Using agent-based modelling to understand the spread of energy consuming social practices in households

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Abstract

To date a great deal of work has been undertaken to describe, qualitatively and in detail, the nature of individual and bundles of domestic energy practices and their elements. But practices have a multitude of short-term and long-term trajectories as a consequence of the variations in their element configurations. This makes for a complex system that has not been investigated adequately. In this paper, an agent-based approach is used to model the processes capable of influencing the daily performances and the long-term evolution of domestic energy practices. Households, practices, and the elements of practices are considered as agents in the model. Households draw elements together to perform the practices. The repeated performance of practices influences changes in the underlying elements, which in turn influences the future performance of practices. In this manner, the processes leading to the performance, the repetition and the reproduction of practices are modelled. The energy use patterns of households, resulting as a consequence of the performance of practices, are also modelled.

Keywords

Agent-based modelling, social practice theory, short-term and long-term trajectories of practices, domestic energy consumption

1 Introduction

Domestic energy consumption accounts for one third of the total energy demand in the UK (DECC, 2013). The residential sector is also a major consumer of energy in other countries (Swan & Ugursal, 2009). To reduce domestic energy consumption, and the associated emissions of greenhouse gases, it is important to understand how occupants use energy in households. Computational modelling enables carrying out exploratory studies to ascertain the role of occupant behaviour on domestic energy consumption. The most common modelling approach is to consider that individuals make rational energy consumption decisions based on the information they have. Models of occupant energy consumption behaviour based on the theory of planned behaviour (Ajzen, 1991) use this approach, e.g. Zhang & Nuttall (2007, 2011).

On the other hand, a growing body of work advocates that energy consumption is not a conscious act, but a by-product of performing activities that require energy (Strengers, 2012; Wilhite, 2005). For example, Pink (2012) notes that watching television is done for the sake of entertainment, and not as a conscious effort to consume energy. This paper supports the notion of seeing energy consumption as a by-product of the activities of normal everyday living. Consequently, the paper proposes a model for simulating the dynamics of the daily performances of energy consuming practices (e.g. heating, cooking, laundry, etc.) and their influence on household energy use patterns.

An agent-based model referred to as Households and Practices in Energy consumption Scenarios (HOPES) is proposed. The model is based on theories of practices that have their roots in the works of Bourdieu (1977) and Giddens (1984). The following aspects are considered. Firstly, that practices are at the centre of social change (Spaargaren, 2003), while individuals are merely the carriers of practices (Reckwitz, 2002). Secondly, that the drawing together of elements, such as meaning (significance, interpretation, image), material (objects, body, mind) and skill (or competence), enables the performance of practices (Shove et al. 2012). Thirdly, that changes in practices are enabled by changes in the underlying elements and the links between elements (Shove et al. 2012). Finally, that energy consumption is a by-product of the performance of practices, which is enabled by the coming together of elements (Gram-Hanssen, 2013).

Households, practices, and the elements of practices are considered as agents in the HOPES model. The processes and the rules defined in the model, which underpin the interactions between agents, are based on the theories of practices literature and on empirical evidence. The HOPES model is intended to serve two main purposes. Firstly, to provide a clear specification of the processes linking households, practices and the elements of practices. Secondly, to model the influence of the interactions between households, practices and elements on the energy use patterns of households.

The rest of the paper is organised as follows. Section 2 is an overview of the agent-based modelling approach. Section 3 is a description of the agents, processes, and rules defined in the HOPES model. Section 4 is an overview of other models of social practices, and lastly, section 5 summarises the purpose of the HOPES model and highlights the issues for further discussion.

2 Agent based modelling: an overview

Agent-based modelling is a recognised method for modelling, simulating and analysing complex phenomena (Gilbert &Troitzsch, 2005). Any real-world phenomenon characterized by the complex network of interactions between one or more categories of social actors, such as individuals, households, institutions, etc., can be modelled using an agent-based approach. There are two main entities in agent-based models: (1) the agents and (2) the environment. Agents are entities that represent the social actors and environment is the virtual world, where agents reside, act, and interact with one another (Gilbert, 2008). Agents can exchange messages with one another, make decisions based on these messages, and act based on the outcomes of their decisions – all this without the need for any central coordination. Unlike textual description, computational modelling with its precise model specifications allows less room for misinterpretation (Gilbert &Troitzsch, 2005). Hence, using the agent-based modelling approach it is possible to develop a clear understanding of how the model processes and rules lead to the emergence of an outcome, which resembles a real-world phenomenon.

3 An agent-based model of domestic energy practices

3.1 Overview of the model

This paper describes an agent-based model called Households and Practices in Energy consumption Scenarios (HOPES). The model is composed of three types of agents: households, practices, and the elements of practices. The household agents are defined by attributes such as housing tenure, house type, energy appliances, occupancy and the working patterns of occupants. The element agents are defined by three attributes: type, state and value. Meaning, material and competences are the three types of elements considered (Shove et al., 2012). Each material element has a value denoting an object needed to perform a practice (cf. Shove & Walker, 2007). Each meaning element has a value representing the social or symbolic significance of performing a practice (cf. Shove et al., 2012). Each competence element has a value representing a skill needed to carry out a practice. The state attribute indicates how actively an element is being used to perform practices. For example, one of the elements in the HOPES model is a washing machine (value), which is a material (type) that is actively used (state) for performing laundry.

Domestic energy practices are the third category of agents included in the HOPES model. While initially it might seem puzzling to treat practices as agents, Macy & Willer (2002) note that computational agents must be 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 have similar characteristics: (1) practices possess both structure and agency (Giddens, 1984), (2) practices have the ability to influence one another (Narasimhan et al., 2015), (3) the coming together of elements enables the performance of practices, and (4) changes in the elements or the links between elements influences changes in the practices, i.e. they adapt over time (Shove et al., 2012).

The practice agents in the HOPES model have two pairs of attributes: active and past practitioners and active and past element configurations. Active practitioners comprise households that perform a practice at the current time step, while past practitioners are those that performed the practice in previous time steps. Active element configurations are the elements and the links between elements enabling the performance of a practice at the current time step, while the ones used in previous time steps are recorded in the past element configurations.

All the agents in the HOPES model (i.e. households, practices and elements) co-exist, act and react within a virtual environment that is defined by the following attributes: a date, time of the day and outside weather. The virtual environment provides the medium for households, practices and the elements of practices to interact with and influence one another.

3.2 Description of the processes linking the agents in the HOPES model

There are four main processes in the HOPES model responsible for governing the interactions between households, practices and the elements of practices. These are called the *choose-elements* process, the *perform-practices* process, the *audit-practices* process and the *adapt-elements* process, respectively. To begin with, the choose-elements process allows a household agent to choose a few appropriate elements from all of the available elements in the system. The perform-practices process then checks if a household agent has the right configuration of elements needed to perform a practice. If yes, then the household will be able to perform the practice by linking together the appropriate elements. If not, then the household will not be able to perform the practice.

The choose-elements and perform-practices processes may be explained with an example. Consider that at the end of the choose-elements process, a household agent has the elements necessary for drying clothes, such as a tumble dryer or a drying rack or a heated rail (material), the practical know-how for using the equipment (skill) and a need for clean clothes (meaning). The perform-practices process would then enable the household to dry the clothes by linking together the three elements. However, if the household did not have one or more of the aforementioned elements at the end of the choose-elements process, then drying clothes would not be possible during the perform-practices process.

The audit-practices process keeps track of the number of practitioners (active and past). The process also keeps track of the element configurations enabling the performance of practices (active and past) as well as the elements being shared across practices. Using all this information, the adapt-elements process updates the elements in the system. Consequently, in the next iteration of the simulation, the choose-elements process will have the household agents choose from an updated list of elements. The processes influencing the interactions between households, elements and practices continue in a cyclic manner (Figure 1). From right to left, it can be seen that household agents (bottom layer) draw the elements together (middle layer) to perform different energy consuming domestic social practices (top layer). In the opposite direction, it can be seen that the repeated performance of practices causes the elements to change, which in turn influences the future performance of practices.

3.3 Description of the rules underlying the process in the HOPES model

Agent-based models have rules governing the decision-making, the actions and the interactions of agents. In short, rules determine what the agents do (Gilbert, 2008). This section presents the rules involved in the four main processes of the HOPES model. The rules are specified using a *condition-action* format, where there is a condition component that must be true to perform an action or a set of actions. An example of a condition-action rule is “If the weather is cold, then I will use the heater”.

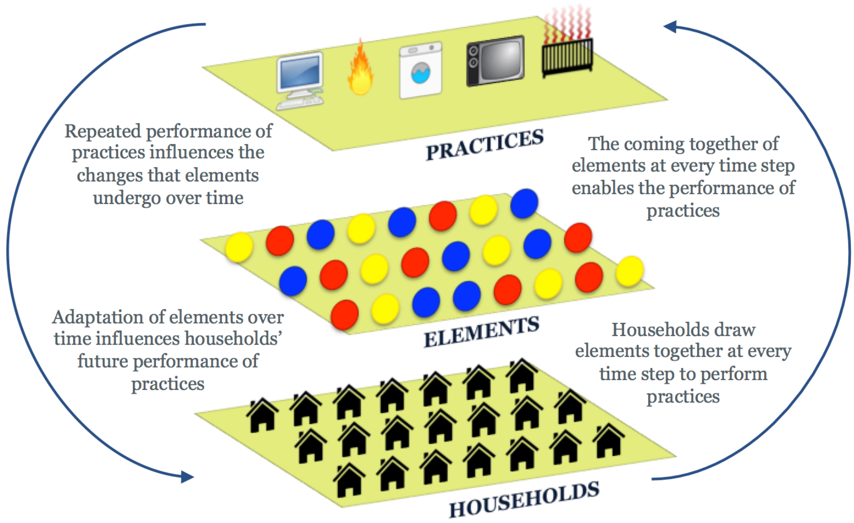

Figure 1: The cyclic nature of the processes in the HOPES model

The rules included in the HOPES model are informed by real-world data obtained from: (1) walking interviews conducted in over 60 households, (2) a household energy use survey involving 1000 respondents, and (3) an energy monitoring study of over 20 households. The data from the walking interviews have been used to formulate the rules linking elements to practices. The results of the energy monitoring study have been used to formulate rules governing the temporal ordering of practices. The findings of the survey provided insights regarding the likelihood of the performance of practices. The rules are described below.

The following rules are involved in the choose-elements process, which enables a household agent to choose a select few elements from the system at each time step:

1. **Choose elements appropriate to the outside weather.** This rule allows a household agent to choose the elements for performing practices based on the outdoor weather conditions. For example, households are more likely to use an electric heater or a gas central heating system (a material element) during the winter months than the summer months. Similarly, households are more likely to want to keep warm (a meaning element) during the winter than the summer. Hence even if a household is always capable of operating the heating equipment (a skill element), the material and meaning elements necessary for performing the heating practice are more likely to be chosen during the winter months. Consequently, the perform-practices process, which enables the linking of elements to perform a practice, will enable households to perform the heating practice only during the winter months.
2. **Choose elements based on tenure, type and occupancy.** This rule allows a household agent to choose the elements for performing practices based on household attributes, such as tenure, type and occupancy. For example, terraced, semi-detached or detached houses may have an option for drying clothes on a line, whereas in flats using a tumble dryer or a heated rail may be more practical.

3. **Choose elements based on working patterns.** This rule causes the working patterns of occupants to influence the choice of elements of a household agent. For example, occupants working from home during the winter months are likely to use the heater to keep warm while working.
4. **Choose elements based on social interactions.** This rule implies that households can influence one another's choice of elements. For example, it is more likely for a household to install solar panels, if a majority of other neighbouring households have also installed them.
5. **Choose elements based on targeted information.** This rule implies that the information communicated to households can influence their choice of elements. For example, providing adequate information about energy efficient appliances or devices (material), may improve the likelihood of households purchasing, and subsequently using those elements for performing the practices.
6. **Choose elements based on the history of practices performed.** This rule allows a household agent to choose the same or similar elements across iterations, in order to repeat the same practices that were performed previously. For example, if it is the habit of occupants to use the shower (skill and material) to maintain personal hygiene (meaning), it is highly likely these elements would be chosen repeatedly across iterations to enable the performance of the showering practice everyday.

The perform-practices process enables the linking of appropriate elements to perform the practices. The following rules, included in this process, enable the linking together of elements at an appropriate day and time.

7. **Confirm that the elements that households have are appropriate for performing the practices.** This rule acts as a checkpoint to determine if at the end of the choose-elements process a household has the elements necessary for performing the different practices. As mentioned previously (see rule 1), a household will be able to perform a practice only if it has the right combination of meaning, material and skill elements. The household will not be able to perform a practice if any of the elements it has is not suitable for that practice.

If the application of rule number 7 succeeds, the following rules, also included in the perform-practices process, enable a household to perform a practice at the most appropriate time:

8. **Perform a practice at an appropriate month of the year.** This rule causes the month of the year (derived from the date attribute of the HOPES environment) to influence the time of the performance of practices. For example, the heating practice will be performed in the winter months than in the summer months.
9. **Perform a practice at an appropriate day of the week.** This rule causes the day of the week (weekend/weekday) to influence the time of the performance of practices. E.g. for working occupants, watching TV during midmorning is more likely to happen on the weekends than on weekdays.
10. **Perform a practice at an appropriate time of the day.** This rule causes the time of the day (an attribute of the HOPES environment) to influence the time at which a household performs a practice, i.e. a particular hour in the 24-hour window. E.g. if occupants work from home or stay at home during the colder months, it is likely for the heating practice to be performed during working hours on weekdays.

The audit-practices process in the HOPES model enables keeping track of the active and past practitioners and the active and past element configurations of practices. Consequently, the following rules incorporated in the adapt-elements process, cause the elements in the system to undergo changes over time.

11. **Adapt elements based on evolution.** This rule causes an element to update its state attribute based on the number of times it has been successfully used to perform the different practices. Elements that are frequently used will remain in the active state, while elements that are used less frequently will switch to a dormant state. Elements that remain in the dormant state for long enough will switch to an inactive state. Inactive elements will eventually be removed from the system.
12. **Adapt elements based on crossover.** This rule causes an element to update its value attribute based on all the different practices it is successfully used for. Values are updated using a genetic algorithm approach (see p. 218 of Gilbert &Troitzsch, 2005). Elements belonging to the same type (i.e. meaning, material or skill) that are the most frequently used will be crossed over to produce newer elements that share the characteristics of both parent elements. As an illustration of this, initially computers were exclusively used for the purpose of computation and TVs were exclusively used for entertainment. Nowadays tablet computers are used for both computation and entertainment. There is a sense in which tablet computers have some of the characteristics of both computers (parent material 1) and TVs (parent material 2).

Rules 1-12 are repeatedly applied at every simulation time step. Together with the different practices performed, the type of energy appliances used by households (provided as input to the HOPES model) influences the actual amount of energy consumed by households. Figure 2 shows the links between the processes and the rules in the HOPES model.

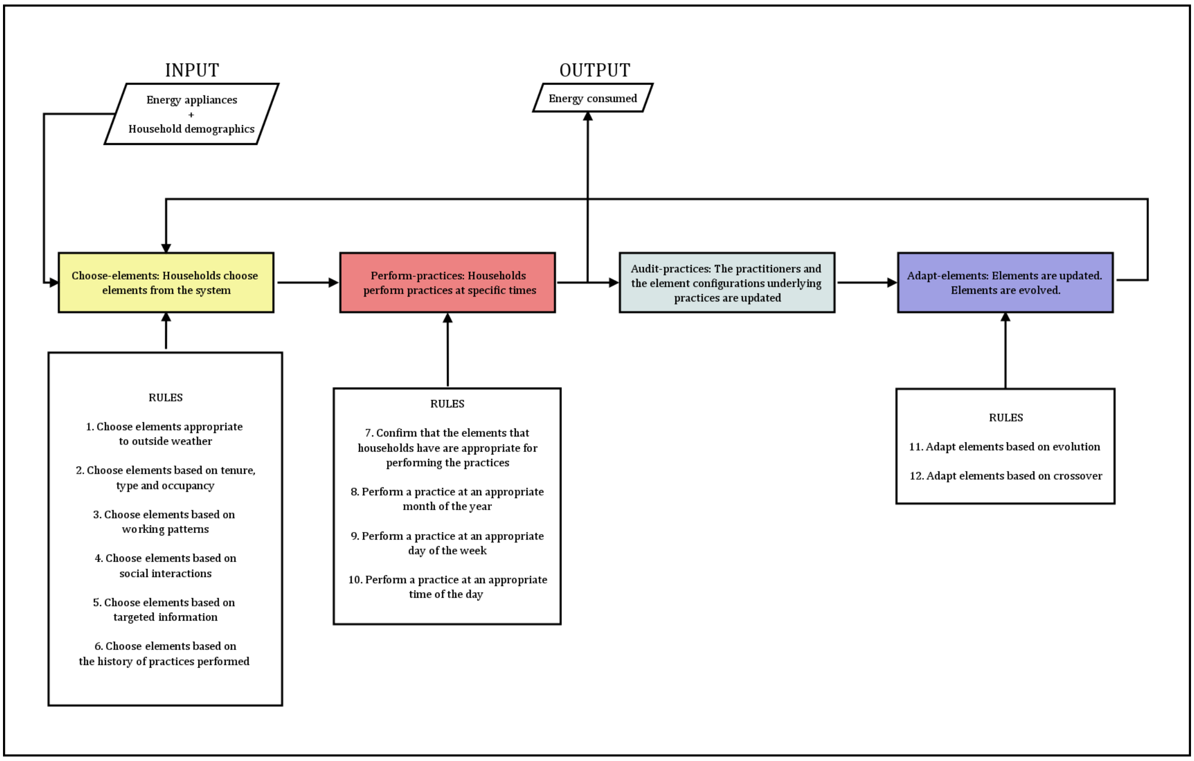

Figure 2 Processes and rules in the HOPES model

3.4 Bringing it all together: the HOPES model concept

Figure 3 brings together all the components of the HOPES model: the agents and their environment (see section 3.1), the core processes of the model (see section 3.2) and the specific rules included in the processes (see section 3.3). The figure also shows the inputs provided to the model and the output obtained from the model. Data pertaining to the demographics of households and the energy appliances used may be provided as input. The actual amount of energy consumed (in kWh) for performing the practices can be obtained as the output.

4 Other models of social practices

There are currently two agent-based approaches to model social practices. The first one considers social practices as an emergent phenomenon. Hence, when using this approach, practices emerge as a consequence of the interactions between the other components of the system. The second approach is to consider practices themselves as a category of agents in the model.

The agent-based model proposed by Holtz (2012a, 2014) is an example of the first approach. Holtz (2012b) conducted a study about meat consumption practices, based on which he proposed that the concept of *coherence* provides a good basis for modelling the emergence and the spread of social practices. He defined coherence as the level of agreement between the different types of elements in such a manner as to enable practitioners to carry out a practice smoothly. Holtz then implemented an agent-based model to simulate the emergence of social practices. In the model, the level of coherence achieved when elements come together and the level of habituation (i.e. individuals' familiarity with a practice) are considered to influence the emergence of an abstract social practice (Holtz, 2012a, 2014). On the other hand, Balke et al. (2014) and Narasimhan et al. (2015) are examples of the second approach, where practices themselves are considered as agents in the system. The HOPES model proposed in this paper is an extension of these two earlier models.

In essence, the main difference between the two approaches is that one focuses on explaining the emergence of a social practice, while the other attempts to explain the short-term and the long-term trajectories of practices. In future, the approaches may be combined in an attempt to understand the complete lifecycle of practices.

5 Discussion and future work

The HOPES model is intended to serve two purposes. Firstly, to improve our understanding of the processes linking households and practices in a recursive fashion, which in turn gives insight into the short-term and long-term trajectories of practices. The second goal is to understand the influence of the performance, the repetition, and the reproduction of practices on domestic energy use patterns. It is expected that the HOPES model can be used as a tool to examine how a practice-centric approach can be used to encourage households to adopt effective short-term changes (e.g. performing laundry during the off-peak hours) and long-term changes in the performance of practices, e.g. using the communal laundry services, district heating services, or altered working practices. Nonetheless, it is also important to determine if the proposed model is *structurally realistic,* meaning the model includes just the key structures and processes required for the organization of a real system, while not being as extensive as the real system itself (cf. Railsback & Grimm, 2011). In case of HOPES, it is important to determine if the model captures the essential aspects of a system of energy consuming social practices. One way to achieve this would be to validate and improve the HOPES model based on stakeholder feedback (e.g. from practice theorists and experts from the energy industry). Another approach is to use real world energy consumption data to guide the process of model development. This is referred to as Pattern-oriented modelling (Railsback & Grimm, 2011). The rules currently defined in the HOPES model are informed by real-world data. However, parameterisation of the rules could be improved further using existing and additional data sources. These are avenues for future work.

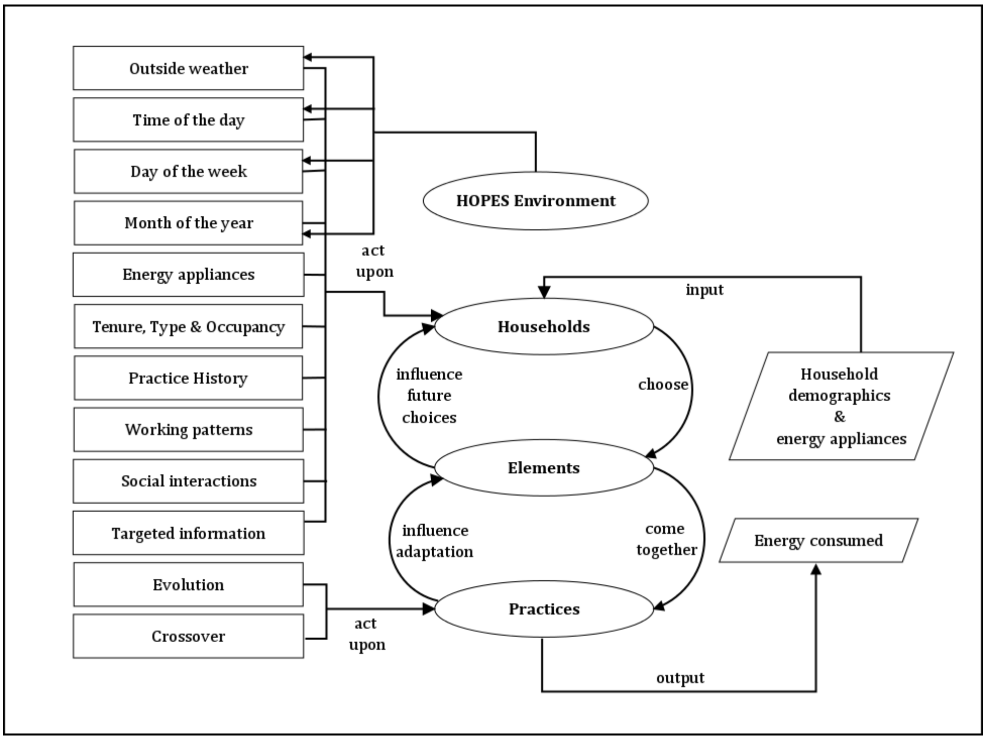

Figure 3 The HOPES model concept

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