HOMEOWNER'S MODELS OF THE HEATING SYSTEM AND HEAT LOSS: EFFECTS ON HOME ENERGY MANAGEMENT

Willett Kempton
Center for Energy and Environmental Studies
Princeton University

ABSTRACT

Homeowner's models of their heating systems and of heat loss are examined through intensive study of a few selected cases. Homeowner's conceptions of these systems are compared with the formal models of our engineering and scientific institutions, and are evaluated for their effects on home energy management. It appears that people's heating system models can have a substantial effect on the management of thermostat setting. Homeowner heat loss models did not have measurable behavioral effects in our sample, even though these models varied substantially from the engineering model.

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INTRODUCTION

This paper analyzes homeowners' mental models of the operation of their heating systems and of heat loss from their houses, and the effects which these models have on home energy management behavior. The purpose of such a study is to learn to what extent homeowners' conceptions of the thermal dynamics of their houses diverge from the models of energy analysts, and, if they do, to what extent the divergence has practical consequences. Divergences matter only if they cause people to be unnecessarily uncomfortable, expend futile management effort, or waste energy. In conducting this type of work one must avoid the temptation to automatically downgrade informal models for being inconsistent with engineering knowledge. Otherwise it is difficult to evaluate the important question: Do the models work for the tasks to which the homeowner applies them?

The models described in this paper concern the control of the furnace by the thermostat, the rate of heat delivery and fuel consumption by the furnace, the loss of heat from the interior space, and the determinants of perceived comfort. Two types of heat management behavior will be related to the models. One behavior is the adjustment of the thermostat in various circumstances: When a steady temperature is desired, when one is not using the house and wishes to save fuel, and when one wishes to heat the house up quickly. The other behavior to be discussed is the "closing off" of unused rooms in the winter (shutting the door and blocking vents or other sources of furnace heat).

The data presented here are cases drawn from an intensive study of a small number of houses. The data for each case are extensive; homeowner models are described through a combination of fine-grained instrumentation and ethnographic interviewing. As a point of comparison with homeowner models, I briefly review two models known to the energy research community: the engineering model of thermostat operation and heat loss, and the physiological model of human body temperature. Such comparisons are common in mental models research (Gentner and Stevens 1983). I then describe an idealized form of a homeowner's folk model. The term "folk model" is used to refer to a mental construct which is not taught in formal institutions, but rather is learned by experience or by communication with non-technical people--the way most of our commonsense knowledge is acquired (Kempton and Lave 1983).

INSTITUTIONALIZED MODELS

I use the term "institutionalized models" to refer to models developed and taught by formal institutions, such as professional societies, design firms, and universities. On the assumption that the readers of this paper are already familiar with these models, I shall not review them in depth, but simply mention the key components which relate to the present study.

Engineering model

For winter heating, the house is considered a closed shell with energy input as fuel and energy output as heat loss to the environment. Heat loss is through the shell, and is proportional to the difference in temperature between the inside and outside of the shell. This discussion will concentrate on homeowner daily energy management rather than shell modifications, so the shell's constant insulation value and air leakage area are not discussed here. Within the house, the furnace is operated automatically by a thermostatic switch, adjustable along a scale calibrated in degrees F--the calibration corresponds to the temperature which the thermostat will maintain. The thermostat simply turns the furnace on and off according to temperature; it does not control the rate at which the furnace runs. (While some units for large buildings do control rate, few home ones do).

A set of management consequences follow from this model, of which the major ones are listed here: To maintain an even indoor temperature, one need only set the thermostat to the desired temperature and leave it; control is automatic. If the house is cold and one wants to heat it quickly, there is no advantage to turning the thermostat up above the final desired temperature, since the furnace runs at only a single rate. With respect to heat loss, the lower the interior temperature the less heat loss and the less fuel consumed. Thus, for economy, one should set the temperature at the lowest end of the comfortable range when the house is occupied, and set it even lower whenever the house is unoccupied or when people are asleep.

Physiological model

Although engineering analyses often stop at air temperature, the physical measurement corresponding more closely to perceived comfort is average skin temperature (ASHRAE 1981). The aspects of this model relevant to this paper are that skin temperature is dependent not only on air temperature, but also on metabolism (affected in turn by activity), humidity, infrared radiation from surrounding objects such as walls and furniture, and clothing temperature.

One obvious consequence of this model is that more clothing makes a person feel warmer (since the clothing layer nearest the body will be warmer). A less obvious consequence concerns heating up a cold house. Since clothing and infrared sources may heat up more slowly than air, when a house has just heated up an occupant may still feel cold even after the air temperature (as measured by the thermostat) has reached the desired setting. Put another way, during transients comfort may lag behind air temperature.[1]

A FOLK MODEL

To contrast with the two institutionalized models, I describe a folk model which people apparently learn from practical experience or from talking with other non-technical people. This folk model has two components: it regards the thermostat as a valve and regards heat loss as spontaneous dissipation. An earlier paper described interview evidence for the valve model of thermostats (Kempton 1986); this paper expands that work by including models of heat loss, and by linking the models to our observations of behavior. Only a few informants possess this folk model in complete form, but many informants use parts of it intermixed with the institutionalized models described above.

In the complete folk model, the thermostat is seen as a continuously-variable adjustment of the rate at which the furnace produces heat, much like a water tap or the gas burner on a cooking range. Heat spontaneously dissipates from the inside of the house, as one informant described it, just like heat dissipates from an oven. The rate of dissipation is proportional to the volume of the space within which it is dissipating, and to the temperature of the air. This folk model has two parts: valve control and spontaneous dissipation. I describe these as a single model not because they are logically connected but because they both arise from non-institutional sources, and they co-occur in many individuals.

One behavioral consequence of the valve model is that one would expect higher thermostat settings to heat the house up more quickly, in the same way that a higher gas range setting will boil a pot of water more quickly. Another consequence is that a steady temperature would be maintained by adjusting the thermostat to balance the heat coming in against the dissipation of heat. Using the range analogy again, this would be like adjusting a low flame to maintain a cooking pot at a steady low boil. The only control mechanism sensitive to temperature is the human operator.

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[1]The amount of lag and its relationship to initial temperatures and other variables is in need of a more quantitative analysis.

Although the folk model is very different from the engineering and physiological models, it makes a number of parallel predictions about the world. The valve model makes the following predictions. Higher settings of the thermostat (valve) will make the house warmer inside. Lower settings lead to lower fuel consumption and colder indoor temperatures. The thermostat may need to be set higher in order to feel warm quickly (predicted by the physiological model, since comfort will lag behind air temperature). More generally, the valve model provides a rationale for making an adjustment to the thermostat whenever one feels too warm or too cold, whereas the engineering model would suggest that one should wait for the thermostat to take care of the problem automatically.

Notice that the valve, conceived to control a continuously-variable furnace, incorporates some consequences of the physiological model into the furnace and thermostat themselves. A higher initial thermostat setting is considered to actually send heat faster, rather than just compensating for lags in clothing temperature and infrared radiation.

The spontaneous dissipation model also makes several parallel predictions to the engineering model, as follows: A larger interior space costs more to heat (this is generally true, given typical U.S. house shapes). Higher indoor temperatures consume more heat. Closing off rooms saves heat.

This section has pointed out the parallel predictions made by both the folk and institutional models. There are also divergences, which will be discussed with the case study data. Although this paper deals with models, I acknowledge that some folk knowledge is held not as part of a coherent model, but as isolated situation-specific learned data (diSessa 1985).

METHODS

This paper is part of a study of home energy management which has combined interviews with instrumented data collection (Weihl, Kempton and DuPage 1984). Seven Michigan houses, selected for diversity, were instrumented over a two-year period. In addition to energy variables such as temperature and furnace operation, the instruments directly measured behaviors such as thermostat setting and operation of windows and exterior doors. Behavior is also corroborated through reported daily schedules in the interviews.

Homeowners' thermal models are elicited in the interviews both through open-ended requests for explanations like "How would you explain why the furnace uses more fuel in the winter than it does in the fall or spring?", and through targeted diagnostic questions like, "Would closing off an interior room (without outside walls) also save fuel?" These data are presented both to provide evidence for the folk models and to illustrate the correspondence between models and behavior.

The data comprise only a few illustrative cases selected by the author rather than a large representative sample. While a case study approach cannot offer statistical validity, it seems necessary to get a complete picture of the phenomena involved, many of which have not previously been reported in the literature. I hope this work stimulates further research which can ask more specific questions on a larger sample.

MENTAL MODELS AND HEAT MANAGEMENT BEHAVIOR

In this section I illustrate the behavioral patterns of two households and show that each corresponds to the verbally elicited folk models.

The first case, House 2, is a white-collar, middle income couple in their early 60's, who I'll call here Bill and Renee. The data on thermostat setting behavior are illustrated in Figure 1. The top solid line is the thermostat setting, measured every fifteen minutes over a one-week period. Interior temperature is the top dotted line, which tracks thermostat setting. Outside temperature is the middle dotted line (ranging from the high 30s to the low 60s), and furnace runtime in minutes per hour is the bottom dashed line. The first two days of this week are warm, and no adjustments are made to the thermostat (the high settings these days are unusual in this house, which would normally leave the thermostat low if the furnace was not needed). From the third day on, the figure shows that the thermostat is set up and down in the regular daily cycle typical of this house.

Consistently with the behavioral data, this household reports a regular schedule of nighttime setback during the interview, both in the oral interview and on a written questionnaire. They report a 62^{o} setting at night and when away, and 70 or 72 when home. On days when both are out working, they leave it down the entire day.

The next question is whether their models of the house and furnace support this behavioral pattern. Bill had a fair approximation to the engineering model of the heating system. When asked why the furnace uses more fuel in the winter, he said "...it's gonna come on more often...because the thermostat is calling for the furnace to come on to maintain the temperature of the house, and the house is radiating... and the radiation rate is a function of the difference of temperature between the outside and the inside". When asked about turning the thermostat down at night: "to allow the temperature of the house to go down at night (pause) I think saves money because the difference between the inner temperature and the outer temperature is less...so there's less heat loss." Apart from the use of the word "radiation" for what engineers would attribute mostly to conduction, this is a very good approximation to the engineering model described earlier.

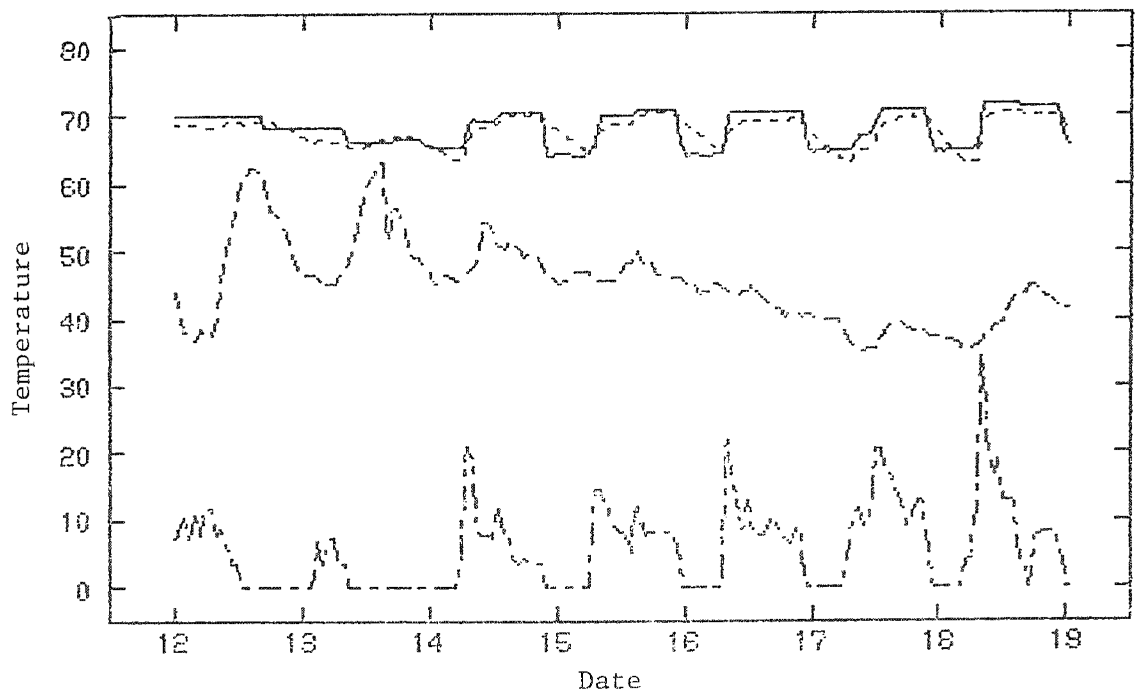

Figure 1. House 2 heating data, 12-18 April 1984. From top to bottom, lines indicate thermostat setting, interior temperature, exterior temperature and furnace runtime (in minutes per hour).

In short, their behavior, leaving the thermostat setting at one point, is consistent with the model elicited in the interview, that the thermostat "Calls for the furnace to maintain the temperature". The behavior of turning the thermostat down at night is justified by recourse to a model of heat loss as proportional to the difference between inside and outside temperature. A model this close to the engineering one is unusual in our data.

They kept a corner bedroom closed off and unheated in the winter, so we explored their model of heat loss further by asking why that would save heating cost: Bill said "it does take energy to heat up cubic feet...so by reducing cubic feet of space [you save fuel]". To more specifically distinguish whether his model of loss is via heated space, rather than the engineering model of loss through the surface, I asked him to compare closing off a room with exterior walls versus one which was completely in the interior of the house. Although he began "I might just guess that the exterior wall might be more advantageous just to reduce the number of cold walls..." he later again refers to the "volume" of the room as determining the saving from closing it off. Since this house, like most single-family American houses, has no large interior rooms, his belief that closing them off would reduce heat loss could not be acted upon. However, the spontaneous dissipation model could mislead choices between closing off, for example, a room with one exterior wall versus a slightly smaller add-on with three exterior walls.

All the families from whom we could get clear responses to the heat loss and interior room questions did use aspects of the spontaneous dissipation model in their thinking. For example, another man who had a fairly clear feedback model of the thermostat was asked about closing off an interior room, a room that "didn't have any exterior walls". He replied that the walls of the interior room would have to be insulated to have a significant effect. His wife said that it would make a difference but not as much as an exterior room. He then said "I don't think it would make a very significant difference because the heaters and the outlets in the rooms are supplying heat ... trying to reach a level of comfort and if you have an interior room ... interior walls aren't insulated anyway so they're still continually going to be losing heat from the other rooms to supply that room that is not being heated." Although he does not explicitly mention consumption as proportional to volume of air, the spontaneous dissipation model is clearly indicated by the notion that the surrounding rooms would have to "continually" supply heat, unless the interior walls were insulated.

The second example of correspondence between thermostat models and behavior is household 5, comprised of Jonelle, her elderly mother, three grandchildren, and occasional live-in visitors. Jonelle's full-time job as a nutritionist supports the entire household. Their thermostat behavior is plotted in Figure 2 for the same week as shown for the previous house. Here we see a much more erratic pattern, no clear repeated daily cycle, and settings ranging from 50^{o} to 86^{o}F. It is unlikely that these thermostat changes reflect dramatic swings in the household's temperature preferences, thus this house is probably using the device in some qualitatively different way from the previous example.

My initial interpretation of the interview data offers a clear example of both informant's ability to meet interviewer expectations, and how this can be overcome through tape recording and follow-up interviews. A superficial reading of the transcript suggests a daily setback pattern. Jonelle said, "I used to make it a habit turning the heat down when I got ready to go to work..." Her grandson says: "I turn it down...around night time when my Ma tell me to turn it down". During the day, she says: "It's hard to exactly say when, you know, we really, uh, turn it up [upon awakening], but I do feel pretty good saying that from 7:30 a.m. to...like maybe 3:30 it's left on one thing". From statements like this during the first interview, I initially expected that we would see a regular daily thermostat pattern like that in the first house.

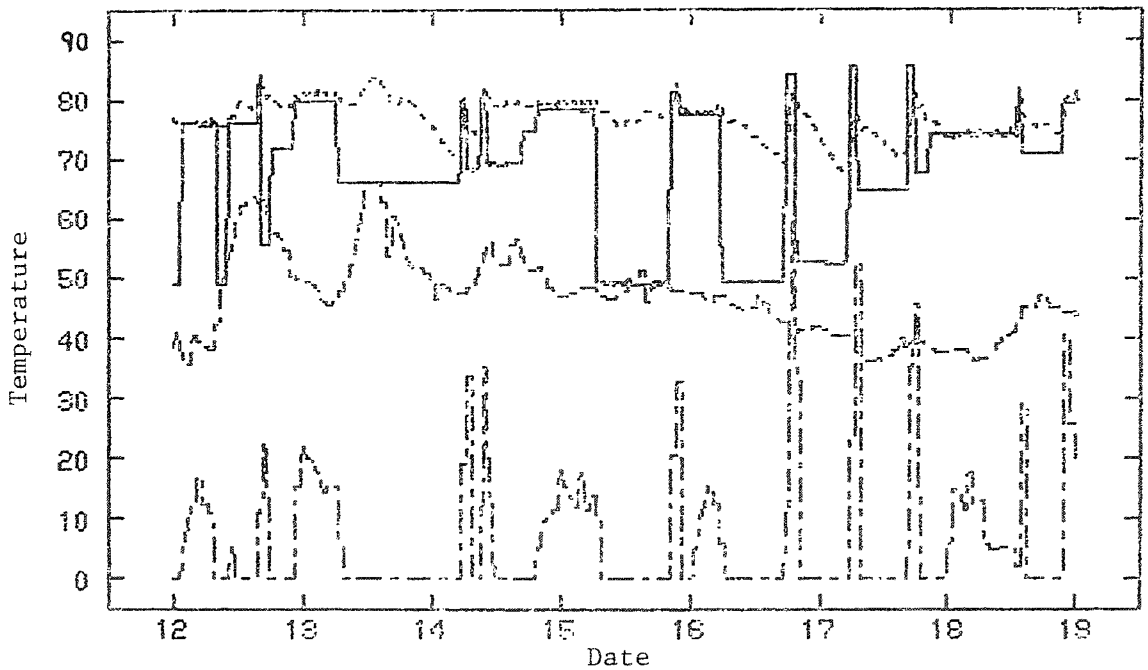

Figure 2. House 5 heating data, 12-18 April 1984.

A closer reading of the interview transcript reveals many references to environmental or personal conditions which require thermostat adjustment, not reported by the prior family: "...it used to be that when I have the oven on, you automatically had to turn the heat down...", "...if it's real hot, set it down to 68 or 70". "I used to try to keep it on about 69 and 80, tryin' to cut down on the gas... But...I've got six of them [kids] going in and out the door, 'cuz they're playin', gettin' cold, and coming back in. Then if I have, maybe four or five grown-ups comin' in...and then by the time you get me in and out, then that, this house is full, you know, turn it up...'cuz you're cold, I mean. But when you're hot, turn it down..." All these reports suggest a need for human intervention to change the thermostat setting.[1]

What is Jonnelle's folk theory about how the house and furnace work? Again, I drew incorrect conclusions immediately after the first interview and before reading the transcript. She described the feedback effect of the engineering model quite clearly in response to my questions

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[1]She also felt that a new thermostat we installed required more frequent adjustment than their old one, although we checked it with our instruments, and had it checked by a furnace repair service, and could find no evidence of abnormal operation.

about what made the furnace turn on and off: "when I figure that it gets to below...that temperature that it...should come back on...every time you hear the furnace...the house is cooled off enough and it's getting ready to kick it back up".

While Jonelle describes a feedback mechanism, she does not consider the furnace to have only on or off states. In the first interview she said that she discourages the children from turning it up to 90, "because 9 times out of 10 you never have to go to 90...", which suggests that sometimes you do have to go to 90. In the second interview we had the advantage of better rapport and ability to discuss graphs of her own behavior in the house. We asked more specifically about turning the thermostat up to heat the house faster: "...if I turn it up as far as it will go, the house will get warm, and [then] you cut it back down". The interviewer asked if she wanted it to get to 75^{o}, would setting it to 85^{o} get it there faster, and she replied: "...when I turn mine's up to 85, I didn't have an idea I was turning it up for it to get to 75...I was turning it up to get the house hot, then when the house got hot, I could turn it back down." "...if it was like say 69 or 65, and I turned it up to 70, it don't seem like to me it do anything. I had to go up over that in order to hear that noise for it to come on 'cuz you know you could hear the furnace when it comes on." She also talks about the "high heat" which comes out at higher settings, and uses the analogy of preheating an oven to a higher temperature to heat it up faster because you get a higher flame.

As in the first example, we find in this household that the theory of how the furnace and thermostat operate are consistent with the behavior when using them. The style of management in this household requires much more active monitoring of interior temperature, since if the thermostat were left at 85^{o} or at 50^{o}, the house would become uncomfortably hot or cold. The figure shows that the house does not reach these extremes because the thermostat is set up when the temperature drops to 70^{o} and set down when it rises above 80^{o}. Since there are many people in this house, since it is rarely vacant, and since several people do adjust the thermostat, this management style does work; it just requires more attention and management effort.

This pattern of frequent changes may appear energy-inefficient on the graph, but we have no evidence that it is. In fact, based on a rough degree-day correction (ccf/degree-day 65^{o}F) we find this house using more energy the subsequent year when a new head of household leaves it on a single (but slightly higher) setting all day.

There is a difference in management strategies which may be as important as the difference in homeowner models. The first house had fixed numerical temperatures which they maintained for comfort. If they felt too cold at the proper setting, they might put on additional clothes, or take other measures. The second house followed the straightforward rule: if it's too cold, turn it up; if it's too hot, turn it down. For elegant simplicity, that's hard to beat.

In these two examples, we see a close link between the model used to conceptualize and explain the operation of the heating system and the behavioral practices managing that system. While two examples cannot provide any proof of a causal link, these case studies suggest a plausible connection from mental models to energy management behavior.

CONCLUSIONS

This paper has explored the models which homeowners have of their heating systems and of heat loss from their houses. In the operation of the furnace and the thermostat, the most common thermostat model corresponds to the engineering model as a feedback system. Another model considers the thermostat to be a valve which adjusts the rate of heat from the furnace through a continuously-variable range. In the one house in which this model was reported by the people who adjusted the thermostat, I found a pattern of frequent thermostat adjustments, with settings varying over a wide range. This management pattern requires more attention and higher management effort of the occupants. It could also cause energy waste if the thermostat setting were forgetfully left high, but that did not happen at this house.

In heat loss from the house, all those who made clear statements considered the house to lose heat in proportion to the volume of heated space, rather than in proportion to the surface area of exterior walls. This was verified when they agreed that closing off an interior room would make the room colder and save energy. This was said even by the few people who volunteered that heat loss was proportional to the difference between indoor and outdoor temperature. Since the decisions actually made to close off rooms always involved rooms with exterior walls, this belief had no measurable consequences. However, it would mean that we should expect very few people to recognize that more energy would be saved by closing off an addition with three exterior walls than by closing off a normal room with one or two exterior walls. It would also imply that energy inefficiency is not recognized when considering building such additions. The attribution of heat loss as proportional to volume of heated space seems to draw from the spontaneous dissipation folk model. It may derive from experience with heating foods, the rate of temperature rise and cooling is related to the volume. That immediate tangible experience might then be extended to the belief that heat must be continually supplied to maintain an even temperature.

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