally?
1b. Do interior environmental conditions vary noticeably across the day and season or are they generally stable?

2. Please indicate whether you encounter the following sources of discomfort:

Prompts

2a. Thermal discomfort:
   o Too hot?
     ▪ When & how often (i.e. almost every day during the afternoon, only on some really hot days in the summer, etc.)?
     ▪ Actions to reduce this source of discomfort? (Ask if each of the following is possible, if it is used when uncomfortable, and how effective it is when used):
       • Adjust clothing?
       • Open/close window?
• Open/close door?
• Turn on fan?
• Open/close air vents?
• Adjust thermostat?
• Adjust blinds?
• Drink cool fluids?
• Mention to co-worker?
• Report to management?
• How long do you wait before acting? Preference for certain actions before others? Why?
  • Affects workplace productivity?
  o Too cold?
    • When & how often?
    • Actions to reduce this source of discomfort? (Ask if each of the following is possible, if it is used when uncomfortable, and how effective it is when used):
      • Adjust clothing?
      • Open/close window?
      • Open/close door?
      • Turn on personal heater?
      • Open/close air vents?
      • Adjust thermostat?
      • Adjust blinds?
      • Drink warm fluids?
      • Mention to co-worker?
      • Report to management?
      • Do nothing?
      • How long do you wait before acting? Preference for certain actions before others? Why?
    • Affects workplace productivity?
  o On a scale of 0=very cold to 10=very warm where 5=neutral, what temperature sensation do you prefer in the winter?
  o On a scale of 0=very cold to 10=very warm where 5=neutral, what temperature sensation do you prefer in the summer?
2b. Poor perceived air quality:
   o Too humid?
     ▪ When & how often?
     ▪ Actions to reduce this source of discomfort?
       • How long do you wait before acting? Preference for certain actions before others? Why?
     ▪ Affects workplace productivity?
   o Too dry?
     ▪ When & how often?
     ▪ Actions to reduce this source of discomfort?
       • How long do you wait before acting? Preference for certain actions before others? Why?
     ▪ Affects workplace productivity?
   o Too drafty?
     ▪ When & how often?
     ▪ Actions to reduce this source of discomfort?
     ▪ Actions to reduce this source of discomfort?
       • How long do you wait before acting? Preference for certain actions before others? Why?
     ▪ Affects workplace productivity?
   o Too stuffy?
     ▪ When & how often?
     ▪ Actions to reduce this source of discomfort?
       • How long do you wait before acting? Preference for certain actions before others? Why?
     ▪ Affects workplace productivity?
   o Bad odor?
     ▪ When & how often?
     ▪ Actions to reduce this source of discomfort?
       • How long do you wait before acting? Preference for certain actions before others? Why?
     ▪ Affects workplace productivity?

2c. Poor acoustics:
   o Distracted by co-worker conversations?
     ▪ When & how often?
- Actions to reduce this source of discomfort?
  - How long do you wait before acting? Preference for certain actions before others? Why?
- Affects workplace productivity?
  - Distracted by office equipment (printer/copier, HVAC, etc.)?
    - When & how often?
    - Actions to reduce this source of discomfort?
      - How long do you wait before acting? Preference for certain actions before others? Why?
    - Affects workplace productivity?
  - Too much light?
    - When & how often?
    - Actions to reduce this source of discomfort? (Ask if each of the following is possible, if it is used when uncomfortable, and how effective it is when used):
      - Close blinds
      - Turn off/dim lights
      - How long do you wait before acting? Preference for certain actions before others? Why?
    - Affects workplace productivity?
  - Not enough light?
    - When & how often?
    - Actions to reduce this source of discomfort? (Ask if each of the following is possible, if it is used when uncomfortable, and how effective it is when used):
      - Open blinds
      - Turn on overhead lights
      - Turn on desk lamps
      - How long do you wait before acting? Preference for certain actions before others? Why?
    - Affects workplace productivity?
  - Glare from daylight?
    - When & how often?
    - Actions to reduce this source of discomfort?
• How long do you wait before acting? Preference for certain actions before others? Why?
  ▪ Affects workplace productivity?
    o Glare from lighting fixtures?
      ▪ When & how often?
      ▪ Actions to reduce this source of discomfort?
        • How long do you wait before acting? Preference for certain actions before others? Why?
      ▪ Affects workplace productivity?

2e. Poor office layout characteristics:
    o Lack of sufficient space?
    o Lack of visual/acoustic privacy?
    o Lack of cleanliness/organization?
    o Do these layout characteristics affect your workplace productivity?

2f. Do any of the above sources of discomfort tend to occur simultaneously?
2g. Aside from being uncomfortable, is there any other reason that you might take some of the adaptive actions mentioned above?
    o Requests/pressure from others in the building?
    o Personal concerns about energy usage?

3. In general, are you satisfied with your ability to manage discomfort that arises in your workplace environment during the course of the day?

Prompts

3a. If not, what would be the best way(s) for the building management to improve this ability?

III. ENERGY CONSUMPTION

1. Who pays the energy bills in your building?

2. Does the building management ever provide information about energy use to the occupants in your office?
Prompts

2a. If so, how do they provide this information?
   o Seminars/Workshops?
   o Advice and/or feedback about the use of certain environmental controls?
   o Other ways?

2b. If not, are you familiar with this approach to saving energy?

2c. Do you believe that this is an effective and appropriate approach to saving energy?

3. What do you think the best opportunities for energy saving are in this building?

Prompts

3a. Particular areas where you see energy being wasted?
   o Energy-wasteful behaviors?
   o Equipment old/inefficient?

3b. Are there any energy conservation measures that you’ve seen implemented elsewhere that might work well here?

3c. Thoughts on the following measures (prompt if they haven’t already mentioned)?
   o Building audit to determine how much energy the building currently uses/areas for improvement?
     ▪ Already being implemented in your building?
     ▪ If not, are you familiar with this energy saving measure?
     ▪ Do you believe this is an effective and appropriate approach to saving energy
   o HVAC improvements (higher efficiency, capture waste energy, improved BMS, etc.)
     ▪ Already being implemented in your building?
     ▪ If not, are you familiar with this energy saving measure?
     ▪ Do you believe this is an effective and appropriate approach to saving energy?
4. If the building management wanted to reduce the energy consumption of your office by introducing a new technology offering greater occupant control opportunities, what measures should be taken to ensure that the technology can be used most effectively by the occupants?

(Examples: Adaptive office lighting & shading systems with manual override, retrofit radiant heating/cooling system with thermostat control, etc.)

Prompts

4a. Design measures?
o Associated technologies are interactive/intuitive

4b. Educational measures?
   o Building management provides occupants with information about technology operation before installation
   o Interactive games guide usage

4c. Rewards/incentives for effective usage

4d. Other approaches for effective adoption?
A.1.2 Frequency, Priority, and Effectiveness of Adaptive Actions when Too Cold and Too Warm

Figure A.1.1 Frequency, priority, and effectiveness of adaptive actions when TOO COOL
Figure A.1.2 Frequency, priority, and effectiveness of adaptive actions when TOO WARM
A.1.3 Occupant Behavior Literature Review

Architecture for the Human Inhabitant: A Literature Review on Occupant Behavior in the Built Environment

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Introduction

Within the practice of architectural design and engineering, there exists perhaps no more conspicuous conflict than that between traditional engineering paradigms for building design and the needs of those human inhabitants charged with living and working in the environments that are resultant of such approaches. Indeed, while the authors of the engineered interior have traditionally favored a carefully orchestrated degree of homogeneity, predictability, and determinacy in their work, the human occupant introduces a design challenge that is inherently heterogeneous, indeterminate, and “wicked” in the vein of the social policy challenges identified by Rittel and Webber over three decades ago (Rittel and Webber, 1973).

In years past, even a rough consideration of such human design elements was difficult or impractical to include as part of an engineering calculation that could help inform the early stages of a building’s development. Recently, however, the increased introduction of stochastic numerical modeling techniques into the architectural engineering field has allowed the possibility of devising engineering design frameworks that can embrace the uncertainties of the building occupant and position their accommodation as a key tenet of sustainable architecture.

The following paper provides a review of existing literature on the building occupant and his or her behavioral characteristics. The review is divided into two sections. The first outlines what is referred to by the term “occupant behavior” in office-type building environments, surveying its various manifestations, motivations, and effects in terms of metrics like building energy use and thermal comfort. The second details various existing methods that have been developed in the literature for characterizing the potential influences of occupant behavior on building design and operation. Based on this understanding of the current state of the art, the third and final section offers recommendations for future research efforts in this area.

1. Occupant Behavior: Manifestations, Motivations, Effects

1.1 Adaptive Occupant Actions and their Relation to General Building Factors

With respect to buildings, the term “occupant behavior” may refer to any number of opportunities that one has to adapt an environment to their personal needs, but it does not necessarily imply the need for direct environmental modification. Within the existing literature, the following types of direct environmental adaptation have been most commonly surveyed: operation of windows and doors, adjustment of blinds and thermostats, use of fans and personal
heating devices, changing clothing, and ingesting cool or warm fluids. The additional possibility of migrating to different parts of the building across the course of a day has been suggested as an effective way of reducing time-of-exposure to an adverse microclimate, but has not been extensively investigated (Nikolopolou, 2003). Moreover, occupants may indirectly exert influence over their surroundings through providing requests that maintenance personnel make adjustment to certain parameters of the environmental conditioning strategy. As Bordass and Leaman (1994) have reported, responsive management of these maintenance requests can yield as good an outcome for the occupant as that of a direct environmental control opportunity.

Though a discussion of the more fundamental motivations behind human behavior will be left to the next section, it is useful here to identify some general causes of unexpected occupant behaviors that have been identified specifically for the built environment. In a 2009 paper examining the influence of occupant knowledge on comfort expectations and behavior, Brown and Cole (2009) reviewed three general categories of factors that have been suggested in the literature to contribute to behavioral “performance gaps”:

1.) Practical/Design factors
2.) Behavioral/Situational factors
3.) Social/Psychological factors

The first category, which is drawn heavily from the earlier work of Bordass et al (1997; 2001; 2004), includes the factors of operational complexity/simplicity, usability and accessibility of building systems, and the responsiveness of available building and personal controls for the occupants. It relates to the finding that when occupants experience discomfort with their surrounding environment, they will “operate what comes easiest, not what is most desirable technically” (Bordass and Leaman, 1994). Accordingly, the advise to building designers would be to “aim to make the bad difficult and the good easy” (Bordass and Leaman, 1994).

The second category considers an occupant’s level of experience with a certain type of environment, the length of time they have spent in a building, their level of knowledge and information about environmental systems/features, the steadiness of their behavioral adaptations, and the extent to which they overcompensate for unexpected levels of discomfort. The first two of these factors critically influence a person’s expectations of their environment, which have been suggested to be an important psychological determinant of thermal comfort responses in previous studies (Brager and de Dear, 1998). The third factor implicates the degree to which occupants are able to effectively use available environmental controls, while the final two factors are more related to how well an occupant is able to meet perceived needs without resorting to extreme, energy intensive behavioral actions (Brown and Cole, 2009).

The third and final category corresponds in many ways to the second, including the factors of one’s perception and attunement to the surrounding environment, individual sense of responsibility, social (normative) influences, and expectations of building performance, as has been touched upon previously. The first factor is similar to the situational factor of one’s knowledge about environmental systems/features in that it is strongly related to the effectiveness of available controls. Added to this relationship, however, is the caveat that controls be relevant to personal actions and control beliefs, which recalls the “locus of control” theory that has been
used to explain why certain people would want to actively engage with their environment while others are content to be more behaviorally passive (Rotter, 1954). The other factors of an individual’s sense of responsibility and normative influences reflect the degree to which personal attitudes and belief systems can lead to certain actions – a concept which will be reintroduced in the subsequent discussion of psychological behavioral theories.

Taken together, this range of factors implies that behavior in the built environment generally results from an individual’s pursuit of overall perceived comfort, but that the attainment of this comfort depends not only on the adjustment of physical (i.e. environmental) parameters but also on cognitive factors that relate to one’s psychological disposition and perception of their behavioral opportunities. Furthermore, each of these factors may be assigned a varying importance based on the specific kind of building space being studied. For example, Bordass et al (1994) found that available controls may cease to be used in an open-plan office environment because a certain control action might be seen as unfavorable by many of the other people occupying the space. Therefore, the factor of “normative influence” would need to be more heavily considered in this case than in the case where each occupant had their own private office environment with little influence from those working around them.

1.2 Fundamental Theories of Behavioral Motivation

While such general factors behind behavioral “performance gaps” in the built environment are only recently beginning to be defined as above, more robust and fundamental theories for human behavior have long existed in research areas outside of architecture and engineering. Here, following the general approach of Andrews et al (2011), a few widely referenced theories from the fields of economics, psychology, and computer science are reviewed.

a. Economic Theory

The primary example of an economic behavioral model is the Theory of Rational Choice, which has been extensively used to formalize and predict the actions of a collection of microeconomic agents. Under this theory, larger economic (or social) patterns of behavior emerge from choices made by selfish individuals who are interested only in maximizing the personal benefits of their actions while minimizing the personal costs. Assessment of such benefits and costs does not draw from internal factors, but from the encounter of extrinsic rewards and punishments for given behaviors (Scott, 2000). Furthermore, each individual is assumed to have perfect knowledge of what outcomes will ultimately result from the decision they make.

Rational Choice Theory is best applied to economic decision-making, where costs and benefits are easier to define objectively. However, there have been attempts to extend it to other fields. Sociologists, for example, have appropriated rational choice frameworks in their work by considering an exchange of social approval and other valued behaviors as analogous to the exchange of goods and services in economics (Scott, 2000). Such extensions have incorporated considerations from behavioral psychology into the individual rationality model, and acknowledged that certain limits can be imposed on an individual’s level of foresight by subjective social and cognitive influences (Homans, 1961; Blau 1964; Coleman 1973). In general, however, the use of an economic behavioral model is more appropriate when
anticipating the collective behavior of a series of individuals, and less effective in characterizing variations in human behavior on an individual-by-individual basis (where subjective differences come into play), as might be desired in the design of buildings.

b. Psychological Theory

Out of the multitude of behavioral theories within the field of psychology, three general approaches can be identified. The first, the *stimulus-response linkage*, postulates that when some stimulus pattern is observed in the world, an action is immediately performed that can be directly linked to the stimulus properties. A second approach asserts that individuals cognitively construct a set of *preplanned actions* that anticipate the need to produce an intended future state of the world based on information about the current and past states of an environment. A final approach introduces a theory of *control feedback*, whereby behavior is simply the control of one’s perception of external states. Here, the theories of Planned Behavior and Perceptual Control will be summarized as prominent examples of the latter two approaches that could be used to formalize the underlying motivations of occupant behavior in a building environment.

*The Theory of Planned Behavior*

The theory of planned behavior states that: “to the extent that a person has the required opportunities and resources, and intends to perform the behavior, he or she should succeed in doing so” (Ajzen, 1991). Intentions are defined to encapsulate the motivational factors of a behavior - reflecting how hard one is willing to try to perform a certain action - and can be understood in terms of three influencing factors: *behavioral beliefs*, which influence attitudes towards a behavior; *normative beliefs*, which determine the impact of important others’ approval or disapproval; and *control beliefs*, which serve as the basis for one’s perceptions of their behavioral control opportunities (Ajzen, 1991). The addition of perceived behavioral control into the overall behavioral scheme is the primary difference between the Theory of Planned Behavior and the Theory of Reasoned Action, which does not consider the notion that people’s behavior can be influenced by their confidence in the ability to perform it (Ajzen, 1991).

Figure 1 illustrates the causal schematic that is put forth under the Theory of Planned Behavior. As the schematic shows, behavioral outcomes are taken to be a function of the salient beliefs (behavioral, normative, control) that are relevant to that behavior. This suggests that instead of simply reacting directly to environmental stimuli through the magnitude of their actions, people form cognitive predispositions (or “intents”) towards executing particular behavioral options that can prevent the environment from ever reaching certain ranges of stimulus outside of a personal target or goal. To the extent that this predisposition is influenced by behavioral, normative, and control beliefs, it depends largely on one’s past experiences with certain actions and their efficacy, as well as on the
experiences of other friends and acquaintances who live or work in the same environment.

While many empirical studies have shown moderate to strong correlations between one’s surveyed intentions and perceived control levels and their observed behaviors (Ajzen, 1991; Godin & Kok, 1996; Hausenblas et al, 1997), a review by Armitage and Conner (2001) found that in a series of 185 independent published studies, the Theory of Planned Behavior accounted for only about 1/3 of the variance in observed behavior, suggesting that its predictive power is on the whole still somewhat limited.

**Perceptual Control Theory**

Unlike the Theory of Planned Behavior, Perceptual Control Theory (PCT) assumes that people act to get what they want in the face of unpredictable events, and counter the disturbances of the world as they occur, actively and powerfully (Taylor, 1999). Under Perceptual Control Theory, human behavior is considered the by-product of a negative perceptual feedback loop, whereby an organism is continually comparing their perception of some external state to an internal reference perception, and acting in order to reduce any discrepancies between the two. Behavior becomes but a means by which the organism can influence the true state of an external environment - which is unknowable, and thus uncontrollable - such that the error between its perception (by the body’s sensory organs, for example) and the desired reference perception is optimally reduced. Under this theory, therefore, behavior can be defined as the control of perceptions (Powers, 1973).

Figure 2 diagrams the general principle of Perceptual Control Theory. In the scheme, a “reference value” of some internal perceptual signal is established by the outputs of higher-level perceptions – for example, by one’s concept of outward “self-image” (Robertson et al, 1999). This reference value is compared to the current perception of a true external state, which may be continuously disturbed over time. If the error between
this current perception and the desired reference perception is substantial, the organism will act (behave) to influence the external state such that its perception will be stabilized towards the reference signal as much as possible. If the error still remains, this feedback loop will be repeated. Note, however, that the organism may learn from the perceived effects of their actions on the external state and adapt or “reorganize” the structure of their perceptual input function such that the perceived states of the environment would be more likely to correspond with the internal reference after a given behavioral action.

The inclusion of a direct component of learning is one of the major advantages of Perceptual Control Theory, especially in the context of a building where one would likely adapt their perceptions of the interior environment and the actions taken to control it by learning from past behavioral experiences and developing expectations about the efficacy of future interventions. Moreover, the concept of feedback (i.e. adjusting as certain magnitudes of perceptual errors are observed instead of planning ahead to prevent these errors from occurring) is more in line with what has actually been reported of occupant behaviors in buildings: as Bordass et al (1994) note, “People may become quite uncomfortable before they take action. This is partly due to inertia (“Maybe the sun will go in soon.”) and partly due to poor control ergonomics”.

Despite these potential points of alignment with the study and prediction of occupant behavior in the built environment, Perceptual Control Theory has received comparatively less attention in the environmental psychology literature than the Theory of Planned Behavior. Nevertheless, it is increasingly being turned to as a simple, yet powerful tool for behavioral interventions- for example, in the treatment of addictions (see Webb et al, 2010) – and has been heralded for its potentially wide range of application (see, for example, a 1999 Special Issue of the *International Journal of Human-Computer Studies* on Perceptual Control Theory).
c. Computer Science Theory

Within the field of computer science, human behavior has been folded into agent-based frameworks for simulation. In these frameworks, each human is modeled as an autonomous agent that actively interacts with other agents and their environment in a manner ranging from purely reactive (automatic response to stimuli) to intelligently adaptive (based on beliefs, goal setting and learning) (Macal and North, 2005). By definition, an agent can be any independent, self-directed entity that operates based on a given set of personal attributes, behavioral rules, memory/resources, decision-making sophistication, and rules to modify behavior (Macal and North, 2005). Agent-based models have been applied to a wide range of applications, from anticipating stock trading behaviors to modeling the growth and decline of ancient civilizations (Macal and North, 2005).

One example of a widely used agent-based approach that has already worked its way into the prediction of building occupant behavior is the Belief-Desire-Intention (BDI) Model. The BDI framework theorizes that agents are “rational and have certain mental attitudes of belief, desire, and intention, representing, respectively, the informational, motivational, and deliberative states of the agent” (Rao and Georgeff, 1998). BDI is an example of an agent-based model whereby the autonomous agent’s actions are motivated by goal-oriented beliefs and are not simply automatic reactions to certain environmental stimuli. The process proceeds as follows (Andrews, 2011):

1.) The agent’s belief processor converts a set of perceptions about the world into a set of beliefs
2.) The agent’s desire processor evaluates whether possible states of affairs are more or less preferable, given the beliefs and existing preference structures
3.) The agent uses deliberation, planning, and decision-making processors to form intentions that satisfy a certain set of desires, outline a series of plans that would carry out those intentions, and selects and executes one of these plan to form the behavior.

As Zhao et al (2006) outline, the advantages of BDI over other agent models include its maturity as an agent-based paradigm, its easy integration into existing modeling softwares and other agent-based systems, and strong philosophical basis (see Bratman, 1987). However, the BDI model is limited in its lack of explicit mechanisms for considering learning, adaptation, and interactions with other agents in a multi-agent system – all of which would be important in the built environment (Georgeff et al, 1999). Nevertheless, Andrews et al (2011) have utilized a BDI framework to incorporate the concepts of the Theory of Planned Behavior into a predictive model of human behavior. This work will be further discussed in the second part of this report.

1.3 Effects of Occupant Behavior on Comfort/Well-Being, Productivity, and Building Energy Use/Operation

From a design perspective, the use of fundamental knowledge about the motivation underlying occupant behavior must be coupled with information that links the behavior to certain operational benefits and drawbacks. Here, the consequences that have been associated with
Inadequate consideration of occupant behavior during the building design process are reviewed in terms of both occupant variables and variables of building energy use and operation.

a. Effects on Building Occupants

In the case of the occupant variables, poor accommodation of occupant behavior in buildings has shown to associate with reduced comfort, self-rated productivity, and well being in many studies. In general, the failure to provide occupants with a perceived degree of control over their surrounding environment has been implicated as a key reason for these unfavorable outcomes. With respect to occupant comfort, a study of thermal comfort for 511 workstations in 10 office buildings by Paciuk (1989;1990) found that occupants’ thermal satisfaction ratings were positively correlated with the availability and perception of control over thermal features of the work environment, while exercised control was negatively correlated with satisfaction. This result has since been replicated in a number of similar field studies on occupant satisfaction and environmental control (O’Neill, 1994; Huang et al, 2004, Huizenga et al, 2006). Other papers have suggested that the observed improvement in thermal satisfaction ratings through perceived control is due to increased tolerance of wider ranges of thermal conditions when control opportunities (i.e. opportunities for adaptive behavior) are present (Leaman and Bordass 2007; Nikolopolou 2003; Toftum 2000). Furthermore, work by Leaman and Bordass has emphasized that the satisfaction benefits of opportunities for behavioral action are contingent upon available environmental controls being well-maintained and simple enough for users to understand, as has been touched upon earlier (Leaman and Bordass 1993, 2001, Bordass et al 1994).

In another of Leaman and Bordass’s studies of occupant surveys from office buildings, the authors found that occupants’ self-rated productivity related strongly to their thermal satisfaction and that inadequate environmental control could thus be extended as an explanation for occupant productivity reductions in the workplace as well (Leaman and Bordass, 2005). Again, this conclusion is supported widely in the literature. In a separate study by O’Neill (1994), for example, the self-assessed performance of 541 managerial and non-managerial workers in 14 office buildings was compared against the degree to which each work space supported organization of work materials, ease of adjustment of storage and display features, and ease of rearranging furnishings. The results showed that environmental control abilities contributed directly to both performance and satisfaction assessments, and that these control options also mediated distractions, privacy, and communication. Related field studies by O’Neill (1995, 2000) found that environmental control could be further tied to reduced work motivation, increased psychological stress, and poorer health, with the availability of environmental control predicting 50% of the variance in overall health assessments for the general office workers. Such observed effects of environmental control on occupant health had indeed already been established by several reports of increased cases of Sick Building Syndrome (SBS) in buildings where good control opportunities were nonexistent (Hedge, 1989; Jaakkola 1989; Preller et al 1990; Hedge, 1993; Harrison, 1987).

b. Effects on Building Energy Use and Operation

In addition to its reported influences on the occupant variables of comfort, productivity, and general well being, occupant behavior has been widely demonstrated to have quantifiable
impacts on building energy use and operation. In the case of non-residential buildings, the degree of these impacts has mostly been estimated by simulation studies. For example, Clevenger and Haymaker (2002) used simple DOE2 models of typical school buildings in warm and cold climates to identify a rough energy use sensitivity of +65%/-40% when occupant input parameters were varied, with peak energy demand being more sensitive to occupant input variation in cold climates (+25%/-30%) than in warm (+/-20%). Their results also show that variation in equipment loads and ventilation rates were the occupant inputs that had the greatest potential influence on energy use.

Other researchers have developed more detailed methods for estimating the effects of occupant behavior in the simulation of office building energy use. Bourgeois (2006) devised a Sub-Hourly Occupancy Control (SHOCC) model that accounts for occupant use of lighting, sun shading, opening of windows and use of equipment, and includes a stochastic occupant presence predictor. He found that primary energy use predictions could be reduced by about 50% given the realistic treatment of occupant manual control of lighting and shading in the simulation procedure (Bourgeois, 2006). Hoes et al (2009) coupled the Bourgeois SHOCC model and User Simulation of Space Utilization (USSU) model of occupant presence into an ESP-r office simulation, and found that performance indicators such as primary energy use and heating/cooling energy demand were more sensitive to occupant behavior in cases where passive design strategies such as heavy thermal mass and increased glazing were simulated. Finally, Azar and Menassa (2010) ran an e-Quest simulation of a 1000 square foot graduate office in Madison-Wisconsin using “High”, “Medium”, and “Low” Energy consuming categories of occupants, which varied in their use of blinds, lighting/equipment use schedules, and hot water consumption. They found that on average, the simulations showed a 39% difference in electricity consumption between “Low” and “High” consumers and an 11% difference in gas consumption.

Outside of these simulation studies, researchers have reached similar conclusions about occupant behavior’s influence on building energy consumption by running statistical analyses with real energy data, though many have been concerned with residential settings. Most recently, Zhun et al (2010, 2011) used two separate methods to demonstrate the influence of occupant behavior on reported residential energy consumption in Japan. In the first, they employed a decision tree method to establish the number of occupants present in a space as a key factor for distinguishing between high and low Energy Use Intensity (EUI) profiles in low-temperature residential districts of Japan. In the second, they ran a statistical cluster analysis on data from 80 Japanese residential buildings such that the influence of all energy use factors except occupant behavior was removed from the consumption statistics. Their results show that average monthly room temperatures still varied considerably within each cluster and that occupant behavior accordingly carried a significant contribution to this operational outcome.

For office buildings, Steemers and Manchada (2010) monitored the energy use of 12 office buildings in the UK and India and were able to characterize differences in energy readings in terms of the each building’s degree of mechanization and environmental control regime. In particular, their study concluded that increased building energy use did not correlate to higher comfort, and that in fact the greater mechanization and control of air-conditioned buildings in the study actually reduced occupants’ ability to adapt to their environment using personal controls,
which in turn reduced satisfaction in spite of the high level of energy expended. Conversely, in buildings where passive control strategies were given to the occupants, measured energy use was lower. This finding corresponds with Bordass and Leaman’s observations about the effect of poor control opportunities on the operation and management system in place for a given building: when controls are poorly designed and difficult to use, occupants tend either to overcompensate in their use of the controls or voice more complaints to the building management, which puts a strain on both equipment and maintenance personnel, resulting in inefficient and wasteful use of energy for environmental conditioning (Bordass and Leaman, 1994).

2. Accounting for Occupant Behavior in Building Design and Operation: Review of Current Methodologies

Within just the past ten years, several methodologies have been developed for either integrating the effects of occupant behavior into the design/simulation process or backing out its influence through statistical analyses on measured energy data. In general, each of these methodologies can be grouped into one of two categories. The first category focuses the effects of building user presence on building operational outcomes. These methods can be as simple as defining whole building occupancy fractions for given times during the day and week or as complex as tracking individual occupant movements around building spaces using agent-based frameworks. The second category focuses on the effects of particular user behaviors and actions on building operational outcomes. In this set of methods, user actions have been predicted according to certain behavioral theories or otherwise identified for their general energy and environmental effects using existing building data. Here, examples of both types of methodological approach to occupant behavior will be reviewed and assessed in terms of their usefulness and limitations.

2.1 Identifying the Effects of Occupant Presence on Building Operation

The simplest method currently used to account for the effect of occupant presence on building energy operation is an informed modification of the standard occupancy schedules provided by energy-modeling softwares like the U.S. Department of Energy (DOE) program EnergyPlus. In these schedules, a “diversity factor” between 0 and 1 is applied to a pre-defined occupant density based on considerations of time and day. Thus, one standard DOE manual sets up a “weekend” occupancy schedule, whereby the factor is 0 for all 24 hours of the day, and a “weekday” schedule, where the factor is 0 between 10:00 PM and 8:00 AM, 1 between 9:00 AM and 6:00 PM (except for a drop to .8 during lunchtime), and .5, .1, and .1 for 7:00 PM, 8:00 PM, and 9:00 PM, respectively, accounting for people working overtime (Winkelmann et al, 1993). This approach corresponds with the ASHRAE Standard 90.1 specifying typical “weekday”, “Saturday”, and “Sunday” schedules (ASHRAE, 2001).

While systematic methods for adjusting these standard occupancy schedules are somewhat scarce, there have been a few simplified approaches developed in the literature, mostly for retrofit scenarios. For instance, Keith and Krarti (1999) devised a multiple linear regression equation that could predict peak occupancy rate as a function of average occupancy, number of rooms, and other variables that combine those two initial variables. The model was derived from
the readings of 195 occupancy sensors from about 1200 rooms in three buildings in Boulder, CO. Raw sensor data included each room’s status as “occupied” or “unoccupied” at 15-minute intervals for a 12-month period, and average occupancy was computed on a monthly basis for each of the 9 hours of a typical workday. It was argued that predicting peak occupancy rate would help in accurately determining savings from occupancy-sensing lighting controls.

In a study of similar focus, Abushakara and Claridge (2008) tested a set of four different occupant diversity factor options against actually surveyed occupancy profiles for a large campus building. They found that of the four options, an occupancy profile that predicted hourly diversity factors based on measured lighting and equipment load profiles showed results most comparable to the extensive walk through survey of the building. Based on these results, they concluded that walk through surveys were not necessary and that accurate occupant diversity factors could be anticipated by simply consulting measured load profiles of building lighting and equipment. While the study relied on existing building data for the formation its model, it was suggested that the model could still be useful in new construction situations where existing data would not be available. In particular, the authors argued that several options of “typical” building lighting and equipment load profiles collected for an earlier ASHRAE project could be used to predict occupant diversity factors in new building designs that shared similar characteristics to these case study buildings (ASHRAE RP-1093, Abushakra et al, 2001). As Bourgeois et al (2006) note, however, the paper’s model would not accommodate building perimeter situations, where daylighting may alter lighting load profiles independently of the spatial occupancy pattern. Furthermore, both this model and the peak model described above would be inadequate in the case where energy use control strategies are sensitive to short-term variations in occupant number.

Other approaches have used more detailed statistical or agent-based models to monitor and/or predict occupant presence in building spaces over certain time periods. As an example of the former, Dong et al (2010) developed a statistical model that could accurately estimate the true number of occupants in a Pittsburgh office space about 73% of the time based on real-time wireless sensor measurements of CO$_2$ and acoustics. The model assumed that occupant presence followed a stochastic Markov process, whereby the probability of future states of occupancy were only dependent on the current occupancy state and held independence from past states. The occupancy number was assigned as a hidden model parameter that could be determined from information about observed parameters (in this case, the environmental sensor measurements). The predictive capabilities of this “Hidden Markov” model were shown to be comparatively better on a daily and weekly basis than alternative Support Vector Machine and Artificial Neural Network methods tested. While these results may carry implications for more effective building operation with regard to occupancy levels, the paper’s methods are limited to a monitoring application where existing environmental data can be continuously provided.

This limitation would also apply to the previously mentioned study by Zhun et al (2010), where a decision tree analysis on monitored Japanese household energy data was used to tie occupancy scenarios to Energy Use Intensity (EUI) outcomes. As Han (2006) outlines, a decision tree is used to show how the value of a target variable can be predicted using values of a set of predictor variables. Here, the tree was generated by an algorithm that splits a pair of binary target variables (“High” or “Low” EUI) into two categories of a node attribute (i.e. “High” or “Low”
occupancy) based on the concept of information entropy, where an attribute that brings about the greatest reduction in entropy (most information gain) is chosen to split the initial variables. The splitting procedure is continued on each node of the tree until a “pure” node that cannot be split by the other data attributes is reached. For this study, the decision tree algorithm derived a starting node of outdoor temperature, and revealed that an occupant threshold of 2 per household could be used to distinguish between “High” and “Low” EUI outcomes. Such findings would be useful in, for example, prompting increased attention to occupant behavior in the design of Japanese households with more than 2 people. As in the Pittsburgh study, however, the underlying methods require monitored data to make an assessment of the building occupancy variable.

For new building design applications, where existing monitoring data is not available and detailed prediction of building occupancy is needed, agent-based frameworks have recently begun to be employed. As described earlier, agent-based models assume each human building occupant to be an autonomous decision-making entity that acts according to certain programmed behavioral rules. With respect to the movement of humans in space, most existing agent models are used to simulate building evacuation scenarios or for the detection of pedestrian traffic patterns (Gwynne and Kuligowski, 2009; Helbing, 1997). Recently, however, Liao and Barooah (2010) extended an agent-based modeling framework to the simulation of real time occupancy in a typical commercial building environment, based on the data of Page et al (2008). The model consists of deciding which building zone the occupant is located in at every given time step, which here is set to a 15 minute interval. Each agent is assigned a nominal occupancy profile, which initializes the occupant’s state during the simulation using a pseudo-random number generator. Here, the nominal profile can be determined either by long-term survey or sensor data, presumably from a building with similar operational characteristics and estimated occupancy patterns. Furthermore, the agents are each assigned a transition probability parameter, which weights those agents currently in a hallway more towards transitioning to another space than those in other zones, who have been previously observed to tend to stay in place. A situation where an agent is absent from the building (holiday, weekend, etc.) is simulated using a random number generator that draws from pre-defined probabilities of each agent having a long absence and the distribution of that absence’s duration. Finally, each agent is assigned an access profile, which specifies which rooms he/she can occupy, and interacts with other pre-specified rules such as a given zone’s maximum occupancy threshold. The authors validated this model against sensor data for a single person, single zone building case, and have scaled the model to a multi-person, multi-zone scenario, which they are currently in the process of validating. While such agent-based approaches show promise for building design scenarios where typical occupancy patterns might not be easily assumed, they still require some degree of data collection to establish their agent rules, and are furthermore not easily integrated into the existing energy modeling softwares, which could tie modeled variations in occupancy patterns to different operational outcomes of the building.

Each of the various methods reviewed above operates under the notion that improved means for estimating real building occupancy levels can lead to more finely tuned estimations of overall energy use and the efficacy of interventions taken to reduce it. In so doing, however, such analyses reduce “occupant behavior” to the simple existence of an occupant in a space,
considering each human in the words of Newsham (1994) as “fixed metabolic heat generators passively experiencing the indoor environment”. As the earlier review of theories for behavioral motivation have demonstrated, a real occupant in a real building environment would be expected to do much more than just exist, and indeed would be likely to take certain adaptive actions that could each have a considerable impact on building operation. In the following section, recently developed statistical and building simulation methodologies that consider this particular aspect of occupant behavior are reviewed.

2.2 Identifying the Effects of Occupant Adaptive Actions on Building Operation

Of the existing methods that simulate actual occupant behaviors in the built environment, most adhere closely to the aforementioned “stimulus-response” linkage used in psychology, whereby each occupant action is seen as a direct response to a particular “stimulus” in the physical environment, whether that be a change in temperature, lighting, wind speed, etc. Far fewer examples have explicitly employed the second psychological model of cognitive “preplanned action”, and none are known to have employed the third “control feedback” model. Thus, only methods following the “stimulus-response” and “preplanned action” approaches will be discussed here, along with a few other statistical examples that do not lend themselves to these classifications.

a. Using the “Stimulus-Response” Approach to Behavioral Action

For the wide majority of existing efforts to model behavioral action in a building, an action is tied directly to a certain environmental stimulus or set of stimuli that can be seen to be responsible for its occurrence. It should be noted that in general, these models have aimed to predict the probability that the action will have occurred, and thus acknowledge some uncertainty in the stimulus-response linkage that might be seen to account for other factors like personality or social influence. Nevertheless, such factors are never explicitly included in the model structures, and thus their characterization as essentially stimulus-response approaches seems justified.

Among the stimulus-response class of behavioral models, those that account for window opening behavior are among the most widely referenced in the literature. Indeed, in a review of existing window opening models, Borgeson and Brager (2008) note that: “we were quite surprised at how much recent work has been published on the subject…there is a fairly coherent picture shaping up of the various potential control strategies and their proper application.” They go on to list the inputs that have been identified for these models as follows: Indoor Temperature, Wind, Insolation, Façade orientation, Air quality, Noise levels, Occupancy patterns, Current window state, and Social factors. Out of these inputs, indoor temperature appears to be the most commonly considered thus far. For example, a widely referenced study by Rijal et al (2007) used multiple logistic regression analysis on binary window opening data collected from 10 naturally ventilated buildings in the UK to identify indoor operative temperature ($T_{op}$) and outdoor air temperature ($T_{out}$) as key predictors of the probability that a window was open:

$$\log(p/1-p)=0.171T_{out} + 0.166T_{op} -6.4$$

(1)
Using this equation, the so-called “Humphreys algorithm” for window opening operates under the following assumptions:

1.) Each occupant experiences a certain “Comfort Temperature”, $T_{\text{conf}}$, which can be calculated according to European Comfort Standard EN 15251. Around this comfort temperature, there is an assumed comfort zone of $\pm 2$ K, outside of which the occupant is uncomfortable.

2.) When the occupant experiences discomfort, it can be decided whether they will either open or close a window (depending on if they are “hot” or “cold”) by comparing the calculated window opening probability from Equation 1 to a random number from a single throw binomial distribution (see Rijal et al (2007) for further details).

3.) When the occupant is within the comfort zone, no action is taken and the window remains in its previous state.

Given these assumptions, the Humphreys algorithm was implemented in the building simulation program ESP-r, and the results enabled comparison of simulated window opening frequencies with those actually observed when collecting data for the study’s naturally ventilated buildings. The authors reported that simulated window opening trends were consistent with the observed patterns.

Another study by Yun and Steemers (2008) on two naturally ventilated buildings in the UK similarly used probit regression analysis to derive window-opening probability as a function of indoor temperature, but also considered the factors of the previous state of a window opening and time of day effects by deriving separate probability models for the following cases:

Office 1 (without night ventilation):

1.) Arrival at building, window state has some probability of moving from closed to open
2.) Intermittent hours of the day, window state has some probability of moving from closed to open
3.) Intermittent hours of the day, window state has some probability of moving from open to closed
4.) Departure from building, if open, window state always moves from open to closed

Office 2 (with night ventilation):

1.) Arrival at building, window state has some probability of moving from closed to open
2.) Intermittent hours, window state has some probability of moving from open to closed
3.) Departure from the building, if open, window state moves from open to closed

* Note: probability of closing window at departure period was observed to be 100% in Office 1, and windows that were closed during the intermittent period for Office 2 did not get reopened.

The authors argued that this probability framework could be applied in dynamic building simulations to yield more realistic evaluations of building thermal performance. However, their data only applied to the summer season. Similar window opening models for both the cooling

Aside from window opening, the simulation of lighting and window blind use has also received a considerable amount of attention in the occupant behavior simulation literature. Many papers reference an algorithm called Lightswitch2002, which was developed for the National Research Council Canada to predict dynamic occupant response and control of lights/blinds in private perimeter offices (Reinhart, 2004). The algorithm is based on field evidence drawn from previously published surveys and original investigations, as well as from an earlier Lightswitch model that had been developed by Newsham et al (1994). Lightswitch2002 takes an approach to lighting behavior that is similar to many of the window opening models, using workplace illuminance to predict the probability of a light-switching event. As in Yun and Steemers (2008), this probability function is broken into three time periods: arrival, intermittent, and absence (departure from building) (see Figure 3). The probability function is further characterized by information about occupancy profile (is the building occupied, and do the occupants consider daylight in their light switching behavior?) and current blind position, which can be controlled automatically, manually by the occupant, or set as permanently fixed. The algorithm can accommodate multiple occupancy response types, from simple on/off switching to dimming to a situation where occupant-sensing technology is in place.

![Figure 0-3](image)

**Figure 0-3** Lightswitch probability functions from Reinhart et al (2004). Shown here are: a.) The probability of switching on a light at arrival, for both an “active” and “passive” user. b.) The probability of switching on a light during intermittent times of the day. c.) The probability of switching off the lights for different times of user absence for lighting systems without controls, with an occupancy sensor, and for a dimmed, indirect lighting system.

The Lightswitch2002 algorithm has been adapted for integration into the energy simulation program ESP-r by Bourgeois et al (2006), such that estimations of the impact that occupant lighting/blind use might have on various energy end uses might be estimated for a number of behavioral scenarios. Here, the authors note the capability of considering both an “active” occupant, who always switches off lights when daylighting is good, and a “passive” occupant, who leaves blinds closed and relies on constant artificial lighting during the day (as shown in Figure 3a). The idea was to use Lightswitch2002 to quantify the difference between “active” manual blind/light control on the one hand and constant (i.e. “passive”) use on the other. To do this, a Sub-Hourly Occupant Control model (SHOCC) was developed that packages all occupant related events into a single module for integration with existing ESP-r modeling structures. The module exists as a separate entity from the regular ESP-r simulation, and it overrides the program’s existing lighting diversity profile and provides updated occupant, blind and lighting information at each time step. Thus, occupants and their interactions with blinds and lighting can be modeled in a dynamic and stochastic way, which in turn provides the more deterministic boundary conditions (solar, lighting, and occupant heat gains, lighting electricity draw) that are
required for every ESP-r simulation time step. Use of this SHOCC approach has turned up some significant findings: when implementing the SHOCC/ESP-r model in the simulation of a standard office in Quebec, Canada (heating dominant) and Rome, Italy (cooling dominant), the authors found that manual versus constant lighting control reduced lighting consumption by 79% in Rome and 77% in Quebec, as well as reducing cooling loads by 42% and 57% and primary energy loads by 60% and 43%, respectively. As was mentioned earlier, other studies such as that by Hoes et al (2009) have also used the SHOCC model to successfully illustrate sensitivity of energy end uses to occupant lighting and blind behavior for different kinds of building designs.

The stimulus-response set of occupant behavioral models carries clear advantages over traditional means of considering the building occupant as part of the design simulation process. Rather than adopt the limited conception of an occupant’s mere presence as representative of their “behavior”, these models realistically consider the fact that occupants will indeed take adaptive actions in the built environment, which in this case can be predicted probabilistically in terms of a given set of environmental stimuli. Moreover, it has been shown that the probability models developed from this set of studies can be integrated into existing energy simulation software to quantify the impact that certain occupant behaviors will have on operational outcomes like energy use or comfort provision.

Nevertheless, the applicability of such behavioral models may be limited by the nature of the data that was used to inform their probability equations. For example, in simulating a mixed-mode building, where the occupants are exposed to both natural ventilation and climate control systems, the use of a window opening algorithm derived exclusively from naturally ventilated buildings may not be warranted. Furthermore, the notion that each occupant’s expected actions can be predicted solely in terms of environmental stimuli, while simpler to implement, does not address the issue that a group of occupants may differ widely in their belief systems and susceptibility to the influence of others, which could both influence the probability that they take behavioral action independently of an environmental stimulus. A few studies have taken these aspects of occupant behavior into more direct consideration in their predictive models, and will be reviewed in the following section.

b. Using the “Cognitive” Approach to Behavioral Action

The most directly “cognitive” approach to behavioral action in the current literature can be found in Andrews et al (2011) with regard to occupant use of artificial lighting. Here, the authors integrated the Theory of Planned Behavior (TPB) into an agent-based Belief-Desire-Intention (BDI) modeling framework. Under this approach, a building occupant perceives their indoor environment, develops preferences, deliberates and chooses a desired outcome and action, and subsequently implements it. Each of these steps constitutes an individual processor within the agent-based framework. The particular priorities of each occupant are represented by a utility function that is used to drive the deliberation processor towards a desired lighting outcome (make darker, lighter, or no change) and ultimately a decision about how to act. The utility function reflects the nature of each occupant’s belief system including control, normative and behavior beliefs, as is specified in the Theory of Planned Behavior. It was defined in the paper as follows:
Occupant Utility = f (lack of benefits to self, lack of benefits to others, costs to self, costs to others)

Each of these four inputs was operationalized using the following system:

1.) Lack of benefits to self is defined in terms of % of time desired lighting service is unavailable
2.) Lack of benefits to others and costs to others are both defined in terms of lighting energy use
3.) Costs to self are defined in terms of effort (number of times lighting controls need to be adjusted), discomfort (% difference between actual and desired performance), and utility bill.

Depending on a given person’s system of beliefs and preferences, each input will carry a different weight within the utility function. Four classes of belief structure were outlined based on certain “universal” value sets defined by social psychologists:

1.) Environmental activist
2.) Good citizen
3.) Healthy Consumer
4.) Conventional Consumer

To ascertain the distribution of these value sets within a real group of occupants, the authors surveyed an office building in New Brunswick, NJ using a short form values instrument that had been developed earlier by Schwartz (2007). Utility functions and weights for each of the four occupant types were defined based on the survey results. Furthermore, a lighting satisfaction survey was administered to determine a “normal” range of illuminance comfort across all occupants. From this information, a human agency simulation model was constructed that could support up to ten different occupant types (occupants were taken to vary by light sensitivity and location within building in addition to their utility function weights). This simulation model was then fed into a RADIANCE lighting design simulation. The RADIANCE tool established an initial environmental condition based on building features and the weather, which could then be altered to a subsequent environmental state based on information from the agency simulation about how occupants would be predicted to act given that initial set of conditions. This process was repeated over the course of a 24-hour period using half of the building occupants as the source of model calibration data and the remaining half for model validation. Results indicate reasonable

<table>
<thead>
<tr>
<th>Case/Attributes</th>
<th>Calibration case (100 runs)</th>
<th>Validation case (100 runs)</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average daily effectiveness (% of time light levels meet targets)</td>
<td>1.22</td>
<td>1.37</td>
<td>11.9%</td>
</tr>
<tr>
<td>Average daily occupant dissatisfaction (0 = satisfied, 1 = dissatisfied)</td>
<td>0.83</td>
<td>0.81</td>
<td>-2.7%*</td>
</tr>
<tr>
<td>Average daily electricity cost per occupant ($)</td>
<td>0.205</td>
<td>0.201</td>
<td>-1.6%*</td>
</tr>
<tr>
<td>Average daily electricity use per occupant (kWh)</td>
<td>2.18</td>
<td>2.14</td>
<td>-1.6%*</td>
</tr>
<tr>
<td>Average daily effort per occupant (# actions)</td>
<td>8.3</td>
<td>7.6</td>
<td>-7.9%*</td>
</tr>
<tr>
<td>Average daily discomfort per occupant (% of time light is too dark or bright)</td>
<td>14.0</td>
<td>13.7</td>
<td>-2.1%*</td>
</tr>
</tbody>
</table>

* Difference between means is significant at the 95% confidence level.

Figure 0-4 Comparing results from the Andrews et al (2011) calibration and validation building simulations.
agreement between the calibrated and validated model runs, and provide estimates of operational outcomes like average daily lighting effectiveness, occupant lighting dissatisfaction, effort per occupant (# of actions), and electricity cost and use per occupant (Figure 4).

The above framework is interesting for its integration of a cognitive behavioral theory into the building simulation routine, but it fails to consider the reality that occupants would learn from their surroundings and accordingly adapt certain behavioral responses over time. Indeed, in this particular agent-based model, each agent is programmed with a certain pre-disposition for action that cannot be automatically updated as time goes on and experience in the building grows. Other agent-based modeling approaches have done more to include a learning component. For example, Azar and Menassa (2010) have developed a simulation routine for a 10 person office in Wisconsin whereby each occupant was characterized as a “High”, “Medium”, or “Low” energy consumer and could convert other building occupants to their consumption pattern through “word of mouth” effect. Here, a “Low Energy Consumer” was taken to have the greatest chance of converting another occupant while a “Medium Energy Consumer” was taken to have the least chance of doing so. So, for example, a “High” consumer was programmed with a 5% probability of converting someone else to his or her consumption pattern per month, while a “Medium” consumer had only a 1.25% chance. By running the agent-based model over the course of several months and coupling the results with an eQuest simulation of daily energy use per consumer type, the authors demonstrated that significant changes in annual energy use patterns (up to 20% from conventionally run simulation) would result from the consideration of these occupant-learning interactions.

c. Other Approaches to Behavioral Action

In addition to the “stimulus-response” and “cognitive” classes of behavioral simulation methodologies, there are a few other statistical approaches in the literature that do not necessarily fit into these classifications. The methodology of Zhun et al (2011), for example, has already been introduced in the first part of this paper. This method does not seek to simulate or predict occupant behavior, but rather to back it out from existing Japanese housing data using a statistical clustering technique. The clustering technique applied a K-means algorithm along with grey relational grades (see paper for details) to identify groups of houses in the data that are most similar in terms of all the characteristics not related to occupant behavior. These characteristics included climate, design features, occupancy number, and building systems and their operation. The resultant clusters of houses could be studied for their monitored energy-end uses and room temperatures, and variations between houses in each cluster could be attributed only to the influence of occupant behavior. An example of the room temperature variation within one cluster is shown in Figure 5. While this approach is not a predictive one, it could nonetheless be used to provide valuable insights to designers about the nature of occupant behavior effects for a given type of building environment (in this case, Japanese housing).
Another statistical approach for use in predictive building simulations is given in Pfafferot and Herkel (2007). In this study, the authors used data about window and door opening frequency in 16 German offices to implement a Monte Carlo simulation of occupant behavior in the energy program ESP-r. For a period of four months, the frequency of window and door opening (i.e. % of windows or doors opened) were recorded for each hour of the day in each of the 16 offices. This data was used to construct an opening frequency distribution for both the windows and doors in each office that could be used in the Monte Carlo procedure. Distributions for occupant heat gains (representing occupant presence) and solar heat gains (representing occupant blind use) were also constructed in this manner. In the Monte Carlo procedure, a random, normal sample would be drawn from the provided mean and standard deviation of each distribution, and used to run a series of building simulation cases (typically 1000) for each office and hourly time step, such that a full range of possible operational outcomes would be yielded due to the stochastic nature of the occupant behavior and presence inputs. Like each of the other behavioral models reviewed, this method’s validity is limited by the richness of its data, especially since here the data only encompassed four months of building operation. However, the authors’ use of a Monte Carlo procedure to capture occupant uncertainties shows promise for future research efforts in this area.

3. Looking Ahead: Recommendations for Future Studies of the Building Occupant

This report has presented a review of the current understanding of occupant behavior within the building design and simulation literature. Going forward, efforts to build upon this existing foundation will depend heavily on the quality of available occupant data that is collected in the field. Accordingly, the following recommendations are offered:

1.) Conduct both transverse and longitudinal surveys. While most of the existing databases (including the ASHRAE RP 884 data) only include point-in-time measurements of a given occupant variable across different seasons, these cross-sectional surveys might miss variations in occupant responses that could be better captured by longitudinal surveys that are carried out at regular intervals across the year. This was shown, for example, in the work by Rijal et al (2007) to develop the Humphrey’s algorithm, where transverse and longitudinal survey data turned up very different regression equations for window opening probability, and the authors concluded that the longitudinal regression held more predictive power. Longitudinal surveys are more difficult to implement and may require more advanced statistical methods of analysis, but would be likely to
provide useful information about temporal occupant-related phenomena at even a weekly or monthly resolution.

2.) Where possible, include direct measures of building operation alongside concurrent sets of occupant survey responses. It is rare in the existing literature that time-resolved occupant responses can be directly linked with real time measurements of building operation, such as indoor environmental conditions and energy use. Of the reviewed articles, the closest that come to this are the many efforts to monitor real time window opening behavior in terms of concurrent measurements of the indoor environment. While this lack of comprehensive occupant-operation data collection efforts is probably due their high cost in time, effort, and money, recent advances in the use of cheap wireless sensing networks and web-based surveying methods may eliminate these difficulties to some degree. In any case, the implementation of standard occupant surveys such as that used in many of the ASHRAE RP-884 subsets might be feasible as a part of a building commissioning procedure, which is increasingly being desired by property owners as a check for discrepancies between design intents and operational realities.

3.) Survey the actual behavioral actions of occupants as well as their possible motivations. While many of the available survey datasets include questions about the availability of environmental control options and the frequency of their use, it is often difficult to make firm conclusions about why certain actions are observed more than others, which often leads to quite general design recommendations such as “make controls effective” or “ensure controls can be easily accessed”. Future surveys might uncover more about the specific motivations behind behavior using unconventional response collection and data analysis techniques. For example, it was mentioned that the Berkeley IEQ Survey included an automatic open-ended prompt for occupants who indicated discomfort with a given environmental condition, which requested that these occupants describe more about why they felt uncomfortable. A selection of such text-based responses was subsequently analyzed using text-mining software and provided some valuable operational insights as reported in Moezzi and Goins (2011). Such a surveying approach, as well as surveying approaches that draw more heavily from relevant efforts in other fields (as in the cognitive values survey used by Andrews et al. (2011)) could prove very useful in future efforts to develop fundamental models of occupant behavior in buildings.

Given the increasing evidence that such priorities are already being worked into ongoing survey efforts, the possibility of developing robust occupant satisfaction and behavior distributions for use in the building design process is looking very bright. Nevertheless, systematic efforts to link the dynamic building occupant to operational outcomes are still in a nascent stage within the architectural design and engineering fields. As such, this report can be used as a reference for establishing the range of existing approaches towards occupant behavior in the built environment, surveying the relative advantages and disadvantages of each, and planning the future directions that will have the best chance of supporting buildings that dynamically engage the needs of their human inhabitants while drawing minimally from natural resources.
References


Frontczak, Monika, Schiavon, Stefano, Goins, John, Arens, Edward, Zhang, Hui, Wargocki, Pawel. 2011. Quantitative relationships between occupant satisfaction and aspects of indoor environmental quality and building design. Accepted for presentation at *Indoor Air 2011, Austin, TX*.


Semi-Structured Interview for Decision Makers
Greater Philadelphia Innovation Cluster (GPIC) Task 4: Policy, Markets, and Behavior

We would like to talk to you about decision making for retrofits for small commercial buildings. We are particularly interested in buildings that are less than 100,000 square feet.

5. What triggers the decision to retrofit a small commercial building?

Prompts

Owner/Tenant Needs
Architectural Considerations
- Programming (spatial adjustments to better support primary activities)
- Aesthetics
- Draw in more customers
- Other
  - Structural/material improvements
Occupant Variables
- Improved Comfort
  - Thermal only or are there other variables of concern for comfort?
- Improved Productivity
- Improved Health/Well-Being
Energy Efficiency
- What generally prompts the desire to be energy efficient?
  - Longer term financial goals (i.e. energy savings, payback)
  - Improved company image ("green" conscious, innovative, etc.)
  - Tax breaks/local, state, and federal incentives?
  - High energy costs?
  - Personal sense of environmental responsibility?
  - Increased asset value of property?
Facility Maintenance
  o Mandatory upgrade to prevent failure?

Code Requirements
  o Which entity’s requirements? Federal government? State government?

6. **Currently, what potential barriers must be considered as a part of this decision?**

*Prompts*

Initial costs and/or projected maintenance costs?
Capital available / allocated for work?
Loss of operating revenue?
  o Displacement of workers
  o Suspension of services (if large retrofit)
Legal barriers (i.e. zoning requirements, building codes, etc.)?
Lack of knowledge about/familiarity with retrofit process?
Design challenges?
  o Building size & complexity
  o Communication between client and architect
  o Keeping design decisions under budget
  o Community feedback
Uncertainty about outcomes?
Timing of retrofit process?

7. **Once the building retrofit process is underway, what specific efficiency measures are targeted?**

*Prompts*

Building Energy Sources
  o Solar
    ▪ PV
    ▪ Solar Hot Water
Ground source heat pump
- Combined Heat & Power
- Wind

Building Orientation & Massing

Building Envelope
- Glazing
- Envelope material and detailing
  - Insulation type
- Shading
- Shape & porosity

Building Environmental Conditioning Systems
- Active HVAC systems
  - Choice of system type
  - Equipment efficiency
- Passive systems
  - Solar gains/thermal mass
  - Natural ventilation
  - Occupant considerations (i.e. improved perceived control)

Building Lighting, Appliances, Plug Loads
- Lighting
  - LED vs. lower efficiency lighting
- Other major appliance improvements?

Interior design
- Colors/textures
- Furniture/office accessories
- Spatial layout (esp. in open plan offices)

Energy demand/pricing
- Demand-response
- Determining how tenants will be charged

Do you see certain of these retrofit opportunities being pursued more heavily in current commercial projects than others? If so, why?

8. Who is most responsible for making each of these key design decisions?
9. **What factors go into the decision to adopt a new or non-standard technology for a building retrofit? (please specify what technology this would be)**

*Prompts*

- Owner
- Architect
- Engineer
- General Contractor
- Tenant
- Code/Zoning
- Energy Services Company

- Do there need to be local examples of success?
  - Willing to invest in an unproven, higher risk technology if the benefits are potentially greater than for alternative, safer options?
- Vendor recommendation?
- Does technical literature matter?
- Energy models or cost calculators?
  - Anticipated payback/Net Present Value?
- What about vendor or Energy Service company performance guarantees?
- Are the “image” implications of adopting novel technologies over more traditional ones considered?

10. **How is the performance of these new technologies estimated? (prior to installation)**

*Prompts*

- Vendor claims/guarantees
- Engineer/architect experience
- General contractor estimates
- Owner experience
- Technical literature information/Previous case studies (describe source)
11. **What metrics are used in decision making about energy efficiency upgrades?**

*Prompts*

- First Cost
- Net Present Value
- Payback period (simple or discounted)
- Benefit cost ratio
- Internal rate of return/return on invested capital
- Increased asset value / rent

Non-financial metrics, such as LEED rating, IEQ, increased productivity.

12. **What values of these metrics must be achieved? Over what time period at what interest rate?**

13. **What are the primary sources of uncertainty to consider when making decisions about a retrofit building design?**

*Prompts*

Operational uncertainties
- Projected monthly/annual energy savings
- System/equipment maintenance and life span
- Occupant variables
  - Uncertainty in comfort/productivity/health outcomes?

Cost-benefit analysis uncertainties
- Length of estimated payback period (can it be guaranteed?)
- Interest rate
- Energy costs
- Costs to society (included or not?)
o Regulatory risk / policy uncertainties regarding long-term availability of government incentives

Structural uncertainties?
o Right financial/energy model choices?

Value uncertainties?
o What bounds do you put on the analysis? (i.e., are externalities considered, etc.)

Other assumptions?

10. **How are these uncertainties normally considered in the decision making process?**

*Prompts*

Bounded sensitivity analysis (explore a range of different assumptions or input values?)

Monte Carlo (repeated simulation of outcome based on uncertainties in parameters?)

Are there ways to establish particular values/ranges of inputs for use in these analyses?

o Examples of values/distributions you might typically use for these analyses?
  ▪ Example: Energy costs (what source is used to project into future?)

11. **Do decision makers view energy efficiency as a way to protect against energy cost volatility and/or other uncertainties that can adversely affect the expense and effectiveness of building operation?**

*Prompts*

Why or why not?
Is so, how is this factor incorporated in decision making?
Formally with risk-metrics or informally?
A.3 CHAPTER III FIRST APPENDIX

The following tables summarize various inputs for the construction of the preliminary 28 energy models.

Table 0-1. Model Internal Gain Inputs

<table>
<thead>
<tr>
<th>Construction (From Outside to Within)</th>
<th>White Roof</th>
<th>Glaze Area</th>
<th>Glaze U-value</th>
<th>Glaze SHGF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1” Stucco 8” CMU R-6 Insul 1/2” Gyp</td>
<td>No</td>
<td>25%</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>1” Stucco 8” CMU R-6 Insul 1/2” Gyp</td>
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The following table summarizes the run number and description for the 198 models. Please remember that the run number refers to two models: the ECM package which has been applied to baseline 1 and baseline 2.

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<td>PV + Smart Grid + Chilled Beams &amp; DOAS + White Roof + Central chiller + HE Boiler + HE Elevators + Lighting Improvement + DP Windows</td>
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<td>PV + Smart Grid + White Roof + GSHP COP 6 + VAV upgrade + HE Elevators + Lighting Improvement + DP Windows</td>
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A.4 CHAPTER III SECOND APPENDIX

Chapter III describes the methodology used to produce the first round of results for use in the forecasting model. However, since creating this model dataset, new information has been gathered for subsequent rounds of model building to develop more accurate GPIC models. The information presented in the following sections represents updated model inputs which represent the collection of better characterization data.

A.4.1 Simulation Settings, Sizing, Geography, and Fabric

According to critique from GPIC peers, the baseline fabrics might more accurately be described with baseline 1 model having a masonry exterior wall construction meeting ASHRAE 90.1-1989 construction code. This masonry wall is constructed of the following materials (listed from outside layer to inner layer):

- 4 inch common brick
- 8 inch heavy weight concrete blocks
- R-6 wall insulation
- ½ inch gypsum wall board

The baseline 2 model has a steel frame exterior wall construction meeting ASHRAE 90.1-1999 construction code. This steel frame wall is constructed of the following materials (listed from outside layer to inner layer):

- 1 inch of stucco
- R-13 wall insulation between 24 inch o.c. steel studs (discounted to R-7.2)
- ½ inch gypsum wall board

Additionally, the glazing area for baseline 1 is reduced from 25% to 20% (Otto et al., 2012).

A.4.2 Internal Gains, Exterior Equipment, and Infiltration

Liu et al. would suggest that the infiltration rate used in the preliminary GPIC study is not adjusted for wind pressures, and suggests that 0.202 CFM/ft$^2$ to take into account a wind-driven design infiltration rate for EnergyPlus.

A.4.3 Mechanical Systems and Definitions

Originally, default or autoset values for design airflow rate were used. However, this is likely not a correct approach. The design airflow rate translates to a required supply air fan motor efficiency which operates at 1800 RPM. For flow rates less than 20,000 CFM, motor power cannot exceed 1.2 HP/1,000 CFM for constant volume fans (for variable fans this is 1.7 HP/1,000 CFM). For flow rates equal to or greater than 20,000 CFM, motor power cannot exceed 1.1 HP/1,000 for constant volume fans (for variable fans this is 1.5 HP/1,000 CFM).

The design supply air pressure drop can be calculated based on break horsepower, fan efficiency, and design CFM (Liu, Thornton, Wang, Lane, & Rosenberg, 2009), where:

121
Design supply pressure (inH₂O) = (brake horsepower x fan efficiency x 6356)/CFM

In this equation, brake horsepower is 90% of the supply air fan motor efficiency. Fan efficiency is estimated at 65% based on 90.1 committee assumptions when developing the standard (Liu, Thornton, Wang, Lane, & Rosenberg, 2009). For all motors, the efficiency requirement is 91%. Baseline 1 systems all fall below the 20,000 CFM threshold for design supply pressure. Therefore the design supply air pressure is 4.46 inH₂O (6.32 inH₂O for VAV upgrade). Alternatively, the baseline 2 systems are all above the threshold, therefore the design supply air pressure is 4.09 inH₂O (5.58 inH₂O for VAV upgrade).