Demystifying Energy Demand using a Practice-centric Agent-based Model

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Abstract: The rational choice framework is commonly used in many energy demand models and energy economic policy models. However, the notion of reasoned decision-making underpinning the rational actor models is less useful to explain the dynamics of routine household activities (e.g., cooking, showering, heating, etc.) which result in energy use. An alternative body of work collectively referred to as social practice theories offers a more practical explanation of routines. It is also argued that practices, i.e. the routine activities that people do in the service of normal everyday living, is at the centre of social change, and hence should be the focus of interventions concerned with demand reduction. One of the main criticisms of social practice theories, however, is that the concepts proposed are high-level and abstract and hence difficult to apply to real-world problems. Most existing practice-centric models are also abstract implementations. To address this gap, in this paper, we present a concrete, empirically-based practice-centric agent-based model to simulate the dynamics of household heating practices. We also use the model to explore consumer response to a simulated price-based demand response scheme. We show how a practice-centric approach leads to a more realistic understanding of the energy use patterns of households by revealing the underlying contexts of consumption. The overall motivation is that by gaining insight into the trajectories of unsustainable energy consuming practices, it might be possible to propose alternative pathways that allow more sustainable practices to take hold.

Keywords: social practice theory; agent-based modelling; energy consumption; demand side management; production rule system; policy tool.

1. Introduction

This paper presents an empirically-informed practice-centric approach to model energy use in households. The response of households to a simulated price-based demand response scheme is also explored. Demand response, a key component of demand side management, is used to encourage consumers to shift their energy use to off-peak periods, e.g. midday or during the night, to result in reduced load during peak periods. A variety of tariff schemes, such as critical peak pricing (CPP), Time Of Use (TOU), and information stimuli, such as real-time, historical, comparative and appliance-specific energy use measures (expressed in Kilowatt Hour) and billing usage (expressed in monetary terms), have been used to stimulate demand response, realised by installing smart meters in households (Davito, Tai, & Uhlaner, 2010).

In power systems research and energy economics, a rational actor approach is commonly used to model consumer engagement with demand response strategies (Papadaskalopoulos and Strbac, 2013; Ye et al., 2015). The models use a utility maximisation framework, wherein the assumption is that consumers would determine the schedule of their appliances by maximizing their perceived utility. In simple terms, the notion is that consumers would make rational decisions to shift their energy use to periods when the tariffs are low. However, what has been found to be the very modest responses to energy demand reduction measures based on these rational actor models has led to calls for a step change in technological innovations or behaviour or both (Committee on Climate Change, 2010).

Another approach called the Attitude-Behaviour-Change model also emphasises the role of individuals in making conscious energy use decisions (cf. Shove, 2010). The assumption is that an individual's attitude towards a target phenomenon (e.g. energy use) will drive their behaviour and the choices they make.

Strengers (2012) and Higginson et al. (2013) illustrate how rational actor models fail to capture the dynamics unique to energy-consuming household practices such as heating/cooling, cleaning, cooking, showering, laundering, etc. They also emphasise that the contexts in which these practices are carried out are not considered in individual-centric rational actor models. For example, postponing laundry in response to demand response price signals may not be possible if clean uniforms are immediately required by the children in the family for school. In this example, then, laundry is not just an act of using the washing machine to consume energy, but a practice that produces an outcome (clean uniforms) that influences another practice (going to school).

A growing body work thus consider a practice-centric approach as an alternative to individual-centric rational actor models. Anchored in the works of Bourdieu (1977) and Giddens (1984), and collectively referred to as theories of practices or social practice theories, these works emphasise that practices are at the centre of social change (Spaargaren, 2003), while individuals are merely the carriers of practices (Reckwitz, 2002). Using a practice-centric approach, an agent-based model of energy use in households called *Households and Practices in Energy-use Scenarios (HOPES)* is described in this paper. The model is used to explore householders' engagement with a simulated demand response pricing scheme.

2. Other practice-centric agent-based models

There are already a handful of practice-centric models, but they are mostly either conceptual designs or abstract implementations. Holtz (2013) studied meat consumption practices at a University in Germany to identify the component elements of those practices, i.e. the meanings, materials, and skills making up practices (cf. Shove et al., 2012, see figure 1). He operationalised a concept called Coherence to model practices, i.e. the fit between meaning and material elements and between materials and skills. Holtz (2014) also implemented an abstract agent-based model to demonstrate the emergence of social practices.

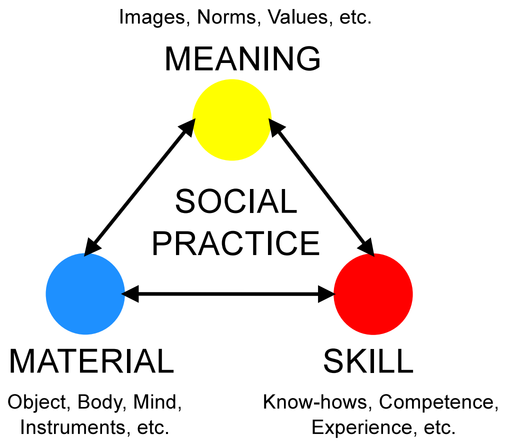

Figure 1 Elements making up practices

Dignum et al. (2014) and Balke et al. (2014) also proposed conceptual models of social practices. By extending the ideas of Holtz (2014) and Balke et al. (2014), Narasimhan et al. (2017) proposed an abstract model to describe the processes enabling the linking of elements to perform practices, the linking of practices and practitioners (e.g. householders), and a process allowing the co-evolution of practices, i.e., two or more practices evolving simultaneously owing to the sharing of elements. For example, the spread of entertainment devices and information, communication and technology devices has influenced the spread of heating practices in households (cf. Spurling, 2015).

Higginson et al. used their findings from an empirical study focused on the performance of laundry practices in households to propose a systems dynamics approach (Higginson et al., 2014) and a network theory approach (Higginson et al., 2015) to visualise (by diagramming) the links between elements contributing to variants of laundry practice.

One of the main limitations of the current practice-centric models is that they are either conceptual frameworks or abstract implementations that do not provide insights into the energy consumption patterns of households. The conceptual frameworks are useful for thinking about the different aspects that need to be considered in a practice-centric model, especially as there is no consensus yet on the characteristics and attributes of social practices that suggest clear intervention targets (Strengers, 2012; Shove, 2014; Higginson et al., 2015). In this regard, the abstract models are useful to clarify and refine the theory itself (cf. Gilbert & Troitzsch, 2005). Abstract models also encourage inter-disciplinary collaboration in developing novel approaches to model energy demand. In fact, this paper arose from one such collaboration between Social Scientists and Power Systems Engineers, seeking to bridge the disciplinary gaps in modelling consumer engagement with demand response pricing schemes. However, since conceptual models do not allow quantifying outcomes, a working implementation of a practice-centric model of energy demand is required. The empirically-informed HOPES model described in the following section is a contribution to satisfy this requirement.

3. Description of a practice-centric approach to model energy use in households

The Households and Practices in Energy-use Scenarios (HOPES) model uses a practice-centric approach to simulate the dynamics of energy consumption in households. The central idea is that occupants combine meaning, material and skill elements to perform various practices in the service of normal everyday living, which in turn affects the energy use patterns of households, such as when and how much energy is consumed. The repeated use of elements across households over time causes elements to adapt, which in turn affects the future performance of practices, and subsequently energy use.

HOPES uses an agent-based modelling approach, which has three main components: (1) computational entities called agents which imitate the behaviour of individuals that make up a system; (2) an environment in which agents reside; and (3) a description of rules which allow agents to interact with one another (Gilbert & Troitzsch, 2005; Gilbert, 2008). The interactions between agents could allow them to do any or all of the following: observe and influence one another, pass or exchange information, copy and learn from one another.

The HOPES model has two types of agents: households and practices. Household agents are defined by demographic attributes such as tenure, type, income, age of occupants, working patterns of residents, etc. The values for these attributes are initialized based on empirical evidence such as the English Housing Survey[1]. The values of some attributes change over time because of the interactions and relationships of households with other agents in the system. Households, conceptualized as collective representations of all their occupants, can intuitively be understood as agents, but considering practices (e.g. cooking, heating, laundry, etc.) as agents is an unusual but a conscious modelling decision.

The motivation for considering practices as agents stems from evidence in the literature. Macy & Willer (2002) describe agents as entities capable of: (1) making decisions and acting independently (autonomy), (2) influencing and being influenced by other agents in the system (interdependent), (3) acting based on simple rules, and (4) adapting and learning from experience. Practices satisfy the autonomy, interdependency and adaptation criteria proposed in the social practice theories literature. It is acknowledged that people, practices and things all have agency (Strengers, 2012) and that people (and by extension the society) and practices shape one another recursively and adapt over time (Shove et al., 2012). For example, the spread of bathing practices resulted in new norms of personal hygiene (e.g. shower before work), which subsequently resulted in new elements (e.g. shower gels and power shower) and newer forms of bathing practices, which in turn influenced the timing and energy demand of showering and bathing practices (Kuijer, 2014).

HOPES considers the elements enabling the performance of practices as entities in the model. Elements have three attributes: type, value and state. Type denotes the element category (i.e. meaning,

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[1] https://www.gov.uk/government/collections/english-housing-survey

material or skill), state denotes how actively an element is used to perform different practices, and value denotes the actual element (e.g. a washing machine is a material element).

The HOPES model case study presented in this paper focuses on the dynamics of the thermal comfort practices of households, e.g., using the heater to increase indoor temperature during colder months, wearing more clothes to keep warm, using the heater for maintaining a comfortable and cosy ambience, etc. We particularly chose to model thermal comfort practices as they were often mentioned in the interviews and the survey we conducted in a sample of UK households to collect empirical data on common household practices. Furthermore, heating is a major source of energy consumption in households (Kuijer & Watson, 2017), and compared to other household practices, such as entertainment, laundry, cooking, etc., thermal comfort practices are more complex as the physical properties of a building and the heating systems used, together with other meaning, material and skill elements, play a critical role in affecting the performance and outcomes of these practices. Therefore, a model of thermal comfort practices in households requires the integration of several different components, each of which are described below.

The high-level interaction between households, practices and elements in HOPES is shown in figure 2. The left-hand side of the figure shows households choosing elements and linking them to perform practices. The right-hand side shows that the repeated performance of practices across households causes the elements in the system to adapt over time. The HOPES model has three main processes to capture these interactions: *choose-elements*, *perform-practices* and *adapt-elements*.

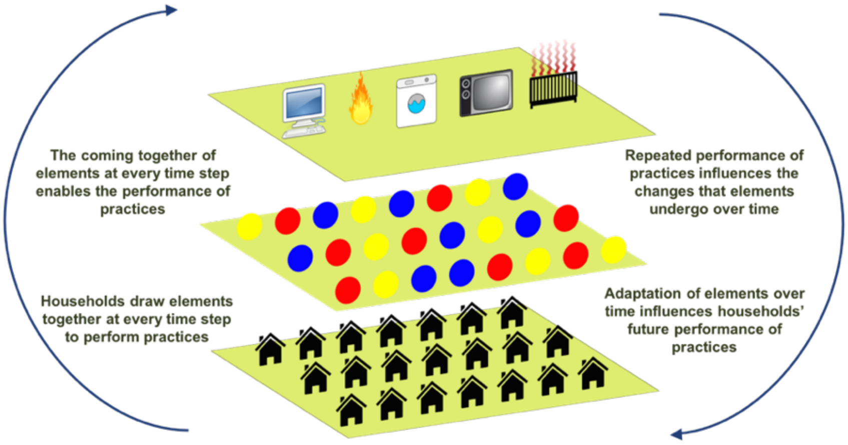

Figure 2: Interactions between Households, Elements and Practices in HOPES

First is the *choose-elements* process. Although it is acknowledged that policy, regulatory, social and technical systems conjointly shape the emergence, spread and dissolution of social practices (Shove et al., 2012), the relationships are nonlinear and the mechanisms regulating the relationships are unknown. The lack of this understanding is a main criticism of social practice theory (Jackson, 2005). Consequently, we chose not to hypothesise the relationship between the different factors influencing the linking of elements to perform practices based on incomplete information. Instead, we implemented the *choose-elements* process, which uses a production rules approach to allow each household to firstly choose the most adequate meaning, followed by the most adequate material, and finally, the most adequate skill at each time step, by traversing a decision tree that assesses the influence of all the relevant factors at that time step.

The production rule system (PRS) used in HOPES has a global knowledge base that contains several rules about the different household contexts influencing the choice of different elements and element configurations (combinations of meanings, materials and skills) enabling the thermal comfort practices. These rules were derived from the analysis of data obtained from semi-structured interviews conducted in 60 UK households and a large-scale survey of UK households (N = 1004). Rules pertaining to the influence of the following factors are included in the PRS: (1) outside weather, (2) tenure, (3) dwelling type, (4) household income, (5) age of occupants, (6) occupation, occupancy patterns and working patterns of occupants, (7) social interactions, (8) practice history and (9) inclination to conserve energy.

Each household in the system has a local working memory that is initialised at the start of a model run and changes over time based on the application of the rules and facts in the global knowledge base. The way in which the global rules affect the local working memory of each household agent is determined by an inference engine, which fires an action in each rule which has its condition satisfied. The inference engine uses a conflict resolution strategy when conflicting rules fire simultaneously (see the early chapters in Friedman-Hill, 2003 for an introduction to rule-based systems). The processes favouring certain element configurations to take hold, while others are used less frequently or not at all, have not yet been analytically explored in the social practice theories literature. Using a production rules approach allowed us to capture the influence of several factors simultaneously influencing a household's choice of elements to perform the thermal comfort practices under different circumstances.

The HOPES model is implemented in NetLogo[2] and the JESS language[3] is used for implementing the PRS. We integrated the JESS PRS in the NetLogo model by adapting a JESS NetLogo extension[4]. Figure 3a shows the set of rules included in the PRS for modelling the conditions influencing the choice of meanings associated with thermal comfort practices. Evidence gathered from households showed that risk avoidance, caregiving, cosiness, hospitality, frugality, generosity, etc., are meanings commonly associated with thermal comfort practices. For example, caregiving is relevant when the occupants in a household are vulnerable to cold weather (e.g. babies, children, elderly people); and hospitality is relevant when entertaining guests during cold weather. On other hand, even when it is comfortably warm (e.g., when the difference between the desired indoor temperature denoted by the set point temperature and the actual indoor temperature is insignificant), some households might still use a heater to maintain a comfortable and cosy ambience (cf. Pink, 2012). Constraints such as household income and energy tariffs (e.g. demand response price signals) further influence the meanings associated with using a heater to boost thermal comfort (see figure 3a).

The meanings relevant to each household agent at each time step subsequently influences the materials and skills chosen for the thermal comfort practices. The material chosen to achieve thermal comfort could be a heating appliance, or a heating appliance with controls (such as a thermostatic radiator valve (TRV) or room thermostat), or just more clothes. The choice between these materials is influenced by whether the underlying meaning emphasises a requirement (meaning = caregiving or hospitality), or added comfort (meaning = cosiness), and a household's view of heating as a resource (which they can adapt over time based on the interactions with their neighbours and social circles). Figure 3b shows how the meanings chosen at each time step and other contextual factors influence a households' choice of materials for thermal comfort practices. The material chosen subsequently affects the choice of skills such that a meaningful configuration of elements results (also shown in figure 3b).

Once the PRS has identified the relevant elements, the second main process in HOPES called *perform-practices* allows households to combine the chosen elements to perform the practice. While one of the outcomes of carrying out the practice is enhanced thermal comfort, other relevant state variables of a household (e.g. the actual indoor temperature) are also affected by the element configurations chosen for performing the practice. For example, using a heater for an hour would provide thermal comfort by increasing the indoor temperature. The rise in temperature achieved would be influenced by several factors unique to each household, e.g., set point temperature, insulation, window glazing, floor area, ceiling height, boiler efficiency, kilowatt rating of the heater, etc. Alternatively, instead of using a heater, thermal comfort could be achieved by wearing more clothes. The outcome would be the same (i.e. increased thermal comfort) in both cases, but the level of thermal comfort achieved, the elements used and the related energy consumption would be different. In turn, these differences affect the type of elements households choose in subsequent time

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[2] https://ccl.northwestern.edu/netlogo/
[3] https://herzberg.ca.sandia.gov
[4] https://github.com/lmmoniz/NetLogoJess

steps. The HOPES model includes a simple dynamic house heating model (adapted from the dynamic system model in Mathworks, 2017, p.47) to simulate the heat gain, heat loss and rate of temperature change in households resulting from carrying out thermal comfort practices (see appendices for a description of the simple heating model used).

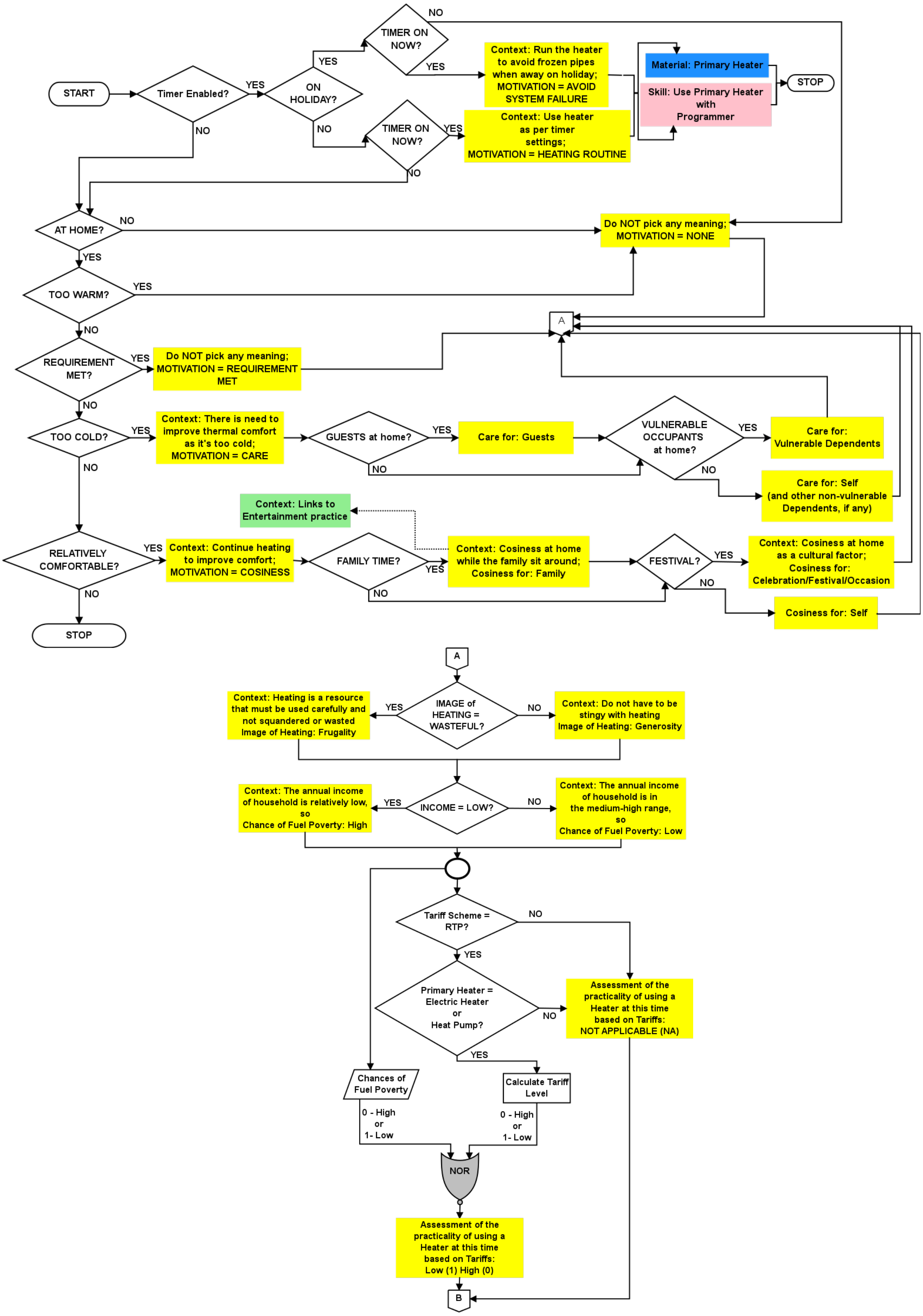

Figure 3a Selection of Meaning

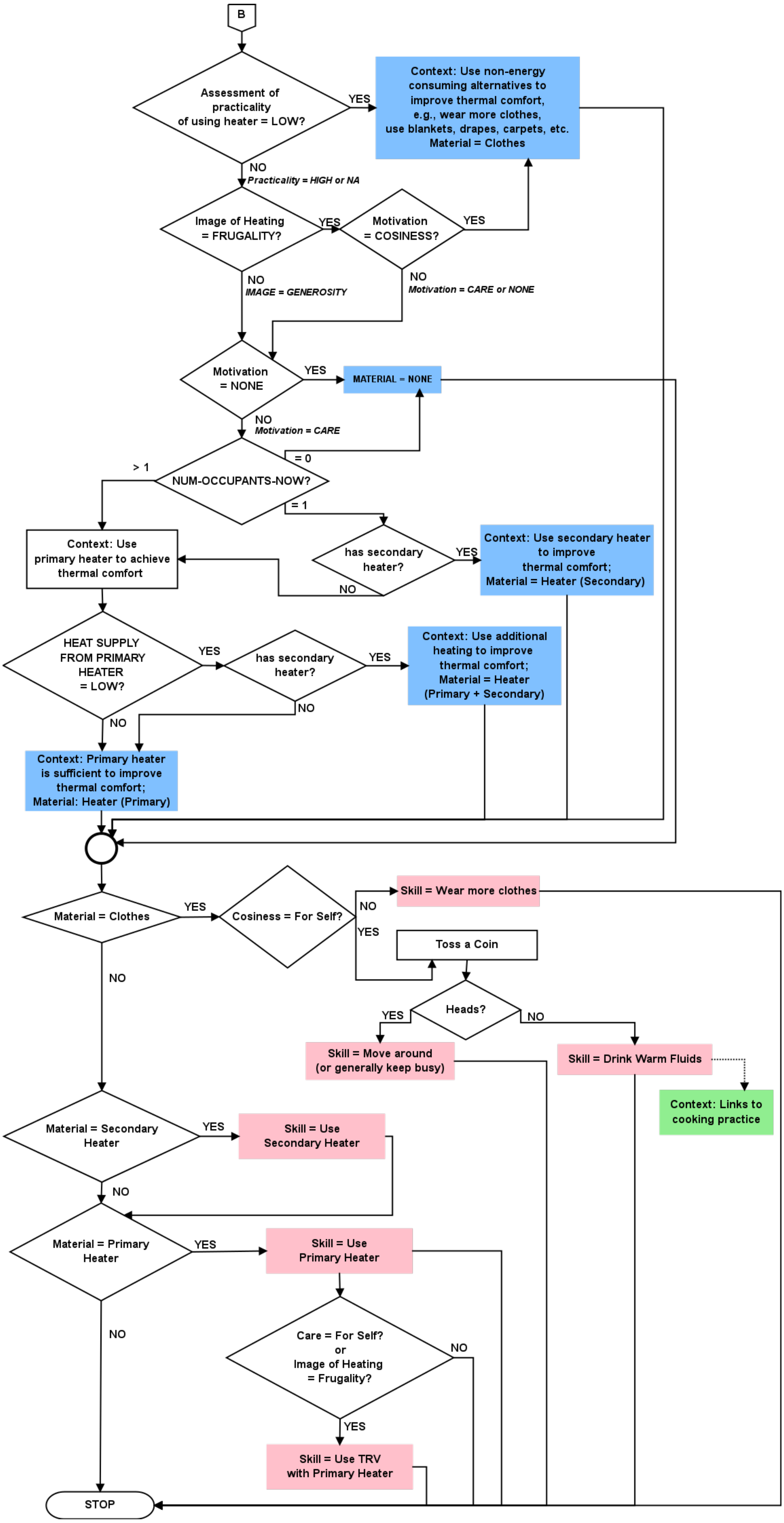

Figure 3b Selection of Material and Skill

Finally, the *adapt-elements* process in HOPES affects the state of the meanings, materials and skills in the system. Elements that are used frequently for performing practices will remain active while those used less frequently will become dormant. If elements remain dormant for a long time, they will become inactive and eventually be removed. Furthermore, elements shared across practices (e.g. a heater that is used for thermal comfort as well as for drying clothes) will have higher prominence and thereby be more accessible to households. Figure 4 shows the sequential ordering of the three processes. The hourly energy use of households is calculated from the practices carried out and the elements used for performing the practices in the previous hour.

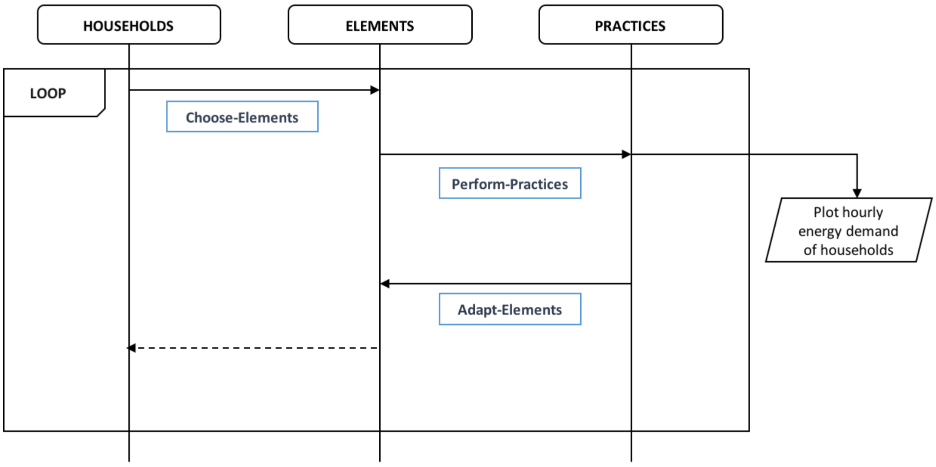

Figure 4 Sequential ordering of processes in HOPES

4. Results

This section presents some initial results obtained by running the HOPES model with 200 household agents for a period of one year from 1st January 2015 to 31st December 2015. First, figure 5 shows the baseline results obtained from a model run without the practice-centric processes, i.e., only a simple house heating model was used. The figure shows the average amount of energy used in households (in kWh) for maintaining the desired indoor temperature (an average of 18°C) corresponds to the rise and drop in the outdoor temperature over the duration of a year[5].

Next are the results obtained in a Flat Rate scenario (FR) where households react to a flat rate (fixed charge) for their heating and electricity usage throughout the year. The top half of figure 6 shows the average energy use of households, which again corresponds to the rise and drop in the outdoor temperature over the year, but in addition, the FR scenario also generates distinct demand peaks in the morning and evening. This is because the contextual factors considered in the FR scenario model the effect of occupancy profiles and occupants' working patterns on the performance of thermal comfort practices, which subsequently affect the energy use of households. We also implemented a Time of Use (TOU) scenario using a simulated dataset of hourly price signals. Households see a new price signal at the start of each hour and classify it as LOW (Tariff = low) or HIGH (Tariff = high), by comparing it with the value of the tariff at the previous time step. This decision is subsequently fed into the PRS, as shown in figure 3a, to allow households to choose the most adequate meanings, materials and skills depending upon the perceived value of the price signal. The second half of figure 6 shows the average energy use of households in the TOU scenario, which again corresponds to the rise and drop in the outdoor temperature and has distinct morning and evening demand peaks. Overall, the outcomes of the FR scenario and TOU scenario do not show any appreciable differences in the amount or time of energy use. This suggests that the tariffs designed to shift or reduce demand did not have the desired effect, and further analysis shows why.

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[5] Note that the estimated energy use for heating is not always zero during the summer months. In the UK, the outside temperature is sometimes below the desired temperature even during summer and in the model the heating comes on at such times. The model does not include solar and casual heat gains, but we plan to include these in a future version of HOPES to improve its accuracy.

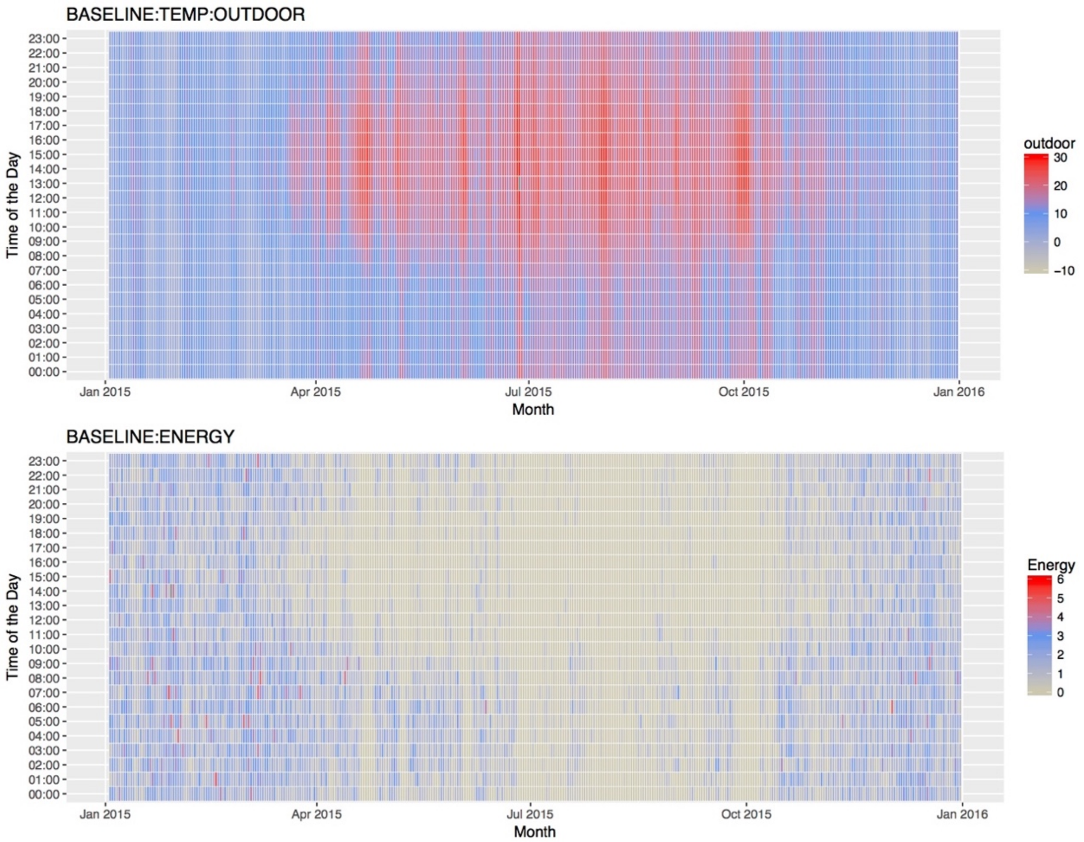


Figure 5 BASELINE: Outdoor Temperature and Average Energy Use of Households

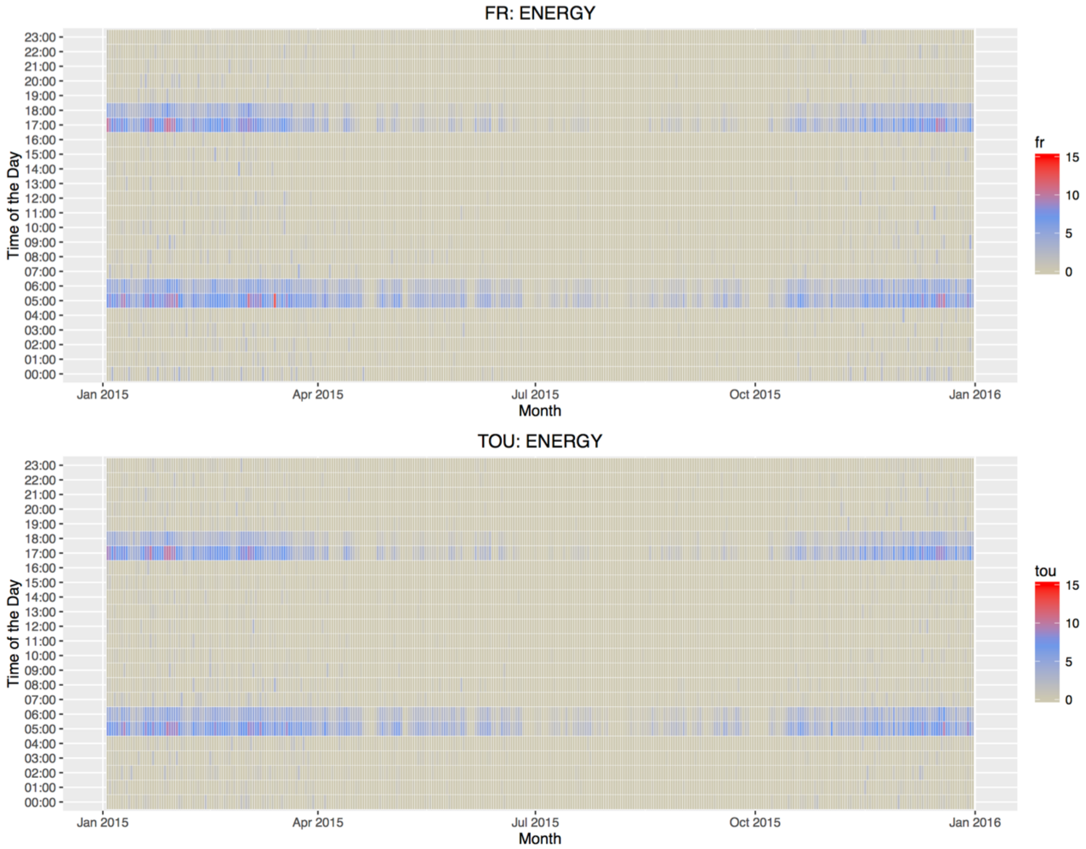
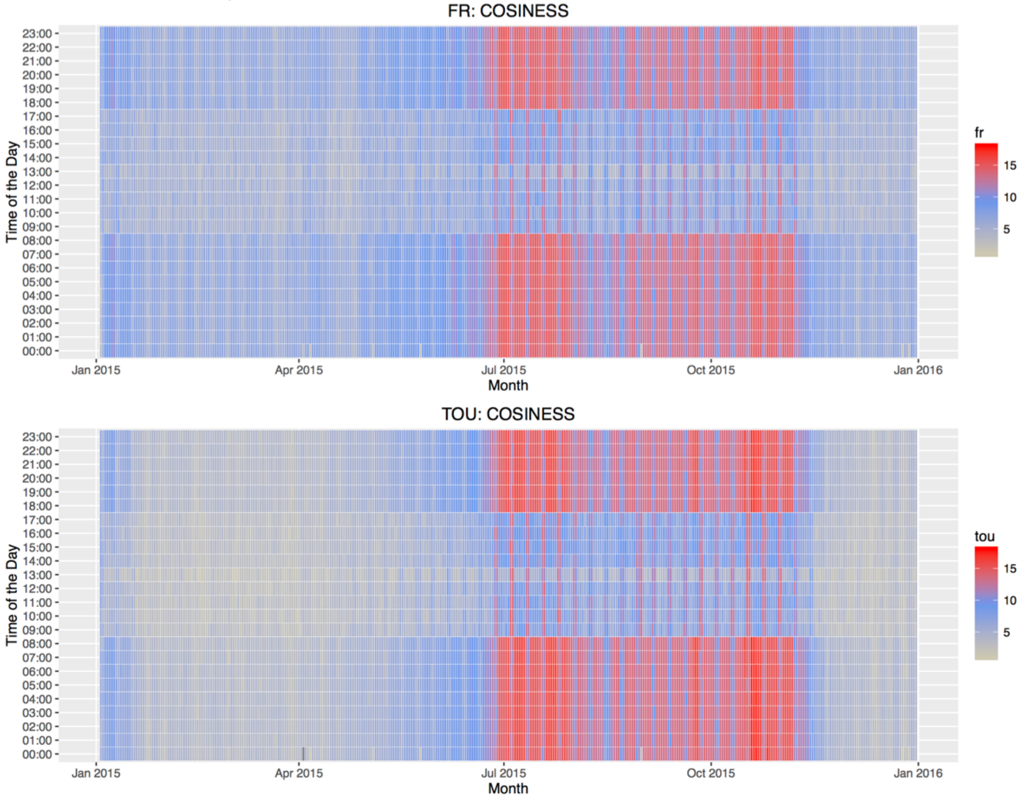


Figure 6 Average Energy Use of Households in the FR and TOU scenarios

Our analysis showed that the meanings associated with the performance of thermal comfort practices are different in the FR scenario and the TOU scenario. The meaning *cosiness* (the motivation to use the heater to maintain a comfortable and cosy ambience) was more prominent in the FR scenario, whereas cosiness was less prominent and *caregiving* (the motivation to use the heater to protect oneself and/or vulnerable dependents from cold homes) was more prominent in the TOU scenario due to the following reason. When households avoid using heater for longer blocks of time due to perceived high prices in the TOU scenario, the indoor temperature drops significantly below the set point temperature, which in turn causes the meaning to become caregiving rather than cosiness (i.e. heating is more of a requirement than comfort). Consequently, when prices go down, households are forced to use the heater to increase thermal comfort. In addition, even when the prices are high, households consume some energy for preparing foods to keep warm (e.g. using a kettle to prepare coffee and tea). In our practice-centric model, based on evidence from our walking interviews, 'drinking warm fluids' is a skill associated with thermal comfort practices. Due to these reasons, the amount and time of energy use is not significantly different in the FR and TOU scenarios, suggesting that a price-based incentive may not directly translate to energy demand reduction in the context of daily life in real-world settings.


FR: COSINESS

TOU: COSINESS

Figure 7 The prevalence of 'Cosiness' in the FR and TOU scenarios

5. Discussion

We presented an empirically-informed agent-based model called HOPES to simulate the dynamics of energy use resulting from the performance of thermal comfort practices in households. The model considers empirically derived meanings, materials and skills pertinent to thermal comfort practices. The differences in the energy demand and the temperature profiles of households resulting from a practice-centric model compared to a simple dynamic house heating model, and more importantly, the insights into the element configurations affecting energy use, illustrate the advantages of using a more context driven practice-centric approach to model household energy demand.

In summary, the HOPES model presented in this paper is an initial but a critical step in the process of demystifying the dynamics of energy use in households using a practice-centric approach. In doing so, the model also provides a concrete logical formulation of some important but abstract practice theory concepts. However, to use the HOPES model to provide a more complete understanding of the dynamics of energy use in households would require the extensions described below.

Firstly, we will extend the model by including the rules pertinent to four other prominent household practices, namely cooking, laundry, entertainment and working from home. Modelling different practices would also allow including rules that enable the sharing of elements across practices (referred to as the co-existence of practices). The consideration of practices as agents will be of more relevance at this stage, to model the interactions between practices.

Secondly, we will add rules which influence the adaptation of elements over time. We will then run simulations for longer periods (i.e., over several years) to analyse the influence of the adaptation of elements on the performance of practices, and subsequently on energy use. At this stage, it will become possible to model the recursive relationship between structure and agency (cf. Gilbert, 1995).

Thirdly, we will quantitatively evaluate the differences between a utility maximisation approach and a practice-centric approach in modelling household energy demand in response to price-based demand response mechanisms. We will do this by comparing the demand profiles obtained from HOPES with the demand profiles resulting from an electricity system analysis model using a utility maximisation framework.

Lastly, the HOPES model is yet to be validated. We aim to compare model results, namely the whole house energy demand profiles and the appliance-specific energy demand profiles of simulated households, with the whole house and appliance-specific energy use data collected from energy monitoring sensors installed in 20 UK households for a period of one year. The REFIT dataset will also be used for validation (Murray et. al, 2016).

6. Acknowledgements

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7. Appendices

Parameters of a simple house heating model

Variable or coefficient	Description
Q_{gain}	Thermal energy transferred from the heater to a room
Q_{loss}	Thermal energy transferred from the room to the outdoor environment
T_{room}	Air temperature of the room
T_{heater}	Air temperature of the air in the heater (constant = 50)
$T_{outdoor}$	Outdoor air temperature (provided as input)
$T_{desired}$	Desired air temperature if the room, aka thermostat set point temperature
$m_{heaterair}$	Mass of air per unit time from the heater
$m_{roomair}$	Mass of air per unit time in the room
C_{air}	Specific heat capacity of air (constant = 1005.4)
$H_{floorarea}$	Floor area of the household
$H_{ceilingheight}$	Ceiling height of the household
$H_{heateroutput}$	Output of radiator
$H_{boilerefficiency}$	Efficiency of boiler (in %) Gas: 80% Electric: 100% Heat Pump: 170%

	Heat Network: 120% Oil: 80% Biomass: 70%
H_{rvalue}	Thermal resistance of building calculated by considering the U-values of windows, wall, floor and ceiling
ρ_{air}	Density of air at 20ºC (constant = 1.205)

Equations for a simple house heating model

(1.2.a) $m_{roomair} = H_{floorarea} \times H_{ceilingheight} \times \rho_{air}$

(1.2.b) $m_{heaterair} = \frac{H_{heateroutput} \times H_{boilerefficiency}}{C_{water} \times (T_{heater} - T_{room})} \times 3600$

(1.2.c) Rate of Heat Gain

$$\frac{dQgain}{dt} = m_{heaterair} \times c_{air} \times (T_{heater} - T_{room})$$

(1.2.e) Rate of Heat Loss

$$\frac{dQ_{loss}}{dt} = \frac{H_{floorarea} \times (T_{room} - T_{outdoor})}{H_{rvalue-floor}} + \frac{H_{floorarea} \times (T_{room} - T_{outdoor})}{H_{rvalue-ceiling}} + \frac{\left(\frac{H_{floorarea}}{20}\right) \times (T_{room} - T_{outdoor})}{H_{rvalue-window}} + \frac{\sqrt{H_{floorarea}} \times 4 \times H_{ceilingheight} \times (T_{room} - T_{outdoor})}{H_{rvalue-wall}}$$

(1.2.f) Rate of Temperature Change in the Room

$$\frac{dT_{room}}{dt} = \frac{1}{m_{roomair} * c_{air}} * \left(\frac{dQ_{gain}}{dt} - \frac{dQ_{loss}}{dt}\right)$$

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