Human-centred models of use for energy efficient residential operation

(or, Smart Homes and Dumb Automation)

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Abstract

How we control the things in our homes that use energy has a large impact on the energy efficiency of the building and automation technologies are seen as promising interventions to improve it. However, these new smart home technologies do little to support more effective use. Why is this? Understanding the failures in these automation approaches leads us to consider the residents' relationship with the control systems and how more appropriate models of this relationship can lead to better outcomes for both user experience and home operation. In this paper we discuss this emerging design space and propose an initial framework for examining home energy management automation, illustrated with examples from a study of residents' experience in advanced "green" buildings.

Introduction

"Technology is a word that describes something that doesn't work yet." – Douglas Adams

How we control the things in our homes that use energy has a large impact on the energy efficiency of the building. But people have very limited energy literacy in understanding these relationships [1] [5]. Even the most committed adopters of "sustainable living" technologies refer to managing a green home as "piloting a ship", requiring constant vigilance and dedicated time [6], [7]. As a result, designers, engineers and policy makers increasingly look to technological solutions to the problems of more efficient home operation: the so-called *smart* home.

The recent proliferation of ubiquitously networked devices (the "internet of things"), sensor-based systems and advances in machine learning have led to the development of commercial smart home systems that are accessible to a wider range of households. A major application of smart home technologies targets energy efficiency, in which automation manages common tasks of heating, cooling, lighting and ventilation to optimize energy use. This forms an explicit theme in the development of efficient buildings, focused on "smart" automation of the building systems and components. The assumptions that automated systems will improve performance is now coded into sustainable building performance metrics like the LEED® or Australian 5 Star green building specifications {USGBC:2016wu}. However, this onslaught of new smart technologies has to date done little to support more effective green building performance [9], [10]. Why is this? Research points to a disconnect between how so-called "smart" systems for energy management are designed and how people use their homes in daily life [2]-[4]. These technologies and patterns of use are the focus of recent design research but knowledge of how they should be most effectively integrated into sustainable home design is in its infancy [11]-[13]. We still know very little about how to design, situate and integrate the various technologies to support residents in energy management, and this is most apparent in the ways in which automation is often implemented. Understanding these failures in such automation approaches leads us to consider what the residents' relationship with the control system actually is,

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and how more appropriate models of this relationship can lead to better outcomes in system design and implementation for both user experience and home operation.

A key component of such a model should include metrics of user experience by which we can evaluate the success of proposed automation strategies. But the design dialogue in the development of efficient buildings has largely focused on how the building systems are automated and manipulation of components for optimal performance rather than on effectively supporting how people use their living spaces.

In this paper we discuss this emerging design space and propose an initial framework for metrics of user "cost". We apply this to results of an ongoing study of residents' experience in high-standard green buildings where automation forms part of the energy efficiency strategy. We propose that adding this perspective of the resident as user will be critical for designers, policy makers, utilities and householders in exploring the potential issues and affordances of sustainable technologies and building designs. Such foci will be important in extending current work both in better understanding what architects term "occupant behaviour" [14] and in the design of better interactive, intelligent and embedded technologies for "greening" homes.

The goal of this paper is not to suggest a single model; rather, we propose directions for embedding these human-centred perspectives in computational reasoning for design. While there is significant research on aspects of building performance and its impact on human comfort there is substantially less understanding of how to assess the benefits against aspects of human experience. We need to understand this for several reasons:

- Design interventions and user experience: if we introduce technologies to support or mandate energy conservation, what impacts will they have on human interaction with the living environment, living practices and on the resident's comfort and acceptance?
- Operational decisions: are we using the right conditions to affect decisions about controlling the residents' environment?
- Operational behaviour: are we technologically manipulating the right things?

Background

Engineers and computer scientists think of "home technologies" as computational, but architects and designers have a more comprehensive view of a building. Brand's common architectural design framework [15] considers buildings as a complex system made up of *layers* with which the inhabitants interact at different scales and over which they have differing scope of control. Of particular interest are *Skin* ((the structure's cover); *Services* (the communication hub of the building, thermal systems, electrical wiring, elevators, etc); *Space* (the layout of the area), and *Stuff* (the furniture and belongings of the inhabitants.) Interactive technologies related to energy efficiency are inherent in all: a window is part of the Skin, heating and lighting are Services, Space affects how easily the residents can adapt and control Services in their environments, and Stuff concerns appliances and devices. In smart home tech, automation in some form is typically applied to elements of Skin, Services and Stuff.

Home automation refers to the use of computation to control these home functions and features automatically. It is typically defined by the system to which they are applied (HVAC, lighting, security) and by the technologies used to determine the conditions for behaviour (sensors, time of day, or other algorithmically defined trigger state [8]). Thus a smart thermostat would be defined as a temperature control system that uses a combination of direct user control, programmable specification using schedule, and machine learning to determine heating and cooling behaviour. None of these attributes, however, explain why it may work may work more poorly than anticipated in achieving energy efficiency in certain contexts {Yang:2013ko}.

The general promise of the smart home – that intelligent operation could be off-loaded to a computational component – has been confounded by the human factor [2], [4], [13]. The technology-driven view often cites complexity, inflexibility and unreliability as the major challenges in these systems. But automated systems have a long history of user resistance and lack of success [16]. A more holistic view considers how these sometimes disparate systems change the dynamics of the home. The more daunting factors are not technological capability but mismatch with daily living practices [17] and with what "home" means as sanctuary, domain and social nexus [2], [18]-[20]. This misalignment of automation strategies with living patterns leads to unsatisfactory experiences with the home [12], [13], [21] and often worse energy consequences because people try to overcome or work around the automation behaviour.

Wilson points out the key challenge of designing better smart homes is to refine what "smart" means in the context of daily life {Wilson:2015je}. We consider an appropriate definition of "smart" technology as "what fits my routines and avoids unnecessary work" [12] in aiming for more energy efficient operation. If designers and householders are trying to assess what kinds of automation may be useful in the home, then surely we need to consider analytical tools that explicitly account for the users' experience, routines, and comfort, as research suggests that poor occupant adoption, use and experience with automated systems directly contributes to poor performance [9], [10], [12], [14]. We therefore propose a framework for considering types of technology in the home that deconstructs them with respect to factors of user effort, interaction, and agency. Our intent is not to recommend one approach over another, but rather to introduce additional metrics and dimensions against which technological interventions may be evaluated for the energy-efficient home.

Home technology through a human lens

Our framework comprises two concepts: dimensions of automation that characterize the relationship between humans and system elements, and human related impacts (costs).

Dimensions

We characterize approaches in how people interact with their home technologies as follows.

A **Control model** defines how system behaviour is specified.

- *programmed automation*: the system decides when and how to act (e.g. automated ventilation) based on rules and conditions determined computationally. These rules may or may not be set by the residents.
- *Delegation*: the user sets a condition for behaviour (eg, a simple thermostat where the user delegates heating/cooling control to the device, based on temperature set point).
- *Manual*: the user controls directly (eg, window shades);
- *Hybrid*: some mix of the above (e.g., the NEST™ is a combination of programing and delegation).

Intervention type defines the behaviour.

- *Direct behaviour* changes the environment (the traditional concept of automation, e.g. automated shades);
- *Notification* (the user is alerted that something needs attention, e.g. a beeping appliance);
- *Recommendation* (similar to the above, but the user is prompted to carry out some action explicitly, e,g. to operate laundry at a lower load period [22]).

Execution level defines the degree of automation and at what level in the system control is executed. It is closely related to the control model, but adds different aspects of user impacts.

- *High* intervention: this is total automation, where the user does not participate (e.g; automated lighting systems);
- *Partial*: the user can interact with some aspects of the system being automated, but not all (e.g. adaptive window shades);
- *Mixed*: This can be considered a kind of "power steering", where the user relinquishes the lower-order manual functions but retains the outcome-specific control.

Agency defines who executes the behaviour.

- Building (e.g., centralized HVAC);
- Resident(s) (e.g. blinds);
- Device (e.g. appliance turning on/off);
- External (e.g. grid management such as a power utility controlling when a pool heater comes on [23]).

Impacts

Technology carries extra costs we must include in any calculation of potential benefits. These can include both specific (extra overhead in accommodating technological function) and general impacts (reduced residential comfort). We consider three kinds of inter-related costs of such interventions through the lens of resident interaction: effort and complexity, user experience, and cost of recovery.

Effort: we believe an essential part of a model of technology use has to include an "effort parameter" that weights how much effort is required for the resident to use it most efficiently. While automation is intended to reduce manual effort, actions become effortful and complex quickly when extra steps are needed for information (understanding why the temperature is not correct) or for compensating for extra technological overhead (resetting the programmable thermostat).

Resident experience and fit: Disconnects between anticipated and real outcomes, or behaviour that contravenes preferred living practices (such as closing shades on a sunny day to enable cooling), not only cause momentary discomfort. They also introduce a level of mistrust with the systems that can result in a sense of losing control and autonomy within the home where it is most important in daily life [18], and can disrupt or redirect domestic practices {Strengers:2013vm}.

Cost of recovery: What happens if the outcome is not what the resident wanted? The cost of being wrong may simply be the effort required to recover a desired state, but may also imply additional technological interventions such as showing system state or providing over-rides. When users try to overcome the systems, as in the case of using motion generators to defeat automatic lighting, one cost can also include increased energy use beyond a manual system.

These human-centred metrics help us to assess different technologies, and they serve to differentiate the dimensions more informatively for a designer seeking to understand tradeoffs in system choice. So, for example, a programmable lighting system for direct behaviour with a high execution level may have a *low* effort cost in execution (no manual steps) but a *high* cost of control specification; a poor user experience because of inflexible behaviour; and a high cost of recovery because the residents spend effort to fool the system conditions and often leave the lights on more often than otherwise. We would predict that manual shades have a manual control model with low effort in specification, but consequently high effort in execution, suggesting they may not always reflect the "optimal" energy use decision. On the other hand, the resident has complete agency in tuning them to the environmental context, and a low recovery overhead, contributing to a positive user experience.

Living in LEED™ User Study

We are carrying out a study with inhabitants' experience of living in multiple-unit green buildings, seen through an interaction design lens where we consider the inhabitant a user and the building as a complex system with which the inhabitants interact. This is not a perspective familiar to architects, engineers and policy makers, who typically look at buildings from the perspective of how they are made, rather than how they are subsequently used [15] [24]. We conducted in-dpeth interviews with 15 residents of LEED Gold mid-rise multi-residential apartments in Vancouver-BC. We probed their experiences in living in these green buildings in semi-structured interviews addressing the following topics: living experience, thermal comfort, lighting, spatial design, alerts, site design, and opinions on sustainability. At no point did we explicitly ask them about the automation systems. However, when discussing the above topics, people immediately reported on automation related issues. We categorized these responses in terms of Brand's layers as interaction patterns that directly relate back to the design and use of automation in the buildings.

Building Automation

The inhabitants interviewed lived in two different LEED™ Gold buildings (a high green building standard). Both buildings had energy-efficient appliances with audio alerts to signal state (finished cycles in the dishwasher and laundry machines, or open door alarms in the fridge.)

However, the units differed in their heating and cooling systems. Building 1 has an electric heating/cooling system with programmable thermostats in each unit that enable the resident to set a desired temperature and a schedule for different temperatures. There is no feedback of energy use. It has manually controllable window shades. Building 2 uses a capillary mat system with simple switch/dial interface. A capillary mat uses mats of multiple thin-gauge tubes that circulate warm or cold water across an extensive surface area, exchanging energy with any nearby mass. These mats were installed in the ceiling of each unit. Hence, the floor of the unit becomes warmer or cooler when the unit below switches to heating or cooling respectively. The user can specify "more" or "less" (dial) in either heating or cooling mode (switch). This building also has a meter at the entry displaying the usage of cold and hot water, energy for heating and cooling, as well as electricity.

Building 2 also has exterior automatic shades that automatically close when the sun starts shining onto the unit directly. The residents can only control the height at which the shades are positioned within a limited range, but cannot directly control the opening and closing behaviour.

Patterns:

1. Appliances (Stuff): Washer/ drier, dishwasher, and fridges all had notification and alerts implemented. The laundry and dishwasher appliances beeped continuously on cycle completion. The fridge beeped if the door was open for too long. This was considered very useful. Users all found the other alerts useful indicators of when to remove clothes or dishes unless the appliances were loaded prior to sleep time – a common practice. Then the beeps became very disturbing, requiring the users to get out of bed to configure the machines enough to turn the alert off.

Analysis: The automation of notification was generally useful, but the uses had no control over it except to open and close the appliances. The assumption that action could be immediate was flawed, and thus the cost of recovery was sometimes unduly high.

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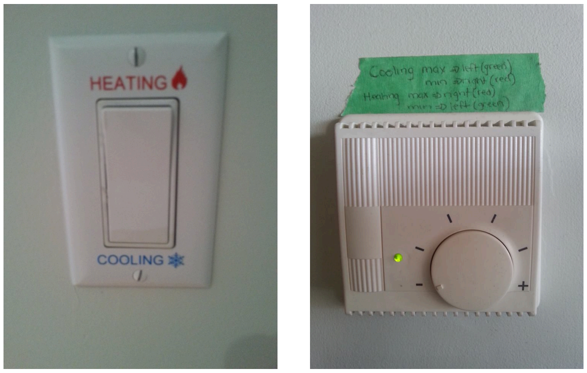

Figure 1. The Building 2 H/C controls

2. **Ventilation/Fans** (**Service**): The bathroom fans were -programmed to run at specific times. The lack of control over the bathroom fan created confusion for users and extra electricity waste since inhabitants also turned the fan on and off when it was required. The noise from the fan was annoying. During the pre-programmed cycle of the fan, the only way to stop was to switch it off from the electrical panel, which was both inconvenient and potentially dangerous for users.

Analysis: Users incurred both the cost of having to over-ride the fans at the level of the home electrical system as well as the manual effort of turning the ventilation on and off when they were actually using the bathroom outside the scheduled times. The additional noise out of context was considered irritating.

3. **Heating and Cooling (Services).** Building 1:The Extremely complex programmable thermostat settings caused misuse of the thermostat. Moreover, the room temperature never reached the set temperature of the thermostat in summer or winter. When the residents questioned the building management, they were told that the system would not be able to meet the desired comfort settings in very cold or hot days and were advised to use other methods, including closing the blinds, to increase comfort. Building 2 residents had a different experience. They could not figure out how the system worked, and were confused there was no way to turn it off. One resident attached instructions written on green tape to the dial system to remind him how to use it (Figure 1). The red/green lights were confusing: red meant "on" and green meant "off". Residents found the glowing lights annoying at night in their bedrooms. In both buildings, residents pointed out that the systems did not work as expected, and that their agency was limited, particularly in Building 2 , to change it. Some bought additional space heaters to address this.

Analysis: Both systems attempted to reduce effort and in fact increased it, as users needed to try to learn the system complexities and adjust their expectations. A lack of information about the heating system capabilities meant residents needed to recover comfort elsewhere. Where some of these were reasonable and sustainable choices, such as buying boots to wear on cold floors, others were not (such as purchasing additional heaters). Finally, the control systems themselves were deemed irritating.

4. **Automated shades (Skin)**: The external shades in Building 2 closed automatically when the sun shone directly on them. This meant that on nice summer days residents could suddenly lose their views. Residents were extremely frustrated with the lack of control over the exterior shades. They found them unpredictable. They reported the system was programmable height-wise, but not time-wise. All found even that limited task of programming the shades extremely complicated. As a result, they disabled the shades by unplugging and would plug/unplug them for control (though this action is highly forbidden as it can damage the system).

Analysis: Users had limited agency in controlling the shades and expended substantial effort in trying to learn how. The behaviour was unpredictable and frustrating, occurring as it did on the nicest of days, and thus seriously reducing their enjoyment of the space. They went to unsanctioned actions to disable the system (an extreme recovery approach).

In general, people reported that the systems did not "work together", and in some cases seemed to contradict each other (for example, showing that cooling was "low" but then closing the shades). With the exception of the notification systems, they had little understanding of why things behaved in certain ways. They unanimously disliked the automated full interventions, and spent significant effort to disable them, but liked the notifications at certain times. Finally, they found the loss of control in their homes discomfiting, particularly when it disrupted what they saw as normal domestic practice (sleeping, enjoying a view by the window).

Discussion and Lessons Learned

These result are congruent with other smart home findings, and in particular with our previous experience designing a net-zero home {Bartram:2011we}.

Technology carries extra user costs we must include in any calculation of automation benefits. In addition to the impacts of disruptive user experience and effort, the piecemeal practice of applying automated or scheduled behaviour with respect to a single element in the home introduces unnecessary complexity and unpredictability, as the systems frequently do not work together. For example, the meter display of energy use seemed contradicted by the eventual bill.

Determining the appropriate intervention should be considered with respect to how accurate the decision-making needs to be to avoid disruption. For example, a recommender system rather than a direct action would be more appropriate when using shades for cooling. The resident retains agency, and the system cost of being wrong is minimized, although the execution cost is higher (the user has to do it). The interaction level of smart home residents with home technologies might be pre-determined and characterized within a control model or execution level, but inhabitants ultimately control and edit systems based on their preferences in ways that can be detrimental to the system, lead to extra consumption, and cause a high cost of recovery.

Lack of information or misinformation about the how automation works and what the system is doing is one of the most dominant contributors to the misuse of automation systems. In case of most technologies, residents are not entirely clear about how to use the system, and/or the scope of system capabilities. As soon as a decision or action is jarring, they seek to avoid or minimize the automation effects. (Pilots often refer to similar behaviour as "escaping" the system). The more the system is in control, the more disruptive the effect is and the higher the cost of recovery.

People respond negatively to the loss of control in their living spaces, leading to lack of trust in the systems. We found in the case of our residents that this has developed into a sense of cynicism towards smart technologies and automation systems.

Conclusions

Understanding how residents control their homes is an emerging area of sustainable design research. Current design tools help architects and engineers evaluate building and technology performance but are limited in their models of how occupants behave. Computational intelligence tools are promoted as promising in the operation of more efficient residences that support people in using fewer resources more effectively. Designers who wish to explore the affordances and potential of these systems will need to be able to explore the impacts of variable degrees of automation. We believe the challenging design question is to balance the appropriate responsibilities and effort between more optimized automation and supported delegation. We have proposed a framework for assessing and measuring the human impacts of automation. We suggest that this should accompany traditional engineering models of predicted and actual performance as an important tool in the design and deployment of green buildings and smart homes.

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