Beyond fabric: how heating practices can be incorporated into domestic energy modelling

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Abstract

It is widely demonstrated that the nature and state of a building's fabric are only partly responsible for the amount of energy used in the building: the behaviour of occupants is also a significant factor. Domestic energy consumption has typically been modelled based on details of building fabric and average internal and external temperatures, with building use factors being included as assumptions for typical occupancy. The UK's Green Deal Occupancy Assessment is an example of an attempt within a policy instrument to include aspects of household occupants' behaviour in its calculations, but this is limited in its ability to compare the effects of different heating practices.

In contrast to the engineering principles approach to domestic energy consumption, there is a growing recognition that energy is consumed in the provision of services such as thermally comfortable rooms, sustenance and hygiene. These energy services are delivered or attained through the performance of practices as defined in social practice theory. By including domestic heating practices as a way of delivering or attaining the service of thermal comfort within homes, aspects of building occupancy can be better included within domestic building energy modelling.

Within this paper, examples are given for how heating practices can be represented in dynamic building energy modelling; in some cases these can be achieved using existing model capabilities and in others, additional inputs and processes are required. These examples are illustrated for the case of heating control practices and the differences of heating energy consumption and temperature profile are shown. This article presents an improved methodology for modelling of domestic heating practices and illustrates this methodology with examples from the authors' own modelling work.

Introduction

Renovation of the existing housing stock has become a priority in recent years, motivated by political and environmental aims. Building energy modelling is a commonly used tool for understanding current energy use and how energy reductions could be made within the residential sector. A large variation in energy use between similar dwellings is often attributed to the effect of occupant behaviour (Gill, Tierney, Pegg, & Allan, 2010; Gram-Hanssen, 2004, 2012), however building energy models do not yet include most aspects of occupancy but use assumptions of 'typical' occupancy. Practices are considered to be the base unit of human behaviour within social practice theory and therefore by incorporating these into building energy models, we can enable the subtle but important differences in how people use their homes to be included in domestic energy modelling.

In this paper, we identify some different types of heating practice and outline techniques for better incorporating these heating practices into building energy models. The paper begins by introducing what building energy models are and the extent to which they currently include aspects of occupancy. We move on to considering the energy services concept and social practice theory as means of understanding energy use in homes, and insight into heating practices is gained from literature. Next is a demonstration of how heating practices can be interpreted and translated into modelling input. Examples from the authors' work are used to illustrate the strategies discussed. This is followed by a discussion of what further steps could be taken to enable building models to best represent how homes are being used.

Building energy modelling

Building energy models (BEMs) allow the calculation of energy demand in a building based on known, assumed and approximate values of building characteristics, weather data and occupancy. Heat demand calculations are based on thermodynamic equations for heat flows into and out of a building, which may be treated as a single or multiple zones. Equations are evaluated over a given time-step; the time step may be short (1 second to 1 hour) or long (a month or a year). Temperatures are averaged over the time step and therefore a shorter time-step allows a model to more realistically represent the dynamic reality of a house. The longer the time step, the more the model represents a steady state calculation.

BEMs can be used for calculating the predicted energy demand of a building or for calculating predicted energy savings following the introduction of energy efficiency measures (EEMs). For these purposes, BEMs have been developed for use in building energy efficiency policy, most notably in the UK the Standard Assessment Procedure (SAP) which is the basis for Energy Performance Certificates (EPCs). SAP is based upon the Building Research Establishment's Domestic Energy Model (BREDEM) which is a steady state model as it calculates energy demand over monthly time-steps. SAP has received criticism for not being adequate measure of building energy performance (Kelly, Crawford-brown, & Pollitt, 2012) and a large performance gap still exists between predicted and measured data.

It is widely acknowledged that building occupancy has a large influence over energy consumption and therefore the use of the established typical occupancy assumptions limits the accuracy of any BEM. This was recognised in the development of the Green Deal, the UK's most recent policy programme in promoting domestic energy efficiency. Calculations of energy savings for a range of energy efficiency measures include information from an occupancy assessment. The occupancy assessment incorporates details on occupancy schedule, set-point temperatures, specification of secondary and alternative heating types, as well as appliance usage. These details have been shown to improve upon the typical model assumptions used previously, however research into the improvement of building energy performance calculations using similar inhabitant behaviour showed only modest improvements in the energy consumption estimate (Ingle, Moezzi, Lutzenhiser, & Diamond, 2014) and does not show signs of accounting for the sometimes threefold difference in energy use seen in similar buildings which is ascribed to the influence of occupancy. The inclusion of occupancy details in the Green Deal Assessment is therefore beneficial in terms of improving the estimations of energy savings following the inclusion of EEMs, but does not go far enough to close the performance gap between predicted and measured energy usage and energy savings. This suggests that there is a limit to the achievable accuracy of such steady-state BEMs, and more dynamic building energy simulations models may be required to increase the accuracy of energy modelling with respect to occupancy. These could have a greater capability to include aspects of occupancy energy using behaviours, which vary greatly across the population.

Energy services and social practice theory

The energy services concept states that energy demand is not driven by a desire for given amounts of kWh of electricity or volumes of gas, but for the services which these energy carriers deliver. Energy services required in residential buildings comprise thermally comfortable spaces, illumination or ambience, to preserve and cook food, to be clean and within a clean environment and to help with activities such as audio visual entertainment and physical exercise. Social practice theory (SPT) is based upon the concept that practices, and not people, are the base unit of consideration for energy consuming activity. Practices can be better understood by considering them to be made up of 'elements', namely materials, competences and meanings (Shove & Pantzar, 2005). Practices are performed in order to deliver or attain a service. For the delivery of thermal comfort, heating practices include controlling central heating, lighting a fire or putting on warmer clothing.

The variation in practices between people and over time could be due to the heating controls available (material elements), their ability to use heating control technologies (skill/know how) or their motivation to save money, limit environmental impacts or attain their desired comfort level (meaning).

Studies into domestic heating practices have been carried out through interviews, ethnographic studies and questionnaires (Madsen, 2014; Peeters, Van der Veken, Hens, Helsen, & D'haeseleer, 2008), or measuring of temperature profiles in one or more rooms (Huebner et al., 2013, 2014; Kane, 2013) or a combination of both (Love, 2014). Other studies of empirical evidence have shown that despite highly efficient and low carbon technologies having been put in place, occupants are seen to rely on alternative, more familiar practices to attain the same service. Examples of this have been using secondary heating rather than engaging with heating system controls (Chiu, Lowe, Raslan, Altamirano-Medina, & Wingfield, 2014), or opening windows rather than using advanced mechanical ventilation with heat recovery technologies (Behar & Chiu, 2011). This demonstrates that the technology or EEMs in place in a house does not determine what heating practices are carried out.

Gram-Hanssen (2010) undertook interviews with householders as part of a broader study focussed on electricity, water and heat consumption in a suburb of Copenhagen, Denmark. Five families' approaches to regulating their indoor environment are described in detail and show evidence of a broad range of practices. These include daily and annual heating periods, temperature of rooms and variation in room temperature within the dwelling, use of heating controls and thermostatic radiator valves (TRVs), circulation of air or heat around the house by opening or closing internal doors and airing of the house by opening windows or trickle vents during the day or at night.

Other literature and studies have reported on practices in which occupants warm themselves rather than the air around them, such as wearing warmer clothes or using personal heating, and this allows them to be thermally comfortable at a lower indoor air temperature (Royston, 2014; Shove, 2003).

APPLYING SOCIAL PRACTICE THEORY TO MODELLING WORK

Two previous examples have been found in literature in which authors have addressed the challenge of bringing aspects of social practices into energy modelling in order to build more representative models.

Higginson *et al* (2014; 2011) used dynamic system modelling to represent the practice of "doing laundry" as an example of how SPT can be incorporated into a bottom-up practice based model of energy demand. Systems dynamic theory allows the portrayal of complex systems into a few simple components characterised as stocks, flows and feedback loops. Their work demonstrates that the practice of "doing laundry" can be mapped as a complex system within the broader life of a household, and that by considering 'stuff', 'image' and 'skill', the boundary of the system is wider than just the washing machine. This enables the identification of a broader space for analysis when looking for possible interventions in reducing energy demand for laundry.

Rodriguez and Calderon (2014) outlined how the insight gained into household heating practices within SPT could be applied to a city scale model for calculating energy demand in the household sector. In their approach, they consider household practices as the base level of energy use and therefore the predicted energy use of the city is based on variety and flexibility rather than typical or average behaviour. They propose the carrying out of a survey to develop a better understanding of how household practices and demand-side flexibility affect energy demand. The outcome of this work would be to model energy demand at residential level and to be able to evaluate how different practice scenarios would affect total energy demand.

These previous studies demonstrate that there is interest in incorporating household practices into models of household energy demand in order to improve tools for investigating how to reduce energy demand.

Modelling heating practices in domestic building energy models

In the authors' broader work (not yet published), a building energy model has been developed with an an aim to incorporate some of these issues relating to user practices. BEMs commonly have the option of modelling occupants' control of heating by defining a heating schedule and a set point temperature in each room or zone, and by specifying a maximum heat output of the heating system. Additional heat sources can be inputted as internal gains (either secondary heating or heat emitting appliances), and ventilation and infiltration rates can be specified, which also contribute to heat calculations. However, there are limits to current model capabilities.

MODELLING TECHNIQUES

In order for heating practices to be modelled, they must be interpreted and translated into the model parameters. This has been done for a range of common domestic heating practices, and Table 1 shows how these align to common modelling parameters. These are then further explained below and the example of heating control is illustrated thereafter.

Internal temperature

The temperature to which a house is heated may be determined by occupant or the present heating system. The occupant's preference may depend on perception of comfort, sensitivity to financial cost or factors related to environmental concern. It may be higher if the house occupants prefer to wear less clothing indoors or lower if they expect to be doing higher metabolic activity. However, if the heating system is not powerful enough to reach and maintain the occupants' chosen temperature, the maximum power of the heating system will determine the internal temperature. For some occupants, different preferences for temperatures throughout the day or during different activities means that they vary the temperature across the house (for example lower temperature whilst sleeping) and this is achieved by various heating control practices. Chosen internal temperatures can be modelled by fixing a set-point temperature and resulting internal temperatures can be modelled by specifying the power of the heating system.

Time over which home is heated

The time over which a home is heated relates to a daily occupancy pattern and to heating control practices. Decisions as to how to regulate heating throughout the day may be according to occupancy schedule or based on 'folk theories' such as learning that it uses less energy to leave the heating on all day. This can be set in building models by assigning a set-point temperature (or maximum heating output) at chosen heating times; heating times will depend on the type of heating control used.

Occupancy schedule is rarely uniform every day and this may or may not affect the time over which the home is heated. In those cases when heating time varies depending on occupancy schedule, models would benefit from having a representative variety of occupancy schedules as the input. Many building models offer the capability of specifying alternative occupancy for different days of the week, but this could also be achieved by coupling building model inputs with statistical occupancy models such as those developed by Aerts et al. (2014).

Heating control

Methods of heating control present one of the largest variations between households. Manual switching on and off of heating system is the most straightforward heating practice and it is commonly seen and reported in literature. This can be simulated in building modelling by setting a desired comfortable temperature set point at times of heating and a low temperature when heating is off, or alternatively setting heating power to full or zero respectively. However, a commonly observed method of setting the heating system on or off was to override the thermostat (30 °C for 'on', 10 °C for 'off') when the temperature reached a certain minimum or maximum. This would simulate as oscillating temperature and heating power through a period of occupancy based conditionally on the internal temperature, and is not commonly available in building modelling. Heating can be manually switched off in unheated rooms by turning off the heater (or setting TRVs to zero) and this can be simulated by setting the heating power in these zones to zero.

In contrast to manually switching heating on and off, thermostats are commonly used to maintain homes at a desired

Table 1. Examples of how heating practices can be interpreted and translated into model parameters.

		Model parameters						
Heating practices		Set point temperature	Heating schedule	Which rooms are heated	Heat sources used	Ventilation/ infiltration	Building geometry	Heating system power
Choice of internal temperature		✓	✓		✓			✓
… including variation throughout house		✓	✓	✓	✓			✓
Time for which home is heated		✓	✓	✓	✓			✓
Heating control	Manually switching on/off	✓	✓	✓	✓			
Heating control	Setting thermostat and then no further interaction	✓	✓		✓			
Heating control	Use of thermostatic radiator valves	✓	✓	✓	✓			
Doors open/closed throughout house							✓	✓
Use of secondary heating			✓		✓			
Airing of house (windows/vents)						✓	✓	✓

temperature. These may either be simple wall thermostats (often coupled with a timer on the boiler for when heating should be on or off) or programmable thermostat for which the temperature can be varied throughout the day. A simple wall thermostat can be modelled as a set-point temperature and coupled with a schedule of occupancy. The programmable thermostat can be modelled in a similar way but with the potential to vary the set-point temperature throughout the day.

The main difference between manually switching heating on and off and heating controlled by timer is that households can set heating to come on early and therefore the home is warm when they arrive. The time taken to warm up will vary throughout the heating season but heating timers are unlikely to accommodate this (commonly set at half an hour before occupancy). This results in some cases of under heating when occupants arrive home (for cold external periods) or unnecessary heating of unoccupied space (for warm periods), and this is particularly the case when occupancy patterns are not uniform throughout the week or the heating season. Smart heating systems are starting to be available on the market which can learn a household's occupancy pattern or recognise when occupants are coming home and heat the house accordingly. To simulate these heating systems a proportional-integral-derivative (PID) control method could be incorporated into a model which could calculate the heat input and therefore time required to raise a room to a desired set-point.

Secondary heating

The use of secondary heating was found to be a common heating practice, whereby a secondary heating device, such as an electric heater, was switched on when the room temperature was deemed too cold, or a wood or gas fire was lit in a living space for temperature and aesthetic reasons. These are typically modelled as a heat gain which is turned on and off according to a use schedule. The use of secondary heating would be better represented if it could be controlled based on the temperature dropping below a certain level in the space in which it is commonly used as it is often switched on in response to an occupant feeling 'too cold' rather than a specified schedule. The availability of conditional control within building models, or set-point temperature bounds as upper and lower limits, could enable decisions (conscious or unconscious) upon which heating practices depend to be represented more realistically.

Internal doors

When internal doors are left open, heat can move between thermal zones. Often the decision is made to keep doors closed when it is desired that the house maintains a temperature gradient (such as a warm living room and cooler bedroom). This can be represented in a model by inter-zone infiltration or by detailing doorways in the building geometry and specifying them as a 'virtual surface'. However, the specification of rate of infiltration through doorways is not straightforward and could be investigated by computational fluid dynamics or by empirical testing.

Airing of house

Open windows can be treated in models as natural ventilation, however specifying the rate of ventilation is non-trivial as it relies on factors such as internal and external temperatures and external wind speed. This factor has been further investigated by Fabi et al. (2013).

ILLUSTRATION: HEATING CONTROL

To illustrate the examples given, a typical UK two bedroomed semi-detached ('duplex') house has been modelled using TRNSYS software. These results are taken from wider modelling work being undertaken by the authors.

In this model the household are a working couple who are absent from the house between 08.30 and 18.30 and go to bed at 23:00. Their comfort temperature for living spaces is 21 °C and bedroom is 18 °C. Four different heating practices are shown for how this comfort level could be delivered. Table 2 shows a description of the four heating practices and explains how these are interpreted and translated into model parameters. By being able to model the practices they might perform, the effect of this on total energy consumption and living room temperature profile is determined, as shown in Figures 1 and 2 respectively.

As can be seen from Figure 1, the energy required for heating differs depending on the heating practice; heating continuously on, controlled by the static room thermostat shows the highest levels of heating energy consumption and manual on/off control of heating system shows the lowest heating energy consumption. However, Figure 2 shows that manual temperature control leads to the temperature of the house being lower than that which is considered comfortable by the occupants for much of the heating period. The different heating controls can therefore be shown to have different impacts on the total energy consumption and the delivery of the service of thermal comfort to the occupants.

FURTHER ASPECTS OF PRACTICES

In order for practices to be better modelled and for the effect of practices to be compared, further aspects could be included in building energy modelling:

- Conditional input: the ability to specify decisions based on decision criteria other than a heating set point or schedule. In the case of manually controlled heating, this could also be represented as set-point temperature bounds with lower and upper limits to trigger heating turned 'on' or 'off' respectively (dead zone control).
- Variation of schedule by coupling with probabilistic model of occupancy based on an individual household or based on larger scale population statistics: As well as allowing an individual household to be modelled over a long period of time, this could allow modelling of the energy use of a larger population whilst avoiding the common occupancy assumptions.
- Consideration of heat flows as stratification in rooms or flows through open door: this could enable a better understanding of how heating practices affect temperature distribution between or within rooms. This could be achieved by breaking thermal zones into smaller sized zones to investigate effects of thermal stratification or by coupling with computational fluid dynamic models.

CONCLUSION

The behaviour of occupants has a significant effect on domestic energy consumption and this needs to be reflected in the results of BEMs, especially as these models are increasingly being used in policy. Social practice theory identifies practices and not people as the centre of analysis in understanding energy

Table 2. Explanation of how heating control practices are interpreted and translated into model parameters.

Heating control practice		Details	Model interpretation
A	Temperature maintained at set-point throughout day.	Occupants leave heating on in house at all times, controlled by static room thermostat.	Temperature set-point set at 21 °C throughout day.
B	Heating switched on and off manually.	Heating switched on in the mornings and evening when the dwellers wake up and return home respectively. Heating is switched off when they leave for work and go to bed.	Heating set-point set at 21 °C when house is occupied, heating turned off (no heat input) when occupants are absent or asleep.
C	Heating set-point temperature controlled by programmable thermostat.	Heating set to come on before they wake up and turns off when they go to work. Heating setback temperature is set whilst out of house. Heating comes on before they arrive home from work and turns down to night temperature before bed.	Heating set at 21 °C between 06:30 and 08:30 and again between 18:00 and 22:30. Heating set-back temperature set to 16 °C during day (08:30 to 18:00) and 18 °C during night (23:00 to 06:30).
D	As C, plus unused rooms are unheated.	As above, but spare bedroom and secondary living space (used as storage room) are un-heated by turning TRV to 1.	As C in occupied rooms. In unoccupied room heating set-point set at 14 °C throughout day and night

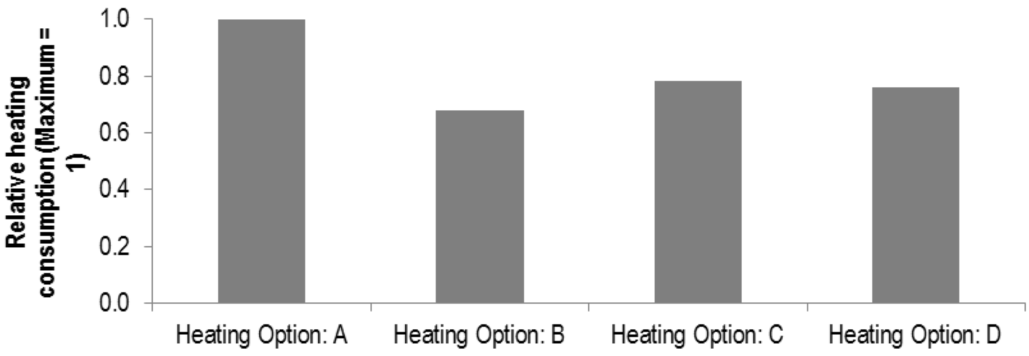

Figure 1. Relative total energy consumption of dwelling over heating period for different heating practices.

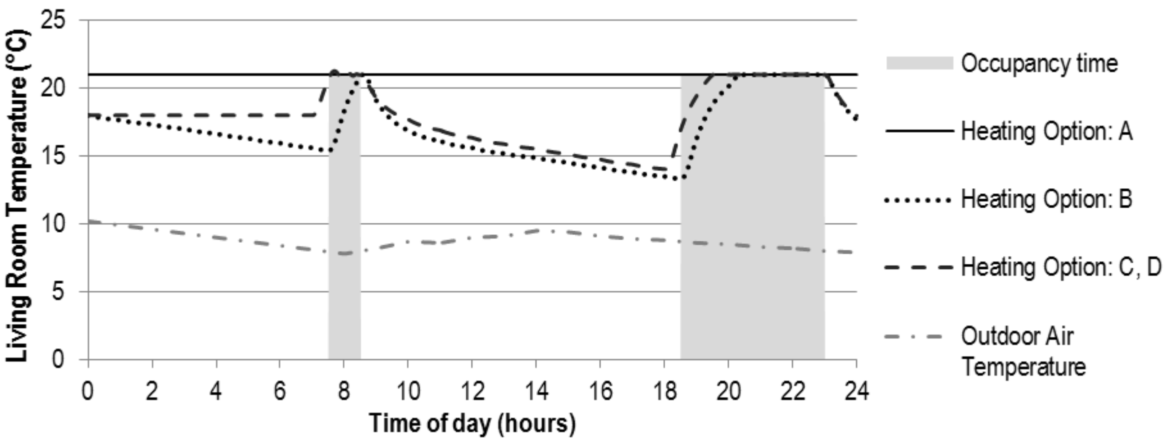

Figure 2. Profile of modelled daily temperature profiles in the main living room for different heating practices.

consumption and therefore there is value in identifying ways of representing these practices in dynamic BEMs. This paper has addressed this using the examples of heating practices and how they can be interpreted and translated into commonly available modelling parameters. This has been illustrated with results of energy consumption and temperature profiles which would result from four different heating control practices. Further ways are highlighted in which dynamic BEMs could enable heating practices to be represented. This work therefore offers a contribution towards bridging the gap between social practice theory and engineering modelling.

There are still a number of limitations to this work, as it is a new approach, and barriers to its immediate application to policy. Dynamic building models are more complicated than simple building models and therefore for this to feed into policy work, not only would the practices aspects need to be fed in, but the models used would need to be made more sophisticated. At the moment SAP is used as a cost effective model but as policy in this area tightens and building performance calculations are used alongside financial instruments, these may be proven to be insufficient. Further work is required in demonstrating the ability for models to be improved through this practice based approach and for the performance gap to be sufficiently closed that the extra complexity in dynamic modelling could be justified. To progress this work further, empirical data would be required against which the modelling could be compared. This would require the collection of data for observed practices along with measured energy consumption for a range of houses.

By improving the ways in which domestic practices can be incorporated into BEMs, this work could contribute to more informed approaches to making retrofit decisions on a small and large scale, and to identifying and understanding factors which lead to high levels of domestic energy consumption.

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