Understanding Behavior Potential: the Role of Building Interfaces

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ABSTRACT

There is a great deal of interest in behavior-based energy savings in both the residential and commercial building sectors. However, the critical role of the interface of building systems with occupants has largely been ignored. Logically, behavioral based savings can only occur when occupants make a decision that impacts building operation or loads. These decisions occur at building-user interfaces. Thermostats and plug loads constitute obvious interfaces. However, there are also many other interfaces where occupants can have either a positive or negative impact on energy use, such as: operable windows, hot water use, light switches, and even stairs versus elevators. Together, all these types of interfaces create the behavioral-potential profile of a given building.

This paper presents a schema to catalog building interfaces and three corresponding key characteristics: (1) normative usage patterns, (2) the up-side potential to save energy via optimal operation, and (3) the down-side potential to squander energy. Within any given type of interface, different technology choices, interface design, control options, and/or behavioral intervention strategies may change one, two, or all three of these values. Similar to the DEER database, such a schema has the potential to rationalize investment in both interfaces and behavioral strategies, prioritizing those that can be shown to have the largest potential impact across building populations. These metrics will help to identify missing information and to clarify the bounds and precision of estimates of savings.

Introduction

In the past decade, there has been much interest in behavior-based energy savings programs in both the residential and commercial[1] building sectors. These behavior change programs are largely based upon employing social-psychological strategies to motivate and change individual and group behaviors. The development of these programs has primarily focused on cultural and subjective norms, attitudes, and perceived behavioral control (among others). Each of these interventions are important elements of behavior change programs. Current behavior-based energy efficiency (B-EE) programs address these human dimensions of behavioral savings through feedback, messaging, motivations, competition, etc., which are all necessary steps. <u>However, such social interventions will only work to the extent that the building interface allows occupants to take an action.</u>

To address this problem, first, it is crucial to understand what the occupants *can* do based on the building interface types and/or availability. Second, once the interface is identified, then it is possible to determine what occupants *should* do to maximize energy savings, and, third, *how to motivate* them to take the appropriate actions. Oftentimes, this first step of identifying what occupants can actually control is missing in current programs. This critical interface between building systems and occupants has largely been ignored. To understand the potential for B-EE

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[1] In this paper, the term ‘commercial buildings’ encompasses all non-residential building types.

in buildings, it is necessary to first understand what behaviors are possible, and to then observe what people actually do. This means that a better understanding of interfaces is needed. To our knowledge, a full list of building interfaces has never been compiled and studied in a systematic fashion.

The primary objective of this paper is to understand, in this system (of occupants, building interfaces, devices and building types), how much variance is there in the potential for energy use? How much of that is a function of the interface type? Can we understand how each of these four things—the occupant, interface, device, and building type—affect the behavioral potential for upside and downside of energy use?

Current Behavior-based Programs and Savings Estimates

Many residential behavior-based programs typically claim 1-2% savings (DNV GL, 2014), and some programs have seen up to 10% savings (Ehrhardt-Martinez, Donnelly & Laitner, 2010); this may seem trivial, but B-EE efforts can amount to significant overall kWh savings, especially when multiplied across millions of potential households. Recent B-EE efforts have primarily focused on how to increase savings through better targeting and messaging.

For example, the Seattle City Light Conservation Resources Division teamed up with OPower to launch the Home Electricity Report (HER) Program, and in 2013, the program realized close to 3.5% savings from norm-based messages, providing energy efficiency (EE) tips and/or offers to residential customers (DNV GL, 2014). These savings are impressive, compared to the 1 or 2% savings from previous years, but perhaps too good to be true as evidenced below.

Smith and Morris (2014) conducted home inventories and oral interviews (*N*=702) in treatment and control households to compare utility rebate redemptions and associated savings of the HER program in PG&E territory. The authors found that, on average, the treated home inventories had one more CFL in use than the control households. This essentially means that the "extra CFL" observed in treatment households was accounting for "approximately 24% (21.7 GWh) of the total electric savings (89.2 GWh) estimated for 2013." In other words, the program was claiming a certain percentage of savings, but nearly one quarter of those savings were actually attributed to existing programs (e.g. lighting efficiency upgrade programs, or just more people signing up for programs in the first place). Overall, these reported residential savings are relatively small, and actual reported savings may not really all be attributable to behavioral measures (Smith & Morris, 2014). It is still unclear exactly what people are doing to achieve these savings. Almost all of reported savings are estimated from utility bills and / or self-reported surveys, but rarely if ever, have these actual behavior changes been observed. In addition, how are people changing their behaviors, exactly? And, are the savings claimed even related to behavior change?

Another study of 1,446 commercial buildings, found that the largest source of year-to-year changes in building energy use were not from weather or efficiency upgrades, but from changes in building operations and occupant behaviors (oftentimes unobservable to evaluators). The study also found that the yearly variance and baseline errors were far greater in some building types, such as offices and warehouses, compared to others with much lower variance, such as restaurant/bars (Bode et al., 2014). This top-down approach holistic approach is both novel and useful in understanding variability in savings and behavioral potential. The annual variance in whole building energy use found across a large population of buildings may usefully describe the expected upper and lower bounds of B-EE. Alternatively, the authors of this paper propose a bottom-up method, based on aggregating the attributes of system types and their interfaces. Combined, these top-down and bottom-up approaches would provide a full assessment of B-EE potential.

Case Study Examples

There are a few buildings that have successfully blended function (EE & building systems), form (building design & interfaces), and behavioral nudges to encourage occupants to maximize energy saving goals. Such thoughtful building designs and interfaces can help motivate interactive occupant behaviors and engagement with building systems.

For example, the design of the Bullitt Center Building in Seattle, WA directly encourages higher behavioral energy-savings potential. By focusing on occupant or tenant related savings, the Bullitt Center has been able to reduce the overall building EUI (energy use intensity, measured in kBtu/SF/year) from 32 to 16, i.e. a 50% reduction. The team understood that the building's users would play a crucial role in reaching the aggressive energy goals, so they intentionally set up the building to encourage the best default behavior (ULI, 2015). For example, one of the occupant energy reduction strategies is to discourage elevator use through a staircase that is fondly referred to as the "Irresistible Staircase." Other tenant-focused strategies include daytime office cleaning, reduction of phantom loads, adjustments of heating and cooling setpoints via use of radiant sources, and 80% laptop / 20% desktop computers. These are novel occupant strategies, but it is possible that even more B-EE savings could be captured through more "interface" design moves such as the irresistible stairs (see figure 1A and 1B).

A second building that has successfully designed for the building-user interface is the LEED Gold Manassas Park Elementary School & Pre-kindergarten (MPES) in Manassas Park, VA. The building was intentionally designed to be a learning tool and educational ecosystem. In particular, design decisions were specifically made to create teachable moments through the building interfaces: "...green lights signal it is time to open the windows. A gage on a cistern shows the rain water level. A bioretention area doubles as an outdoor classroom. Even the pipes of the HVAC system are painted red and blue to mimic illustrations of veins and arteries in human bodies" (Knox & Davis, 2010, p.37). Students and teachers can easily interact with the building to maximize comfort, while also saving energy. Informational plaques explain building features, and students routinely implore teachers to "open the windows" or "close the windows" based on real-time feedback from the building interfaces (see figure 1C).

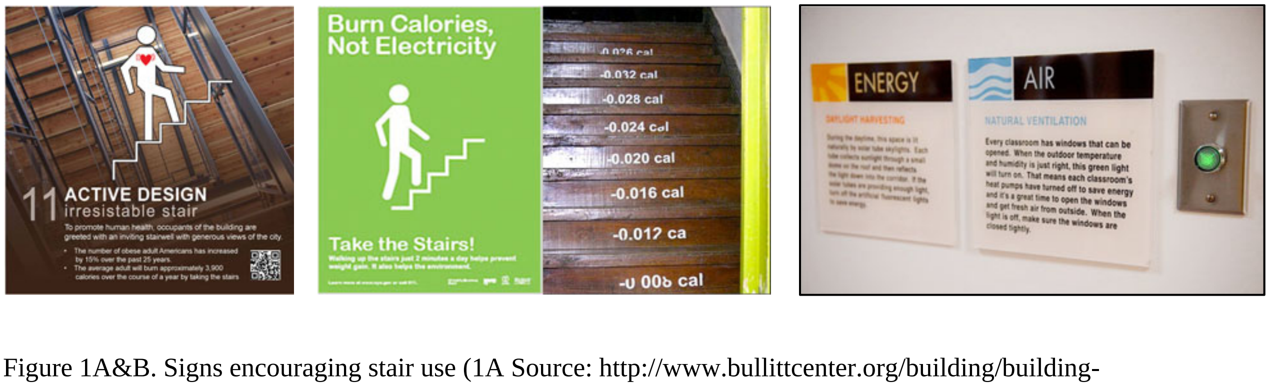

Figure 1A&B. Signs encouraging stair use (1A Source: http://www.bullittcenter.org/building/building-features/active-design/; http://www.bullittcenter.org/). 1C: Informational Plaques at MPES. Source: Sam Kittner

Building-user Interfaces

In a building, there are many potential interface points where occupants can have either a positive or negative impact on energy use, such as: operable windows, hot water use, light switches, thermostats, and even stairs versus elevators, etc. *(a more comprehensive list is provided below).* Taken together, the summation of all these types and qualities of interfaces create the behavioral-potential profile of a given building. The authors of this paper believe that for any given building, a B-EE potential can be described based on its available interfaces. We suggest that the B-EE potential should consists of three values: the up-side energy savings and the down-side risk of increased energy use, and a normative expectation of the resulting sum of these two, given the occupancy of the building.

Types of Behavioral Decisions

Perhaps as a way to think about the range of potential interactions between the occupant and the building, we can use a more familiar example of automotive efficiency to describe various behavioral interfaces and decision points. So we ask the question, in the context of automotive efficiency, what can an owner or user do to maximize or minimize the EE potential of that vehicle? An owner/user has the following choices:

- Decision 1, **System Selection**: select the efficiency of the system (i.e. choose to buy a Prius or a Hummer), and its features (heated seats)
- Decision 2, **To Use or Not to Use**: decide how often to use the system, or substitute alternative modes (drive, walk, bike, bus, carpool)
- Decision 3, **Utilization**: once an owner has decided to drive, they can then decide how much, i.e. how far and how frequently (total miles driven per vehicle)
- Decision 4, **Utilization Rate**: decide how heavily to load it up. Are 5 people in the car vs 1? Are you pulling a heavy trailer full of stuff? (miles per person)
- Decision 5, **Maintenance**: decide how well to maintain the car (tune ups, tire pressure, gasoline quality, oil changes, etc.)
- Decision 6, **Operational Efficiency**: decide how efficiently to drive (i.e. start / stop, acceleration, run the AC, open windows, etc.).
- Decision 7, **Meta-System Optimization**: are there car usage decisions beyond transportation? Do you also use your car to put your babies to sleep? As your private air-conditioned office? To charge your cell phone? If you have an electric vehicle, do you respond to off-peak pricing signals?

The thought experiment above allows one to think through all of the different ways that someone can interact with a car, or a building device, and all of the different ways that these decisions have a particular consequence on the resulting energy use. This same logic can be applied to occupants and building interfaces. One of the key differences is that an occupant is typically only able to navigate *some* of these decision points, depending on the building, type of the design, the level of control, and the types of interfaces. Some interfaces may only enable a yes/no decision, while others enable continuous adjustments. In general, homeowners have most of these decisions available to them, including purchasing, operation and maintenance of equipment, while in commercial buildings, those decisions are distributed among many players, including designers, owners, managers and occupants.

Building Interface Schema

The next section presents a variety of schema to catalog building interfaces. There are many possible ways to classify building interfaces. The most obvious is by end use and device type—e.g. lighting system plus occupancy sensor; or HVAC system plus programmable thermostat. This is how the market currently thinks about them, and how they are most commonly studied and implemented in programs, i.e. only one end use and one device type at a time. This paper, in contrast, seeks to consider the whole field of building interfaces holistically, and perhaps set the stage for a broader field of study of building-human interactions.

End Uses. Starting with the obvious approach of classifying interfaces by end use, a list of potential residential energy use interfaces is rather daunting, and the magnitude of the behavioral component in energy use becomes apparent:

- *HVAC*: fire places, furnaces, thermostats, radiant floors, radiant lights, portable radiant heaters, electric blankets, room humidifiers, window swamp coolers, condensers, compressors, personal fans, room fans, air filters, whole house fans…
- *Windows, Doors and Thermal Zoning*: operable windows, storm windows, sun screens, blinds and roller shades, awnings, interior and exterior doors, garage doors, sunrooms, attics, basements, skylights, exterior vegetation...
- *Lighting*: interior hardwired lighting, plug in lamps, night lights, holiday lights, indicator lights, flash lights, candles, exterior hardwired lighting, plug-in party and holiday lighting, security lighting…
- *Entertainment and Office*: TVs, set boxes, recording and gaming devices, CD/DVD players, radios, desktop and laptop computers, printers/faxes/copier/scanner, digital storage and backup devices, UPS and battery systems, shredders, phone chargers, room monitors, security systems…
- *Food Prep*: refrigerators and freezers, stoves, ovens, microwares, tea pots, coffee makers, espresso machines, rice cookers, crock pots, warming plates, wine coolers, blenders, mixers, juicers, and many other miscellaneous cooking devices…
- *Cleaning*: showers, sink faucets, tubs, spas, dishwashers, clothes washers, clothes driers, gray water recovery, recirc. pumps, washing machines, dryers, irons, vacuums, steamers, hair dryers, curlers, electric tooth brushes, and many other miscellaneous health, hygiene and cleaning devices…
- *Garage and Hobbies*: garage door openers, car heaters, electric car chargers, lawn mowers, weed whackers, leaf blowers, other yard tools, workbench tools, trash compactors, compressors and tire pumps, sewing machines, aquaria, exercise equipment, treadmills, saunas, and many other hobby devices…
- *Pools and Landscaping*: pool, pond and fountain pumps, filters, sweeps, and heaters, barbeques, fire pits, exterior radiant heaters, misters, ice melting, irrigation pumps and timers, electronic pest control…
- *Transportation and Conveyance*: Taking a larger urban-system energy view, it is useful to think about transportation systems as part of a home’s characteristics. A plug-in electric car obviously draws power directly from a home, and a stair-lift or elevator likewise substitute power for human activity. But on a larger scale, nearby sidewalks and bus-stops may also constitute behavioral interfaces for a home.

Commercial Buildings. A list of interfaces for commercial buildings will be similar, but likely shorter. This is because many more commercial systems will have centralized control, with fewer opportunities for occupant interactions, whereas homeowners typically are involved in the purchase, use and maintenance of *all* the energy using equipment and features in their home. Commercial buildings with a residential aspect, like firehouses or hotels, will include most of the residential interface types listed above, but perhaps at a bigger scale. "Conveyance" is perhaps one end use more common to commercial settings, including escalators and elevators, people movers, lifts, conveyor belts, and personal transportation systems, like trams, scooters, golf carts, bikes and skateboards commonly used within large campuses. Industrial buildings, furthermore, may have other types of interfaces unique to their industry.

Interface characteristics. More conceptually, interfaces could also be considered by level of control and mode of control. Below is a short list of other interesting ways to characterize building interfaces, each then discussed further in turn, using a gradient from the simplest and most direct form of interface to progressively more sophisticated and complex systems.

- *Who*: individual v group; private v public; diffuse v centralized
- *How*: direct v indirect; physical v analog v digital; manual v electronic; local v remote
- *Granularity*: one device v many devices per interface; on/off v multiple levels v continuous adjustment;
- *Temporal*: timed or time-delayed; instantaneous v pre-programmed
- *Complexity*: one input to one outcome, v one input to many outcomes, v many inputs to one outcome, v many inputs to many outputs
- *Feedback*: directly observable effect (lights go off), indirect and/or delayed effect (eventually I am comfortable, eventually the food is more frozen), direct feedback (indicator light goes on), direct reporting (cumulative energy use is reported), indirect or delayed reporting (cumulative savings over the past month).

Who: a key aspect of any building interface is who has access to it. Also, does it require special knowledge or tools to operate it? For example, in a home, can small children reach the light switches? Can grandma operate the DVD player? Is a manual required to adjust the thermostat? In commercial settings, the questions are often about individual versus group control, as with window blinds, or individual versus centralized control, as with thermostats. "Who" primarily influences how many decision makers are involved.

How: the simplest interface is physical movement: open a door or window. Physical interfaces can be made less direct via the use of levers, gears or dials. Mechanical systems can be made electronic, with analog interfaces, or digital. Once electronic, interfaces can be local or progressively more remote, from infrared TV remotes to smart phone applications. "How" primarily influences the ease of operation.

Granularity: the simplest interface has a one-to-one relationship with the device being controlled. For one-to-many, skylights can be ganged together with one crank, and hundreds of lights linked together with a single switch. A many-to-one example is a fan controlled by temperature, CO2 sensors, and manual override dials. Another element of granularity is whether the control is yes/no, multi-level or continuous, as in a single light switch, high-medium-low operation, or continuous dimming. "Granularity" primarily influences the nuances of control.

Temporal: the simplest interface is immediate. There is no time delay for starting or stopping, no waiting or warm-up times, no prediction of future conditions. With progressive and more sophisticated options, start and end times can be pre-set, stand by and warm-up times can be predicted, and other external factors, like weather or pricing, can be anticipated. Self-learning devices might be considered to provide an even higher level of feedback, where the devices historical performance informs subsequent operation, independent of occupant decisions. “Temporal” factors most strongly impact patterns of use.

Complexity: The simplest interface has one input or motivation for one output or result. For example, turn on the task light to read a book. But many energy uses have multiple motivations. For example, you might turn on a TV for entertainment, to offset a lonely house, or at night to show ‘we are home’ to increase your sense of security. Fans can be turned on for thermal comfort, ventilation, odor control, or even to provide white noise. For automated systems with multiple motivations, there are often multiple sensory inputs, such as office lights controlled by occupancy sensors, daylight sensors, and DR signals. Programmable interfaces may even use contingent logic to determine the outcome for the device, such as ‘if this plus this, then do that, unless such and such also occurs.’ “Complexity” thus determines the predictability of use patterns. As interfaces become less singular and more complex, the interactions among multiple inputs make the outcomes increasingly difficult to predict.

Feedback: the simplest interface provides feedback to the user via direct observation (the light is off). When direct observation is not sufficiently reliable, dials or digital readouts can provide information about power levels. More sophisticated feedback starts to provide a historical record of use—how often and how much has the device been used—over varying time periods—one day, one week, month or year. An even greater level of sophistication starts to translate that historical record of use into implications, for percent savings, for cost, or reaching EE goals. “Feedback” primarily influences rational decision making and supports long term optimization.

Each of these interface characteristics has a different impact on patterns of energy use and how much behavioral potential is available from a given device or building system. As interfaces become increasingly more sophisticated and complex, the behavioral potential may become either more, or less, certain. The simple, direct, physical interfaces are easy for us to understand, such as ‘open the door.’ As interfaces go digital, with all the myriad of possibilities for interactive formats and embedded logic, the net behavioral potential becomes less clear. There is sometimes a hope that we can automate our way out of this morass, by taking decisions away from the individual and giving it to a more predictable source, some rational third party who will properly program the interface for optimum performance, however defined.

Manual vs. Automated Building Controls

This past discussion leads to another set of questions: Is it fundamentally a good thing to have a building with more occupant control, or less? Do more levels and types of occupant controls increase the savings potential (and other positive outcomes, such as the comfort of occupants)? Do they instead increase energy use? Or do they just muddle the picture, creating confusion and conflicts? Another key questions is: Do buildings that enable a wide range of occupant behavior / interaction, result in more, or less, energy use? Or do buildings that preclude or inhibit occupant behavior (with static systems, or automated building interfaces) result in lower energy use?

The current default assumption among the EE community is that occupant control options should be limited and that there is an energy “cost” associated with allowing individualized control (Glicksman & Taub, 1996). Thus, many building engineers and designers strongly favor automating building controls and centralizing the *control* of controls (i.e. with building or facility manager, or even a third party). This preferred approach leads us to believe that current building practices typically tend to reduce, or even prevent, occupant control. So, should buildings be completely automated to eliminate these pesky behavioral variables? Based on the studies discussed below, probably not. The following examples clearly identify why occupant overrides are so important to building energy use, occupant comfort, and overall occupant satisfaction. For instance, Galasiu and Newsham (2009) conducted a study (*n*=19) on occupancy sensors and accessible personal lighting controls, and they found that when occupants could choose their own light levels, (1) there was a net 25% energy savings, and (2) occupants were generally more satisfied with their visual conditions. This study provides a relatively straightforward example, but when occupants have control over their built environment, these interactions can become quickly complicated depending on the type of interfaces available.

Some of the complexity of the issues of human interactions with controls can be illustrated with examples from recent studies of window blind operation. Window blind operation is interesting as takes us into the more complex side of building interfaces, where there are many possible interface types, and also multiple motivations for adjustments and multiple consequences for building energy use, including views, privacy, daylighting, thermal comfort, and solar heat gain and heat loss.

Occupant attitudes toward automated controls: a window blinds example. Throughout the literature, especially with regard to visual and thermal comfort, many studies have addressed occupant attitudes toward automated blind controls, and ultimately, results have been variable. In the highly touted New York Times demonstration site, Lee and others (2007) found that user overrides were infrequent and that the automated system dictated 98% of all blind movements, implying high satisfaction with the system. In an earlier study, Inkarojrit (2005) surveyed 113 office workers in two buildings in California, and only 44.5% of the subjects indicated a preference for automated louver blinds, while the remaining majority (55.5%) of users preferred manual blinds.

Alternatively, Reinhart and Voss (2003) reported that 88% of occupants would override the automated blinds to reopen the blinds after an automated closure. In Escuyer and Fontoynont's study (2001), most occupants valued the automatic daylight-linked systems, but expressed a preference for being able to control and override the system. Velds (1999) concluded that occupants would be more willing to accept lighting and blind control systems if they included a user interface; the main occupant complaint was the inability to personally override the systems. Similarly, in Galasiu and Veitch's (2006) extensive luminous environment and control literature review, two of their conclusions were that (1) "photocontrolled shading devices also need overriding occupant controls if they were to be accepted, and (2) integrated controls for both lighting and shading can be acceptable, but were most accepted when a degree of manual control was provided" (p. 740). Results of these studies varied, as some occupants preferred automated shading, whereas others did not. A common thread throughout the literature is that automation is typically acceptable, as long as occupants have the option to override settings.

The case against *total* building automation. Human subject research has consistently shown that occupants not only want control of their environments, but they will get grumpy, and increasingly inventive if their attempts at control fail. Indeed, many of the illustrations below prove that occupants will find their own ways to gain control of their buildings, when it is not available otherwise (see figure 2A,B,C). In addition, if occupants understand the building and environmental control systems and interfaces, then they may contribute to lower building energy use, while also increasing their overall satisfaction with their work environment (Janda, 2011). Alternatively, if users do not understand building controls (or if they are deprived of control), energy use may increase if systems are overridden incorrectly and/or occupants may be less satisfied with their environment due to decreased thermal or visual comfort.

Figure 2: 2A: a bag placed over vent to prevent air movement; 2B: popsicles placed on thermostat to “trick” settings, and 2C: aluminum foil placed over window. Source: author’s photograph & google images.

Overall, it is important to save building energy use, but also important to keep the people happy, satisfied, and productive. The ultimate goal of building functionality is to support occupant comfort. However, this is oftentimes difficult to achieve because individuals do not all have the same comfort criteria. Therefore, it is important to enable the building to adjust locally for individual occupants. As illustrated by the Galasiu and Newsham (2009) study above, additional savings can be gained by providing local occupant control because, rather than striving for a uniform standard (80% MPV[2]), individual control will tend to result in average preferred light levels (50% MPV).

These points illustrate the importance of recognizing the “user” part of the building-user interface equation. In addition to physical comfort, occupants who can successfully interact with their buildings are likely to feel more ‘at home,’ implying a level of emotional comfort. Along with this feeling may come other intangibles, such as a desire to care and maintain their environment, a greater sense of pride, and even love of place. These are the sorts of attributes that are present and valued in the most highly functioning communities.

The next step. So far, this paper has introduced the following concepts: (a) the building-user interface has been largely ignored in past behavior-based programs, and (b) occupants are complicated creatures and their behaviors can be determined and influenced by any number of variables (i.e. level of control, knowledge, thermal and visual comfort, feelings, culture, etc.). The interfaces and schema identified above provide an excellent foundation to break down this complex problem, but ultimately, the goal should be to quantify the three elements of the B-EE potential profile: (1) normative usage patterns, (2) the up-side potential to save energy via optimal operation, and (3) the down-side potential to squander energy. Within any given type of interface, different technology choices, interface design, control options, and/or behavioral intervention strategies may change one, two, or all three of these values. The summation of all these types and qualities of interfaces create the behavioral-potential profile of a given building. Such a schema has the potential to rationalize investment in both interfaces and behavioral strategies, prioritizing those that can be shown to have the largest potential net-positive impact

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[2] The Predicted Mean Vote (PMV) model requires that at least 80% of the occupants be satisfied.

across building populations. An attempt to create such a database will immediately help to identify missing information and to clarify the bounds and precision of estimates of savings.

Metrics of Performance to Quantify the Behavior-Potential Profile of Buildings

As this topic further evolves, it will be important to identify and develop appropriate metrics to quantify the behavioral-potential profile of buildings. It might make sense to model the structure of these metrics after California's Database for Energy Efficient Resources (DEER), which compiles information and data for a wide range of energy-efficiency measures for use in program design and evaluation. DEER establishes a precedent for estimating the average costs and benefits of both residential and commercial efficiency measures (DEER, 2016). DEER catalogs technologies in terms of the predicted average energy savings per device across a large aggregate of buildings (i.e. per dishwasher or per CFL), unless savings per SF is more applicable. As EE systems become more complex, and contingent upon context, DEER's widget-based approach breaks down. It is important here to consider the old maxim: "Optimizing a subsystem will sub-optimize the system" or its corollary: "Optimizing a system requires sub-optimizing the subsystems." Thus, adding human behavior as a component of EE system design may require some serious rethinking of subsystem design!

However, DEER's basic concept of trying to catalog all the types of EE interventions can be very helpful when trying to compare alternatives and optimizing the whole building's EE potential. Ultimately, the B-EE goal should be to better understand the up-side energy savings potential and down-side energy liabilities of different interface types. One can imagine an extensive table of building types, end uses, devices and interface types that quantifies not only engineering assumptions, but also normative usage patterns, the upper and lower bounds of energy use, and perhaps even standard deviations based on sufficiently large observational studies. For illustrative purposes, in the table below, the authors have attempted to sketch out the variables that might be in play for a range of residential HVAC interface types. The interface types are graded from simple to sophisticated. 'Best B-EE Case' and 'Worst B-EE Case' attempt to describe the upper and lower bounds of energy savings possible based on behavioral choices available to the occupant. Ultimately, we would hope that these descriptive assumptions could be quantified, based on observational studies, to predict the bounds of normative behavior.

Table 1: Behavioral Variables for Residential HVAC Control Interface Types: An Example

Interface Type	Energy Variables	Best B-EE Case?	Worst B-EE Case?	Default?
1. Manual Thermostat	Upper and lower HVAC temp. settings, hrs. of operation	No HVAC use	Continuous use, at extreme settings	ASHRAE comfort assumptions
2. Simple Programmable (analog, daily)	Above, plus pre-heats & setbacks	No HVAC use	Continuous use, at extreme settings	Code operational requirements
3. Complex Programmable (digital, weekly, w temp. overrides)	Above, plus variable comfort settings, fan operation	Individualized comfort during occupancy, little or no use when un-occupied	Continuous use, at extreme settings	Code operational requirements
4. Complex Programmable, & Communicating	Above, plus DR or price signal response	Above, plus DR reductions	Continuous use, at extreme settings	Code operational requirements, with some DR reductions
5. Programmable, Sensing, Self-learning (e.g. Nest)	Above, plus self-adjusting patterns of use	Individualized comfort during occupancy, little or no use when un-occupied	Standard comfort during occupancy, little or no use when un-occupied	Code operational requirements

Ultimately, people use energy in buildings, and we want them to use less. If this is the goal, then it is paramount to begin to identify and understand all possible interface points between the human and the built environment (as illustrated in the example above) so that utilities and owners can make informed and targeted decisions for behavior-based programs to maximize potential savings.

Discussion and Conclusions

To truly maximize behavioral saving potential, it is likely that a marriage of automated and manual controls is the ultimate solution. The automated system would set the defaults based on historical patterns and the upper and lower boundaries of allowable operation for long term efficiencies, while intermediate adjustments would allow fine tuning to current occupant preferences and short term manual overrides to address immediate occupant needs. This way the automated system reduces the behavioral risk, by bounding the problem, while the occupant adjustments increase comfort, satisfaction and energy savings due to more tailored use.

Per the earlier discussion of how occupants creatively defeat automated systems, it is likely that allowing an appropriate range of occupant overrides to any automated systems also reduces the risk of complete failure, via occupants defeating or disabling the automated system. Thus, an interesting behavioral study might look at the difference in both energy savings and persistence of systems with varying degrees of automation and occupant-accessible controls.

Fundamentally, if the grand goal is to save building energy use through targeted occupant behaviors, then the building design and associated interfaces must facilitate this goal. Observation studies are needed that report how humans actually respond to different controls and interface types. Also, building system interfaces cannot be optimized without a deeper understanding of (1) occupant comfort / preferences and (2) interface effectiveness. The EE literature is full of anecdotal stories, but very, very few careful observational studies of sufficiently large populations that would support predictive models of how behavior, and energy usage outcomes, vary with different interface approaches. In order to progress towards buildings that minimize all environmental impacts, and maximize health and well-being, we will need this information to support better design, policies and programs.

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