Residential Resource Use Feedback Technology: A Framework for Design

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ABSTRACT

Providing effective feedback on resource consumption in the home is a key challenge of environmental conservation efforts. However, existing approaches have relied on a variety of assumptions about effective techniques without a unifying theoretical foundation, or a means of reliably comparing the strengths and weaknesses of different approaches. This is a design space in need of some structure. We present a comprehensive framework for the analysis and design of tools that provide feedback on residential resource use. We base this framework on our research experience in three contexts: 1) the design and implementation of energy management systems in two high-profile sustainable homes, 2) an ongoing review of the relevant literature, and 3) an analysis of existing products and tools in the marketplace and research community. We propose five sets of dimensions upon which these tools may be mapped: Context, Behaviour, Human Factors, Aesthetics, and Data. The framework serves both the investigation of existing instances and the design of future systems. We offer this framework in order to deepen our understanding of design approaches in this domain, and in hopes of establishing a common set of terms to characterize the field.

KEYWORDS: Sustainability, residential resource consumption, feedback, framework.

INDEX TERMS: H.4.0 [Information Systems: Information Systems Applications — General]

1 INTRODUCTION

A key challenge of environmental conservation efforts is the support of sustainable resource use in the home. Efforts to reduce our ecological footprint involve increasing awareness of how resources are used, and providing opportunities for residents to change their behaviour. The literature reveals an active and growing research interest in this domain, and numerous product offerings in the marketplace address this growing need. This has led to the production of a wide variety of devices and software interfaces that aim to increase awareness and motivate conservation. These tools take many forms: point-of-consumption feedback devices, information dashboards, mobile tools, ambient indicators, artistic visualizations, analytical interfaces, and feedback embedded in smart appliances.

However, these approaches have relied on a variety of assumptions about effective techniques without a unifying theoretical foundation. This gap has left researchers without a method for analyzing and comparing existing instances or a design framework to use in the development of new tools. Previous efforts have delimited several of the important factors to take into account [4][9][10], but have not thoroughly considered many of the important dimensions in this design space.

2 BACKGROUND

Our work in this area has grown out of our contributions to two high-profile sustainable housing projects. The first, North House, is a net-zero home that placed 4th at the U.S. Department of Energy Solar Decathlon 2009, an international competition to design and build the most energy efficient solar-powered home. We developed the Aware Living Interface System (ALIS), an interactive visualization, control and social networking system to support informed resource use in North House. It includes embedded displays with passive and interactive modes, web-accessible tools, mobile visualizations, and informative art.

West House, our second and current project, is a small footprint sustainable laneway home developed in partnership with the City of Vancouver that debuted at the Vancouver 2010 Olympic Winter Games. The second implementation of ALIS for West House includes new prototypes in ambient displays and further integration with existing commercial technologies.

3 MOTIVATION & SCOPE

During these projects, we have investigated existing tools that provide feedback on residential resource use, both to draw inspiration and discover opportunities for improvement. We found that designers and researchers have approached this application space with a variety of assumptions about residential resource use. These include how to motivate conservation, how to express the data, how much time residents are willing to spend managing their resource use, appropriate placement of displays, and effective representations to use. However, little theory exists to structure the space of design possibilities, leaving practitioners to discover what works in their specific context without a clear understanding of how their solutions relate to others. Thus, we were motivated to extract parameters from our analysis of existing work and our own applied experience in order to develop an abstract model of the dimensions of the design space. We anticipate that this knowledge will improve the design of future systems by indicating successful strategies, demonstrating underserved opportunities for feedback, and providing a structure to explore design possibilities.

Further, our applied knowledge in designing interactive ecosystems of feedback technologies has provided us with pragmatic insights into where tradeoffs are likely to occur when deploying these systems in real-world environments. As a highly situated and context-sensitive venue for conveying information, designers are faced with a multitude of constraints not typically associated with traditional interface design and information visualization. For example, the physical layout of a home will introduce numerous constraints on placement, visibility, aesthetic choices, and interactive affordances. Similarly, designing for the idiosyncratic habits and expectations of users in home environments requires sensitivity to how such tools are likely to be used in everyday activities, and to how they cohere with other elements in the home [2]; simply hanging a screen on the wall is only going to help residents make some kinds of decisions. In this context, designers need prioritization schemes to decide what to do, and guidelines regarding how best to meet their specific goals. A framework that maps out these important considerations enables an informed design process.

The dimensions we propose can be considered as general design parameters with variable ranges. Though we have striven for completeness, these dimensions are not necessarily exhaustive; particular design cases may stretch the framework we outline, or fall outside of its scope in one or more dimensions. As an emerging design space, we expect that new developments will warrant continued refinement of the parameters of the framework.

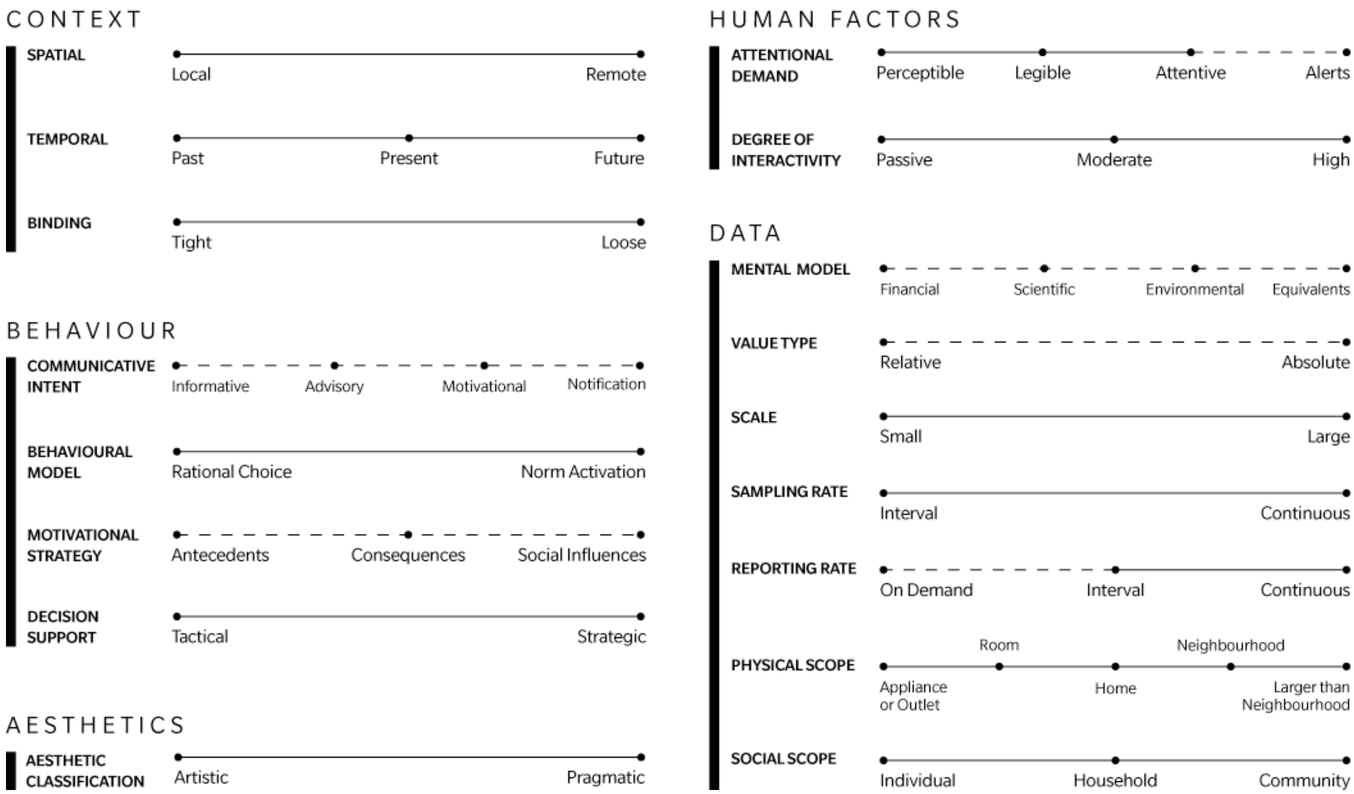

Figure 1: Our proposed framework for the design and analysis of residential resource use feedback technology.

4 DIMENSIONS

The framework is grouped into five categories: Context, Behaviour, Human Factors, Aesthetics and Data [**Figure 1**]. Each encompasses a different set of aspects related to the provision of feedback on residential resource use. Each dimension delimits the range of values for a given property. Most are arranged on a spectrum of continuous values (indicated by a solid line), while others are composed of discrete values (dashed line). For each dimension, we briefly address the following:

- *What question does it answer?*
- *What range of values does it encompass?*
- *Why is it important to consider?*

4.1 Context

Contextual dimensions consider how the feedback is situated in space and time, and how it is bound to its use context.

4.1.1 Spatial

Where is the resource consumed, in relation to where the feedback is provided? Local feedback — often termed "point-of-consumption" feedback — is provided at the source of consumption, while remote feedback is removed from the location of consumption. The spatial location of a tool is important in relation to the kinds of activities it supports: local instances eliminate the effort of attributing consumption to a particular appliance or activity, and support at-a-glance awareness, while remote instances enable analysis at convenient locations.

4.1.2 Temporal

When is the resource consumed, in relation to when the feedback is provided? Tools can provide feedback on past and present consumption, and sometimes offer predicted data on future use. As Chetty et. al. [4] and others [7][9] have found, real-time or near real-time feedback is necessary to enable residents to link their behaviour to resource use by connecting causes and effects. However, past and anticipated future data can assist residents in making strategic decisions and comparative assessments.

4.1.3 Binding

How tightly bound is the representation of the feedback to the context in which it is delivered? This dimension indicates the degree to which a tool is coupled to its context of use, and how specific its representation is to its circumstances.

An example of a tightly bound feedback instance is the Power-Aware Cord, a customized power bar inlaid with electroluminescent wire, described by its designers as a "visual overlay of digital information on a real world object." [6] When active, the cord displays light either at a static intensity or as pulsating or flowing patterns, with intensity and frequency mapped to the current electrical draw of the attached devices. The designers explicitly intend a tight coupling between representation and context, stating, "our aim is [...] that users might perceive the light patterns as the actual electricity in the cord [...]. By this, we mean that people might talk about and refer to the light just as if it would be the electricity itself, even if they on a logical level would realize that it is just a representation." [6] This tool specifically seeks to make electricity visible, and conveys this through the familiar object of a power bar: a direct conduit for energy consumption. By building the richness of a familiar use context directly into the representation of the data, designers can leverage the knowledge of that context to aid interpretation and reduce the learning required to comprehend the feedback.

In contrast, abstract, loosely bound representations can be used in any context. For example, the information provided by an interface such as Microsoft Hohm or Google PowerMeter is decontextualized from any specific circumstances, delivering feedback through abstract visualizations that can aid comprehension within any frame of reference, and can be displayed on any digital device.

4.2 Behaviour

Behavioural dimensions encompass the communicative intent, behavioural model, motivational strategy, and decision support parameters of a tool. Others have noted the gap between the psychological literature and the design of feedback on resource consumption [4], and as such the incorporation of these dimensions is central to our proposed framework.

4.2.1 Communicative Intent

What is the communicative intent of the feedback? Instances of resource feedback technology typically seek to inform, advise, or motivate conservation, or notify users of important system changes. The Kill-A-Watt electricity usage monitor simply provides information, without communicating any advice or encouragement to the user. Other tools like Microsoft Hohm provide advisory statements such as "Lower the temperature setting on your water heater and save $48 per year." Stepgreen.org is an example of a tool that seeks to explicitly motivate sustainable behaviours by enabling users to set and track their progress toward green goals.

4.2.2 Behavioural Model

What psychological model of behaviour change does the feedback address? In their discussion of designing eco-feedback technology, Froehlich et. al. [4] distinguish two broad categories of pro-environmental behaviour models. Rational choice models "assume that human behaviour is regulated by a systematic process of evaluating expected utility." [4] In this model, the benefits of a given action must outweigh its effort costs in order for an individual to take action. Perceived costs and benefits often extend beyond financial considerations to matters of convenience, comfort, and personal habits and values. The Blueline PowerCost Monitor exemplifies the rational-economic model of pro-environmental behaviour, providing feedback to users by displaying the real-time financial costs of their energy consumption. In contrast, norm-activation models are based on the premise that moral, personal, and social norms drive behaviour change. Selecting an appropriate behavioural model is related to the anticipated audience for the tool, and its expected use context. It will also inform the display units, physical and social scope, and scale of the data used to drive the feedback.

4.2.3 Motivational Strategy

What motivational strategy does the feedback utilize? Environmental psychology identifies three categories of strategies for motivating resource conservation: *antecedents*, *consequences*, and *social influences* [7]. Antecedents, including generic information, prompts, and persuasive media, are not sufficient in isolation to promote energy conservation: awareness does not always equate to behavioural change. Consequence strategies include feedback, incentives, and disincentives[1][7]. Social influences, such as presenting the consequences of behaviour contingent on the performance of a group, are effective in promoting conservation[1][7]. For example, comparing use between an individual or group to others in their neighbourhood, or to others with similar lifestyles [1][3][7].

Tools for motivating residential resource conservation typically use feedback, a consequence-based approach. However, research has demonstrated that feedback alone is not always a reliable method of motivating conservation in the long term, and that both consequences and social influences are strengthened when used in tandem. The motivational strategies selected by the designers of a feedback instance will be closely interrelated with the communicative intent of the tool, its behavioural model, and the kinds of decisions it is intended to support.

4.2.4 Decision Support

What mode of decision-making does the feedback support? Some forms of feedback support in-the-moment, tactical decision-making. For example, a time-of-use cost indicator on a smart appliance helps a resident decide whether now is a good time to run the dishwasher or turn on the air conditioning. Others support long-term, strategic decision-making. Google PowerMeter, with its analytical interface and in-depth metrics of past consumption, assists residents in making decisions about where to focus their energy conserving efforts: for example, inefficient appliances, wasteful heating systems, or standby power losses. Deciding which mode of decision-making to target with a tool will affect design choices in many dimensions of the framework, particularly spatial, temporal, attentional demand, and degree of interactivity.

4.3 Human Factors

Human Factors dimensions encompass the attentional requirements a tool demands, and its mode of interactivity.

4.3.1 Attentional Demand

What level of attention does the feedback require? In a home setting, we cannot rely on designing for a task-focused user in a traditional screen-based environment [3][10]. In fact, many of the feedback types we have considered do not fall into this paradigm. In this context, attentional demand is more complex than the dichotomy between focal and peripheral perception. We propose a gamut that ranges from perceptible to attentive, with alerts as a unique type requiring its own consideration.

Perceptible instances provide ambient feedback that supports at-a-glance awareness. Legible feedback requires some basic interpretation, but is not necessarily task-oriented, and provides on-demand information. Instances requiring attentive focus are typically associated with a traditional computing environment, and offer task-oriented utilities. These tools provide explicit information to support detailed analysis and sensemaking.

Alerts, due to their nature, demand the user's attention. These may be notifications about thresholds of use tied to systems with notification as their communicative intent. As utilities move to tiered pricing, such alerts can cue the resident that resource costs have increased, or that they are nearing a conservation target.

4.3.2 Degree of Interactivity

What degree of interactivity does the interface afford? The degree of interactivity of an instance can be mapped on a spectrum from passive to high. In passive interaction, the user does not manipulate the tool or interface, but changes they make elsewhere — for example, turning an appliance off — are reflected in the feedback. Conversely, higher degrees of interactivity enable manipulation of the tool through physical controls or a software interface in order to reconfigure available views. The degree of interactivity afforded by a tool will be linked to its mode of decision support, and its attentional demand, as well as its data sampling and reporting rates.

4.4 Aesthetics

What are the aesthetic criteria of the visualization? Kosara's distinction between artistic and pragmatic information visualization offers a useful system for classifying visualization systems based on aesthetic criteria [8]. Pragmatic visualizations focus on enabling the exploration and analysis of data sets. Instances of pragmatic visualization are recognizable and readable as visualizations of information, and the representations they use are generalizable to other data sets. In contrast, artistic visualizations primarily aim to "communicate a concern, rather than to show data." [8] Artistic visualizations are not always immediately recognizable or readable as visualizations of data, but can be learned over time.

The aesthetic dimension represents an important factor in our framework, as it expands the realm of visualization beyond analytical concerns toward a broader spectrum of representation and communication. Aesthetic factors will be closely enmeshed with design decisions regarding the binding of a feedback instance, and will affect the expressive potential of an interface.

4.5 Data

Data dimensions encompass the mental model, value type, scale, sampling and reporting rates, and the physical and social scope of the feedback.

4.5.1 Mental Model

What mental model does the data address? Feedback on resource consumption is typically expressed in one of four mental models of resource use, each with associated units of expression. Financial models translate usage into dollars and cents. Scientific models express use in commonly accepted measures, such as kilowatt-hours (kWh), or litres (L). Environmental models translate usage into emissions, expressed in units such as kilograms of carbon dioxide (kg CO^2). Finally, equivalency units translate use into commonly understood terms. For example, consumption activity may be expressed in "buckets of water, bags of coal," or "stacks of wood," [4] or the equivalent of daily activities, such as, "as much hot water as it takes to fill the bathtub." [4] In relation to environmental and equivalency models, Wood and Newborough note that "the accuracy of estimating such indirect effects [is always] questionable," [11] and as such can be problematic.

4.5.2 Value Type

Are the data presented in absolute or relative terms? Data can be expressed in absolute (40 litres) or relative terms ("10% more water than yesterday"). Relative terms emphasize comparison, while absolute values stand independently.

4.5.3 Scale

How large is the data set, as measured by the number of discrete data points available for simultaneous display? This straightforward dimension allows the scale of the data set to be mapped, from small — which we consider to be fewer than 10 discrete data points — to large. The Kill-A-Watt can report one discrete data point at a time. In contrast, information dashboards such as Pulse Energy can represent tens of thousands of data points simultaneously.

4.5.4 Sampling Rate

What is the sampling rate of the data? Data is either sampled continuously or at some measured interval. The Kill-A-Watt samples continuously in real-time, while energy bills use data sampled once every one or two months.

4.5.5 Reporting Rate

What is the reporting rate of the data? The reporting rate of the data is limited by but not always equal to the sampling rate. Continuous reporting means that data changes are immediately reflected in the feedback. Other feedback is gradually updated at some interval, though the data to drive it may be sampled continuously.

4.5.6 Physical Scope

What physical scope is encompassed by the data? Some devices are dedicated to providing feedback on individual outlets or appliances. Others are scoped to rooms, homes, neighbourhoods, or larger geographic areas such as cities. The physical scope of the data is distinct from an instance's spatial dimension. The spatial dimension reflects where the feedback is provided in relation to where the resource is consumed, while the physical scope is concerned with the physical scale that the data encompasses.

4.5.7 Social Scope

What social scope is encompassed by the data? The social scope delimits the human scale at which the data is collected. Conventional energy bills are scoped to households. Other tools collect data from entire communities to drive their feedback.

5 Conclusion & Future Work

The natural next step for our work is evaluation and validation. Here we are concerned with confirming the practical utility of the framework. That is, does it promote insight into the design and analysis of tools in this design space? Can it be operationalized within this scope? Continued refinement of the framework and efforts to analyze an extensive sample of existing instances will help to answer these questions.

Developing feedback for a home environment requires designers to make a series of tradeoffs. The goal of providing timely and in-depth feedback on resource use is constrained by unpredictable schedules of residents, varying levels of attention, diverse mental models, and numerous other factors that are beyond a designer's control. By delineating the dimensions of this design space, we hope we can provide a tool to approach these tradeoffs with clear goals and a sound understanding of the relevant considerations affecting the outcome.

References

[1] W. Abrahamse, L. Steg, C. Vlek, T. Rothengatter, "A review of intervention studies aimed at household energy conservation" *Journal of Environmental Psychology*, 25 (3), pp. 273-291, 2005.

[2] R. Aipperspach, B. Hooker, A. Woodruff, "The Heterogeneous Home," *Proc. UbiComp*, pp. 222-231, 2008.

[3] L. Bartram, J. Rodgers and K. Muise, "Chasing the Negawatt: Visualization for Sustainable Living," *IEEE Computer Graphics & Applications*, 30 (3), pp. 8-14, 2010.

[4] M. Chetty, D. Tran, R. Grinter, "Getting to green: Understanding resource consumption in the home", *Proc UbiComp*, pp. 242-251, 2008.

[5] J. Froehlich, L. Findlater, J. Landay, "The Design of Eco-Feedback Technology," *Proc. CHI*, pp. 1999-2008, 2010.

[6] A. Gustafsson and M. Gyllenswärd, "The power-aware cord: energy awareness through ambient information display," *Proc. CHI Extended Abstracts*, pp. 1423-1426, 2005.

[7] R.D. Katzev and T.R. Johnson, *Promoting energy conservation: An analysis of behavioural research*, Boulder, CO: Westview Press, 1987.

[8] R. Kosara, "Visualization Criticism—The Missing Link Between Information Visualization and Art," *Proc. InfoVis*, pp. 631–636, 2007.

[9] J. Pierce, W. Odom, E. Blevis, "Energy Aware Dwelling: A Critical Survey of Interaction Design for Eco-Visualizations," *Proc. OZCHI*, 2008.

[10] Z. Pousman, J. Stasko, M. Mateas, "Casual Information Visualization: Depictions of Data in Everyday Life," *IEEE Transactions on Visualization and Computer Graphics*, 13 (6), pp. 1145-1152, 2007.

[11] G. Wood, M. Newborough, "Energy-use information transfer for intelligent homes: Enabling energy conservation with central and local displays," *Energy and Buildings*, 39, pp. 495-503, 2007.